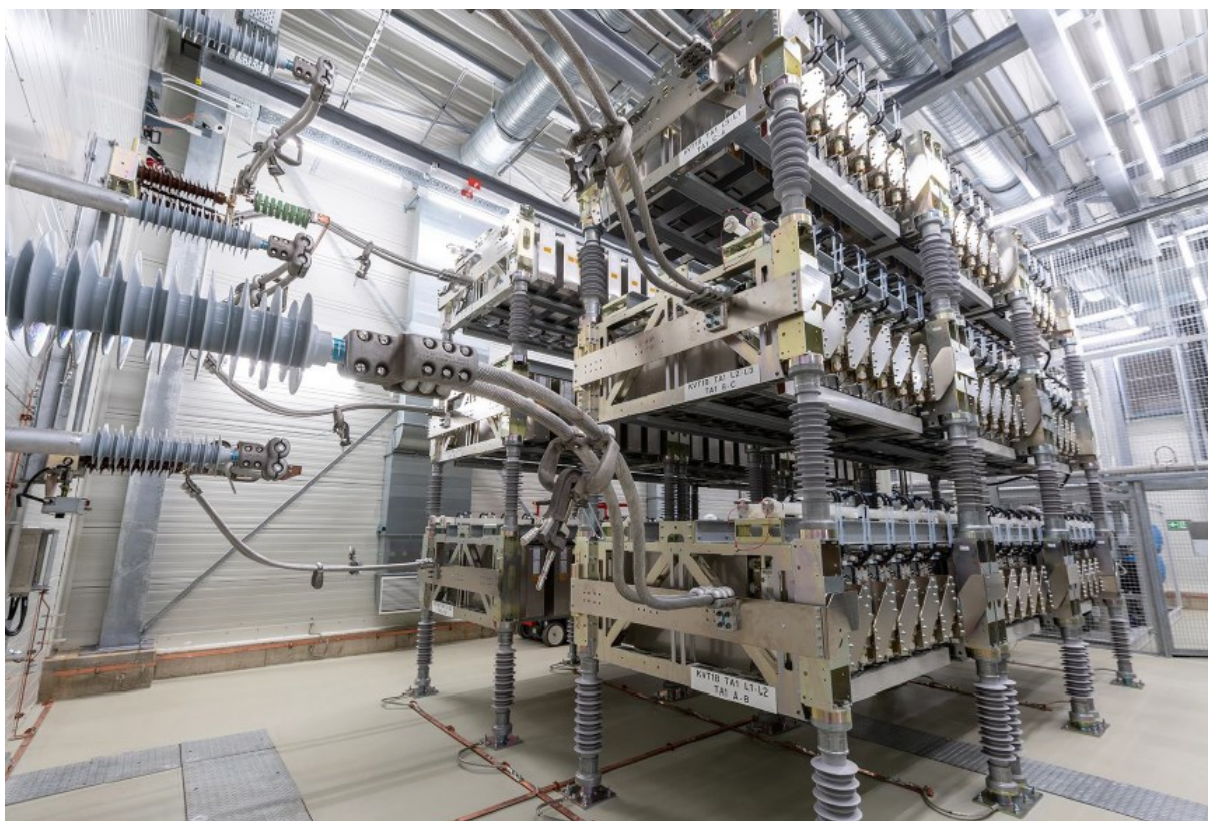




Final report dated 16.06.2023

COSTAM

Comparative performance assessment of STATCOM technologies based on modular multilevel converters architectures



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Résumé

La question fondamentale à résoudre est la suivante : « Quels sont le type, l'architecture et la stratégie de contrôle optimaux des technologies STATCOM pour augmenter la capacité d'accueil des sources d'énergie renouvelable dans les réseaux de distribution ainsi que pour fournir une flexibilité du réseau de distribution vers le réseau de transport ? ». Cette question est abordée à la fois avec une approche théorique et une approche pratique. En effet, les analyses se basent sur la littérature et en même temps sur un cas d'étude précis du bénéfice d'intégration d'un STATCOM dans le réseau moyenne tension (MT) existant de SIL. Un résumé des activités réalisées jusqu'à présent pour répondre à cette question est fourni ci-dessous.

L'analyse de la littérature concernant une multitude de structures de STATCOM a été effectuée. Après évaluation et comparaison des différentes structures, les convertisseurs de type Modular Multilevel Cascaded Converter (MMCC) ont été sélectionnés. En effet, ces structures permettent de travailler dans une large plage de tension en raison de leur modularité, elles présentent une bonne robustesse aux perturbations du réseau et sont capables de fonctionner même pendant un déséquilibre ou un défaut du réseau. Plus précisément dans ce type de convertisseur, les topologies Single Star Bridge-Cells (SSBC) également appelée Cascaded H-Bridge (CHB) en connexion étoile, Single Delta Bridge-Cells (SDBC) également appelée CHB en connexion triangle et Double Star Chopper-Cells (DSCC) également appelée Modular Multilevel Converter (MMC) présentent ces avantages sans être les topologies les plus complexes et les plus coûteuses de cette catégorie.

Un des critères importants pour l'utilisation d'un STATCOM dans le réseau électrique est sa capacité à fonctionner dans un réseau déséquilibré ou en cas de défaut du réseau (notamment un court-circuit). Lorsqu'un déséquilibre de tension ou un court-circuit intervient, la puissance par phase dans le convertisseur STATCOM est déséquilibrée. La difficulté avec ces 3 topologies est l'absence d'un bus DC commun qui empêche un échange automatique des énergies entre les phases. De ce fait, il faut utiliser une stratégie de contrôle supplémentaire afin de gérer ce déséquilibre de puissance par phase. Après une analyse approfondie des stratégies de contrôle, il en ressort que la topologie SDBC ne peut pas répondre à tous les critères du projet. En revanche, les simulations détaillées réalisées sur la topologie SSBC avec la stratégie de contrôle supplémentaire Zero Sequence Voltage Control (ZSVC) démontrent son fonctionnement de manière permanente dans tout type de déséquilibre de tension même durant des courts-circuits. Finalement, les simulations détaillées et les tests du prototype de la topologie DSCC en condition réelle avec contrôle des énergies proposé dans ce projet ont démontré que cette topologie peut continuer de fonctionner dans tous les états possibles du réseau de manière permanente sauf le court-circuit de 2 phases vers la terre. Dans ce cas-ci, le DSCC ne peut continuer de fonctionner que pendant quelques secondes avant un déséquilibre interne trop important. Etant donné la durée d'un court-circuit d'au maximum 5s de manière générale, cette topologie avec ce contrôle pourrait quand même satisfaire tous les critères. D'autres types de contrôle pourraient améliorer cet état de fonctionnement. Cela est un des points d'évolution du projet.

Une analyse des technologies de STATCOM disponibles à ce jour sur le marché a été effectuée. Elle traite de 11 fabricants différents et décrit les produits disponibles sur le marché. De plus, les produits sont comparés selon leur topologie et selon les fabricants pour analyser plus en détails le marché. Il en ressort notamment que les convertisseurs modulaires (SDBC et SSBC) sont de plus en plus utilisés notamment pour les applications à haute puissance. Pour finir, une liste des STATCOMs potentiellement implantable dans le réseau des SIL étudié est proposée.

Du point de vue réseau électrique, une partie du travail a aussi consisté à étudier les améliorations apportées par le STATCOM sur le fonctionnement du réseau électrique MT des SIL en intégrant massivement de nouvelles sources d'énergie renouvelable (RES). Pour ce faire, un modèle d'une partie du réseau MT avec charges et production PV a été réalisé avec les données fournies par SIL et MétéoSuisse. Sur la base de simulations annuelles, les effets des différents emplacements et modes de réglage du STATCOM en régime permanent ont été comparés. Les résultats montrent que la puissance de STATCOM requise pour un fonctionnement optimal peut être relativement élevée, jusqu'à 5 Mvar. Dans ce cas, il est préférable de placer les STATCOM à proximité de la sous-station de départ HT/MT ou à des nœuds bien interconnectés. Si la puissance disponible au STATCOM est limitée (en raison de contraintes d'espace ou financières), le meilleur emplacement est un nœud bien interconnecté, au « milieu » d'un feeder MT. L'efficacité d'exportation de la puissance réactive depuis le système de distribution vers le système de transport a été analysée pour deux cas de figures



relativement simples. Les résultats démontrent que les interconnexions complexes entre les deux systèmes de distribution et transport de Suisse occidentale limitent le potentiel d'un tel concept pour un STATCOM placé en MT. De meilleurs résultats seraient obtenus en plaçant le STATCOM en haute tension ou très haute tension.

Grâce à l'analyse approfondie du réseau MT fourni par les SIL, il a été possible de recréer ce réseau à échelle réduite dans le laboratoire reconfigurable des Réseaux Intelligents (Relne) de la HEIG-VD via un principe d'agrégation des charges et des lignes expliqué dans ce rapport. Ce réseau à échelle réduite a permis de tester le prototype DSCC (développé par la HEIG-VD) fonctionnant en mode STATCOM en condition réelle dans différents scénarios. Trois scénarios ont été réalisés :

- réseau faiblement chargé
- réseau fortement chargé
- réseau avec forte production basée sur la projection d'installation de PV selon les perspectives énergétiques suisse 2050+

Le laboratoire Relne permettant de mesurer les courants, tensions et puissances à n'importe quel endroit, cela a permis d'évaluer les bénéfices du STATCOM sur le réseau selon le scénario. Il en ressort que, quel que soit le scénario envisagé, le STATCOM est capable de réduire la déviation de tension par rapport à la tension nominale. Il est à noter que le STATCOM est le plus profitable lorsque le réseau est fortement chargé. Il est en revanche le moins profitable dans des conditions de forte production.

La dernière partie du projet consistait à partager et à discuter les principaux résultats du projet COSTAM avec des GRD suisses et Swissgrid. La première étape a consisté à réaliser une enquête sur la gestion de la puissance réactive dans les réseaux de distribution. Les résultats de cette enquête ont permis de préparer l'organisation et le contenu d'un workshop. La deuxième étape était la tenue du workshop permettant de partager les principaux résultats du projet COSTAM, les résultats de l'enquête et discuter des différents thèmes liés aux questions de puissance réactive dans le réseau de distribution principalement. Sept GRD ainsi que Swissgrid ont participé à ce workshop qui leur a permis de mieux comprendre les technologies actuelles disponibles pour la compensation de puissance réactive et les points de vue de chacun sur le sujet.



Summary

The fundamental question to answer is: "What is the optimal type, architecture and control strategy of STATCOM technologies to increase the hosting capacity of renewable energy sources in distribution networks and to provide flexibility from the distribution network to the transmission network?" This question is addressed from both theoretical and practical perspective. Indeed, the analyses are based on the literature and at the same time on a specific case study of the benefits of integrating a STATCOM into SIL existing Medium Voltage (MV) network. A summary of the activities carried out to date to answer this question is provided below.

A literature review of a multitude of STATCOM structures was carried out. After evaluating and comparing the different structures, the Modular Multilevel Cascaded Converter (MMCC) was selected. These structures can operate over a wide voltage range due to their modularity, they are robust to network disturbances and are capable of operating even during a network imbalance or fault. Specifically, in this type of converter, the Single Star Bridge-Cells (SSBC) topologies, also known as Cascaded H-Bridge (CHB) in star connection, Single Delta Bridge-Cells (SDBC), also known as CHB in delta connection, and Double Star Chopper-Cells (DSCC), also known as Modular Multilevel Converter (MMC), offer these advantages without being the most complex and expensive topologies of this category.

An important criterion for the use of a STATCOM in the electricity network is its ability to operate in an unbalanced network or in the event of a network fault (such as a short-circuit). When a voltage imbalance or short-circuit occurs, the power per phase in the STATCOM converter is unbalanced. The difficulty with these 3 topologies is the absence of a common DC bus, which prevents an automatic exchange of energy between phases. As a result, an additional control strategy must be used to manage this power imbalance per phase. After an in-depth analysis of the control strategies, it emerged that the SDBC topology could not meet all the project criteria. On the other hand, detailed simulations carried out on the SSBC topology with the additional Zero Sequence Voltage Control (ZSVC) control strategy demonstrate that it operates permanently under all types of voltage imbalance, even during short circuits. Finally, detailed simulations and experimental tests of the prototype of the DSCC topology under real conditions with energy control proposed in this project have demonstrated that this topology can continue to operate in all possible network states on a permanent basis except for the two phases line-to-earth short-circuit. In this case, the DSCC can only continue to operate for few seconds before excessive internal unbalancing occurs. Given that the duration of a short circuit is generally no more than 5s, this topology with this control could still meet all the criteria. Other types of control could improve this operating state. This is one of the project's development points.

An analysis of STATCOM technologies available on the market today has been carried out. It covers 11 different manufacturers and describes the products available on the market. In addition, the products are compared by topology and by manufacturer to provide a more detailed analysis of the market. In particular, it shows that modular converters (SDBC and SSBC) are becoming increasingly popular, especially for high-power applications. Finally, a list of STATCOMs that could potentially be implemented in the SIL network studied is proposed.

From a power grid point of view, part of the work also involved studying the improvements brought about by STATCOMs on the operation of SIL's MV power grid by massively integrating new Renewable Energy Sources (RES). To this end, a model of a part of the MV network with loads and PV generation was created using data supplied by SIL and MeteoSwiss. On the basis of annual simulations, the effects of different STATCOM locations and control modes under steady-state conditions were compared. The results show that the STATCOM power required for optimal operation can be relatively high, up to 5 Mvar. In this case, STATCOMs should be located close to the HV/MV feeder substation, or at well-interconnected nodes. If the power available to the STATCOM is limited (due to space or financial constraints), the best location is a well-interconnected node, in the "middle" of a MV feeder. The efficiency of exporting reactive power from the distribution system to the transmission system was analysed for two relatively simple cases. The results show that the complex interconnections between the two distribution and transmission systems in Western Switzerland limit the potential of such a concept for a MV STATCOM. Better results would be achieved by placing the STATCOM in High-Voltage (HV) or Extra-High-Voltage (EHV).



Thanks to an in-depth analysis of the MV network supplied by SIL, it was possible to create this network on a reduced scale in the HEIG-VD Intelligent Network reconfigurable laboratory (Relne), using a load and line aggregation principle explained in this report. This reduced-scale network was used to test the DSCC prototype (developed by HEIG-VD) operating in STATCOM mode under real conditions in different scenarios. Three scenarios were carried out:

- underloaded network
- highly loaded network
- network with high production based on the forecasted PV installation according to the 2050+ swiss energy perspectives

As the Relne laboratory can measure currents, voltages and power at any location, it has been possible to assess the benefits of STATCOM on the network depending on the scenario. The results show that, whatever the scenario, STATCOM is capable of reducing the voltage deviation from the nominal voltage. It should be noted that STATCOM is most profitable when the network is highly loaded. On the other hand, it is least profitable under conditions of high production.

The final part of the project involved sharing and discussing the main results of the COSTAM project with Swiss DSOs and Swissgrid. The first step was to carry out a survey of reactive power management in distribution networks. The results of this survey were used to prepare the organisation and content of a workshop. The second stage was to hold a workshop to share the main findings of the COSTAM project and the results of the survey, and also to discuss the various issues relating mainly to reactive power in the distribution network. Seven DSOs and Swissgrid took part in this workshop, which gave them a better understanding of the current technologies available for reactive power compensation and the points of view of each party on the subject.



Main findings

- STATCOM market study: This is a useful tool for the DSO in case they want to install a STATCOM in their network.
- Deep analysis of SSBC and DSCC STATCOM topologies and suitable control strategy for use even in unbalanced voltage conditions.
- Simulations shown that STATCOM best location in a MV network is a well-interconnected node. This can save time for DSO decision making.
- Reduced scale tests in Relne laboratory demonstrated that STATCOM improves voltage deviation in the network whatever the network load state (even with a scenario of high PV production). STATCOM is most profitable when the network is heavily loaded. On the other hand, it is least profitable when production is high in a distribution network.



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Abbreviations

ANPC:	Active Neutral-Point Clamped
BC:	Bridge Cell
BESS:	Battery Energy Storage System
CHB	Cascaded H-Bridge
CNPC:	Cascaded Neutral-Point Clamped
COSTAM:	COmparative performance assessment of STAtcom technologies based on Modular multilevel converters architectures
CSC:	Current Source Converter
CUF:	Current Unbalance Factor
DMS:	Distribution Management System
DS:	Double Star
DSCC:	Double Star Chopper-Cells
DSO:	Distribution System Operator
DVCC:	Dual Vector Current Control
EHV:	Extra-High-Voltage
FACTS:	Flexible AC Transmission Systems
GRD:	Gestionnaire du Réseau de Distribution
HEIA-FR:	Haute Ecole d'Ingénierie et d'Architecture du canton de FRibourg
HEIG-VD:	Haute Ecole d'Ingénierie et de Gestion du canton de VauD
HT:	Haute Tension
HV:	High Voltage
FC:	Fixed Capacitor
FCI:	Flying Capacitor Inverter
FC-TCR:	Fixed Capacitor - Thyristor Controlled Reactor
KCL:	Kirchhoff's Current Law
KVL:	Kirchhoff's Voltage Law
LPF:	Low Pass Filter
LV:	Low Voltage
MMC	Modular Multilevel Converter
MMCC:	Modular Multilevel Cascaded Converter
MSC:	Mechanically Switched Capacitor
MSR:	Mechanically Switched Reactor
MT:	Moyenne Tension
MV:	Medium Voltage
NNPC:	Nested Neutral-Point Clamped
NPC:	Neutral-Point Clamped
NSCC:	Negative Sequence Current Control



OLTC:	On-load Tap Changers
PCC:	Point of Common Coupling
PI:	Proportional Integral
PIR:	Proportional Integral Resonant
PLL:	Phase Locked Loop
PS-PWM:	Phase-Shifted PWM
PSI-LVRT:	Positive Sequence Injection Low-Voltage Ride-Through
PV:	PhotoVoltaics
PWM:	Pulse Width Modulation
QDS:	Quasi Dynamic Simulation
Relne:	Laboratoire de Réseaux Intelligents (Reconfigurable network laboratory of HEIG-VD)
RES:	Renewable Energy Sources
SC:	Short-Circuit
SDBC:	Single Delta Bridge-Cells
SFOE:	Swiss Federal Office of Energy
SiC:	Silicon Carbide
SIL:	Industrial Services of Lausanne
SM:	SubModule (cell)
SSBC:	Single Star Bridge-Cells
STATCOM:	Static synchronous COMPensator
SVG:	Static Var Generator
TCR:	Thyristor Controlled Reactor
THD:	Total Harmonic Distortion
TSC:	Thyristor Switched Capacitor
VSC:	Voltage Source Converter
WPx:	COSTAM project Work Package number x
ZSCC:	Zero Sequence Current Control
ZSVC:	Zero Sequence Voltage Control



1 Introduction

1.1 Background information and current situation

Swiss energy strategy plans massive integration of RES (e.g., wind or solar power) into distribution power grids. This massive integration can lead to some network issues like harmonics, voltage fluctuations and the increase of the faults. However, distribution grid must continue to address the national grid-codes. To do so, additional systems can be used to address grid code compliance requirements (e.g. reactive power compensation, voltage control, fault ride through capabilities and so on) and secure the grid, protecting a renewable energy plant against network faults, voltage drops and other issues that often result in the wind turbines or solar arrays tripping offline. These systems use capacitors and inductors. They are inserted in the network when necessary and are split in 2 categories:

- Switched systems: made either of capacitors or inductors, they are inserted using an adequate switch. These systems are called MSC and MSR;
- Power electronic systems (FACTS): they are converters based on different semiconductors, topologies and controls.

Switched systems are switched with very low frequency and the reactive power amount is fixed. They are not able to address all issues above mentioned contrary to power electronic systems that are fast and able to address all of them. This is the reason why the COSTAM project only deals with power electronics systems.

Furthermore, they can contribute in provision of flexibilities from distribution grids toward high voltage transmission grids. In Switzerland, Swissgrid maintains the voltage of the extra-high-voltage transmission grid (220 or 380kV) within a very narrow range, by acting on the reactive power exchanges of the power plants directly connected to the transmission grid. However, from January 1, 2020, new other players can participate in maintaining the voltage, using their power plants and/or facilities directly connected to the transport network, namely:

- Power plant operator;
- DSO;
- Operator of neighbouring systems;
- Manager of customer installations.

The power plant operator must actively participate in maintaining the voltage, while the others are required to participate semi actively. The latter three, if they meet the technical requirements, can prequalify for active voltage support using one or more installations. The implementation of the voltage plan is based on the principle of "power and capacities" of the participants. They must support voltage level by continuously adapting the exchange of reactive energy. The reactive energy exchanged is divided into 3 ranges depending on the requirements of Swissgrid, as follows:

- Non-compliant range: reactive energy is billed by Swissgrid to the participants;
- Compliant range: reactive energy is paid by Swissgrid to the participants;
- Free range: reactive energy is neither billed, nor paid by Swissgrid to the participant [1].

In this context, it is evident the interest for the DSO's and other participants to improve their capability of management of the reactive power in their whole grid. Based on above considerations, power electronic technologies for reactive power compensation are especially of interest. Among different power electronic technologies for reactive power compensation, STATCOM technologies are the most promising. They form a subgroup of the global FACTS family and was deeply analysed in this project (see [2]).



1.2 Purpose of the project

The key research question of this project based on the challenges mentioned in the previous section is:

"What are the optimal types, architectures and control strategies of STATCOM technologies to increase the RES hosting capacity of distribution grids as well as provision of flexibilities from distribution grid toward transmission grid?"

1.3 Objectives

Firstly, this project proposes a state of the art of the power electronic devices used as reactive power compensators and explains why STATCOM topologies based on Modular Multilevel Converters architectures are the most promising STATCOM topologies to address the issues linked with massive integration of RES at distribution grid level and flexibility provision towards transmission grid level. In the same time, a market technologies analysis is realized to verify literature and see actual market trends.

Secondly, the real MV distribution grid of SIL (Lausanne DSO, partner of the project) is used as a case study to deeply analyse the best modular architectures selected by the first objective. To use it properly, a model the SIL MV grid has to be realised. RES hosting capacity increase and reactive power exchange between distribution and transmission grid are also analysed.

Thirdly, the location of STATCOM inside the MV grid, control strategy, as well as the sizing of STATCOM reactive power is realised thanks to performance indices defined for this project.

Fourthly, thanks to the previous work, the best modular architectures are deeply investigated (controls, simulations and tests) from the power electronics point of view based on the SIL MV grid. The aim is to validate the idea that these modular topologies are promising candidates in a real case study of a Swiss DSO.

Fifthly, STATCOM LV prototype is tested in the Relne laboratory which is set up as the in case-study MV network. The experimental results confirm the benefits of the STATCOM from a power system point of view.

The final objective, to extend the study and tailor it to the needs of other Swiss DSOs. A suitable workshop will be organised with them to share the findings of this project and highlight other possible scenarios in which STATCOM can contribute to solve issues.



2 Description of facility

HEIG-VD team already developed in previous projects 2 different LV modular converter prototypes presented in Figure 1. These prototypes have a 5 [kVA] power capacity for a balanced LV operation. The one on the left side is planned to be used for the SSBC/SDBC topologies and is composed of 5 cells by phase (total of 15 cells). The one on the right side will be used for the DSCC topology; it contains 5 cells by arm (total of 30 cells). One cell is shown on Figure 2.



Figure 1: LV modular converter prototypes



Figure 2: One submodule (cell) of the prototypes

In the next steps of the project, these prototypes will serve to verify the simulation results. Furthermore, the tests will be realised in the Relne Laboratory, located in HEIG-VD facility. This laboratory, with nominal power of 100 kVA, consists of flexible hardware and software platform capable to emulate a wide number of grid topologies. The schematic of possible applications is given in Figure 3. Even if the project is dealing with MV grid, it is possible to represent a MV grid operation in an equivalent reduced LV scale thanks to Relne laboratory.

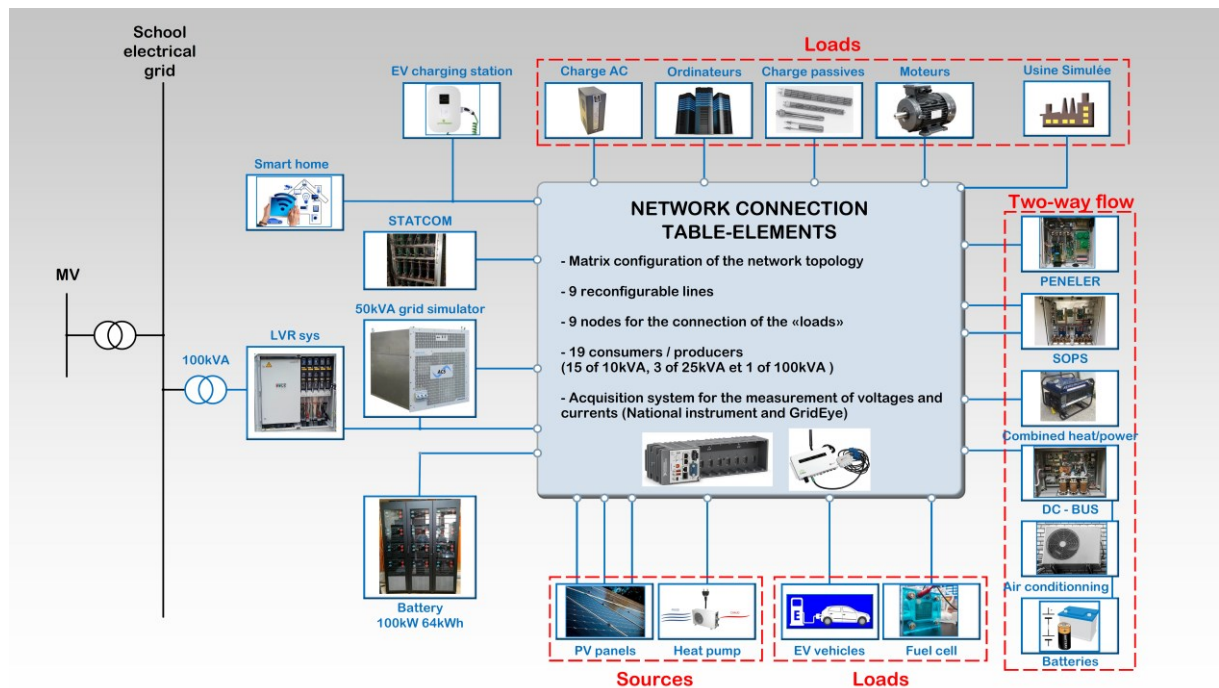


Figure 3: Relne Laboratory structure



3 Structure of the final report

This project is organized in nine main technical work packages. The content of these work packages is presented hereafter:

- **WP1: Modular STATCOM structures analysis.** This analysis is divided into 4 parts. The first part focuses on overall reactive power compensators state of the art leading to the selection of the most promising architectures (modular STATCOM) to address distribution grid issues. The second part analyses the mains SIL defaults grid states STATCOMs should cope with. These two parts are presented in detail in deliverable [2]. The third part is an analysis of the STATCOM technologies available on the market with a special chapter listing possible market products that could fit with SIL MV grid case study. Detailed results are presented in [3]. The final part was the deep comparison of most promising architectures among modular STATCOMs in case of high grid voltages imbalance (especially based on defaults considered in [2]) via simulations. Furthermore, DSCC STATCOM prototype experimental tests were realised to confirm simulation results. The results of this last part are fully detailed in [4] and section 4.3 of this report. All results of WP1 are summarized in section 4.
- **WP2: Preliminary system (grid) analysis and test cases definition.** In this work package, the possibilities to place a STATCOM into the SIL MV grid are analysed. Two different network areas are selected. All the useful information to study and simulate the sites are gathered. Each network area envisaged is a MV grid fed by a HV/MV substation. One site has the advantage of being a substation connected to the EHV network of Swissgrid and also of having a high number of solar generation systems connected to the LV network supplied by this substation while other one is planned to eventually host a wind farm with a power generation up to 30MW. A set of quantitative performance indices used to assess the benefits of STATCOM for grid operation are defined. This part is presented in detail in [5]. All results of WP2 are summarized in section 5.
- **WP3: Test cases simulations.** In WP3, grid simulations for the network areas selected in WP2 are performed in order to evaluate the benefits of the STATCOM insertion. A preliminary benefits analysis of different STATCOM locations, sizes and control objectives is also carried out by comparing these options against each other and to other approaches for (distributed) voltage control. This contributes to specifying the control and ratings of a STATCOM for different use-cases in MV networks. Similarly, this work is considered in the requirements for the Relne Laboratory set-up (WP5). WP3 also includes the development of load/generation scenarios for the present and future situation of the network considered. This part is also presented in detail in [5]. All results of WP3 are summarized in section 6.
- **WP4: STATCOM prototypes modifications.** According to the results of WP1 and taking into account the results of WP2 and WP3, the existing prototypes are modified to fulfil the requirements. Namely, the prototypes are modified to be the LV representative reduced scale of a full scale MV system, especially concerning topologies, control and hardware. The two prototypes are then installed in the Reine laboratory. Detailed explanations are available in [6]. Main explanations of WP4 are summarized in section 7.
- **WP5: Relne Laboratory setup.** In this work package the Reine laboratory is set up to realise experimental tests based on the SIL MV case studied in WP3 with DSCC STATCOM prototype. A network reduction technique is applied to reduce the size of the network while the main characteristics are kept. The line parameters of the LV Relne network are adapted to fit MV case study. A set of emulators (static loads) and real generations (such as PVs) are programmed and installed according to the requirements of each test. The detailed results of WP5 are presented in section 8 of this report.
- **WP6: Laboratory tests.** The DSCC prototype is tested in the Reine laboratory according to scenarios based on the WP2 and WP3 results. The test results are acquired in the Relne laboratory via voltages, currents and power of each Relne node and line. Thanks to these results, the benefits of the STATCOM in these scenarios is explained. The detailed results of WP6 are presented in section 9 of this report.
- **WP7: Design feedback.** This work package was explicitly dedicated to project risk management. There is nothing to share with the reader in the final report for this work package.
- **WP8: Generalisation of the STATCOM applications.** This work package is devoted to the extrapolation and generalisation of the test cases studied in WP3 to a more general application in



the Swiss context, with the hypothesis of increasing penetration levels of RES. This will allow to better understand the use of Modular STATCOM in real application cases. A workshop involving swiss DSOs and Swissgrid was organised in order to investigate other possible problematics and applications to be studied. Section 10 of this report presents workshop organisation and outcomes.

- **WP9: Dissemination and Final Report.** This work package is devoted to the dissemination activities and the writing of the final report. The final report is the current document. The list of technical papers already published or under review are listed in 14.

The work packages results of the projects (detailed or summarised results) are presented in this final report from section 4 to 10.



4 WP1: Modular STATCOM structure analysis

This section summarizes all activities and results linked with WP1. More precisely:

- section 4.1 gives the results of the state-of-the-art analysis of STATCOM converters that are the most promising for COSTAM project scope. Furthermore, the best topologies selected for a detailed analysis are reminded. Furthermore, all the possible voltage states (including faults) at the location where it is best suited to connect the STATCOM in the SIL MV grid “B” are summarized. Detailed explanations are available [2].
- Section 4.2 summarizes the results of the STATCOM market technologies analysis. Furthermore, a tool table is provided with STATCOM market products available that could fit SIL case study. Detailed explanations are available in [3].
- Section 4.3 deeply compares the most promising STATCOM topologies (SSBC and DSCC) via simulations. The comparison results are presented in section 4.3.9. In addition, DSCC STATCOM prototype tests were realised confirming simulation results (see section 4.3.10). After reading this section, the reader will know which STATCOM modular topologies are able to operate under every possible grid voltage state (including short-circuit condition).

4.1 STATCOM structures comparison and possible grid voltages

4.1.1 Modular structures comparison and selection of best topologies

Different existing converter technologies have been studied and compared. The topologies selected for a STATCOM application are MMCCs. These topologies have the main advantage of being able to work in a wide voltage range due to their modularity. Moreover, the number of voltage levels can be selected according to the desired THD, they are robust to network disturbances and are able to act on network unbalance. The decision diagram is shown in Figure 4.

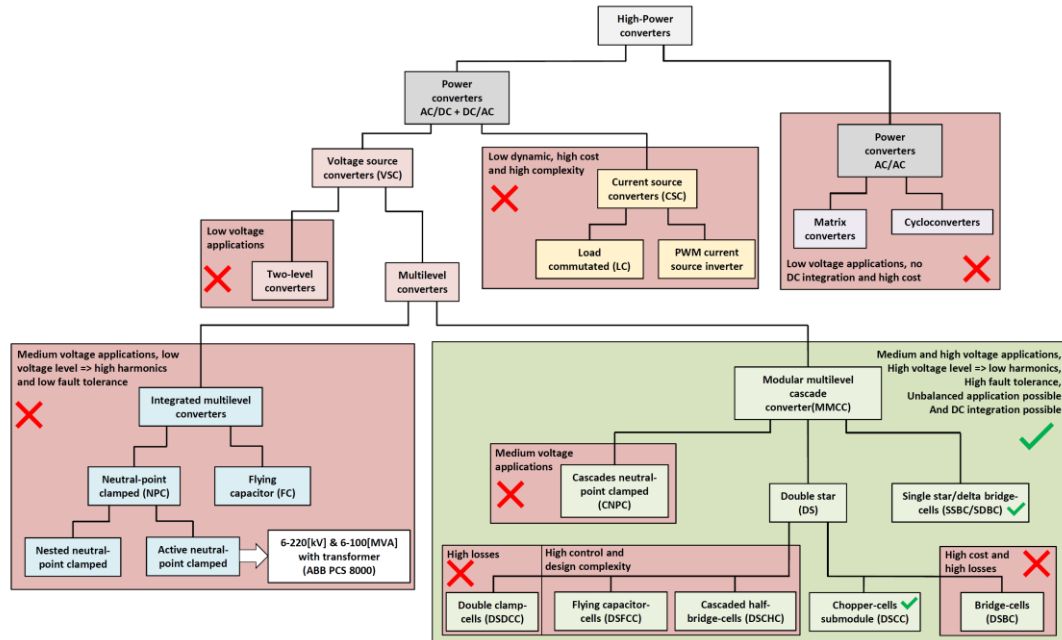


Figure 4: Decision diagram, taken from [2]

The three final topologies selected, all from the MMCC type, are the Single Star Bridge-Cells (SSBC), the Single Delta Bridge-Cells (SDBC) and the Double Star Chopper-Cells (DSCC). For a detailed explanation of the choice, see [2].



4.1.2 Possible voltages applied to the STATCOM in SIL MV grid

The SIL MV grid voltage is well balanced in normal operation. However, sometimes, some temporary faults can appear in the network. The main faults that could happen are single-phase and two-phase to earth short-circuits, generating strong unbalance (U^-/U^+). Based on the results of [5], the idea of this section is to present all the possible unbalanced voltage the STATCOM has to struggle with. During these temporary unbalanced the objective is that the STATCOM continue to operate.

Thanks to the results taken from [5], the location to put the STATCOM in the MV grid is selected. This is the “Boisdavaux” substation that can be seen with “D” in Figure 70. Based on this location, 4 faults were analysed to give all the possible unbalances (U^-/U^+). They are listed above:

- single-phase to earth short-circuit directly at the “Boisdavaux” substation;
- two-phase to earth short-circuit directly at the “Boisdavaux” substation;
- single-phase to earth short-circuit at the “Polny” substation (that can be seen as “B” in Figure 71)
- two-phase to earth short-circuit at the “Polny” substation.

A detailed analysis of the voltages at STATCOM substation for each of these 4 faults is performed in [2]. The results (using symmetrical components U^+ and U^- , presented in [2]) are summarized in the Table 1.

Substation	Boisdavaux				Polny			
Short-circuit type	single-phase		two-phase		single-phase		two-phase	
	Amplitude [pu]	Phase [rad]	Amplitude [pu]	Phase [rad]	Amplitude [pu]	Phase [rad]	Amplitude [pu]	Phase [rad]
U^+	0.986	2.624	0.492	-2.094	0.987	-2.211	0.640	-0.259
U^-	0.006	2.405	0.492	2.094	0.005	-2.524	0.352	-2.213
U_z	0.992	-0.519	0.492	0.000	0.996	0.923	0.493	1.915

Table 1: Grid voltage sequences at “Boisdavaux” substation when a fault occurs in the grid, taken from [2]

From the results presented in Table 1, three cases can be defined:

- Single-phase short-circuit: no matter in which substation the default occurs, the positive and zero sequences are near 1 [pu] and the negative sequence is near 0 [pu].
- Two-phase short-circuit in Boisdavaux: the three sequences have the same amplitude. It gives a high degree of unbalance $\frac{U^-}{U^+} = 1$.
- Two-phase short-circuit in Polny: the three sequences have different amplitude. The degree of unbalance is high, $\frac{U^-}{U^+} = 0.55$.



4.2 STATCOM market technologies analysis

The aim of this part is to make a review of main STATCOM technologies available on the market nowadays. Then these technologies are compared based on the following criteria:

- Converter topology (architecture and power modules);
- Voltage level: LV, MV or HV;
- Power range;
- Cooling system;
- Footprint;
- Cost.

The first job was to select trusted manufacturers. Methodology is presented in Figure 5.

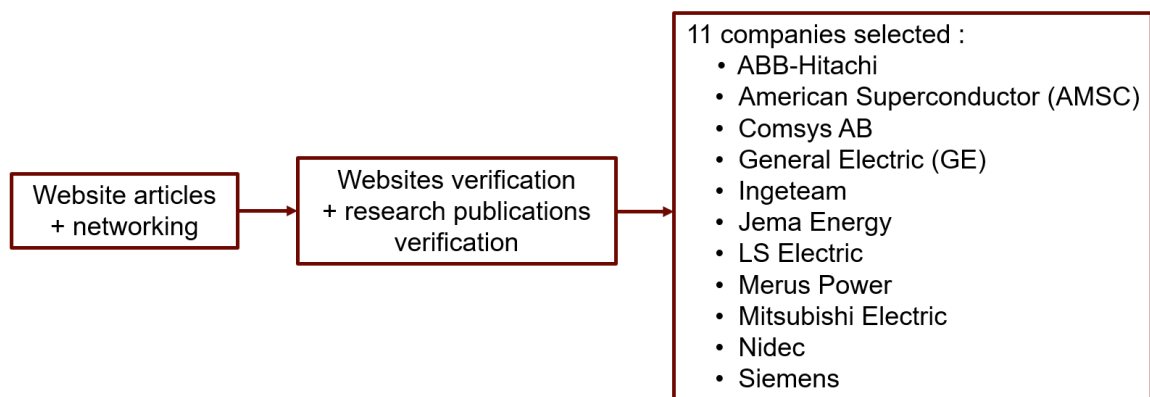


Figure 5: Manufacturers selection methodology, taken from [3]

Then a table with STATCOM products and their criteria above mentioned is proposed for each selected manufacturer. All these tables are available [3].

Every STATCOM products are then compared between their topologies and their manufacturers according to criteria above mentioned.

All elements analysed are finally applied to the SIL MV grid case study of the project. A list of possible STATCOMs that could fit the SIL case study is provided. This list is presented in [3] and is recalled in Table 2. The colours in the table are respectively green for 2-level converters, orange for SSBC and blue for 3 level NPC. Detailed explanations of Table 2 are available in [3].

Cost information are sensitive and manufacturers do not want to let them publicly accessible. This is the reason why in [3] and Table 2 cost information is shown as confidential. A separate report containing this information was sent only to the partners of the project.



Model name	Manufacturer	11 kV voltage fitting	Power range available [Mvar]	Topology	Cost estimation [kUSD]
PCS100	ABB-Hitachi	Possible if transformer adapted	1.076 and 10	2-level	no information
VAR PRO	ABB-Hitachi	Possible if transformer adapted	1 and 10	2-level	no information
D-VAR	AMSC	Possible if transformer adapted	2 to 10	2-level	CONFIDENTIAL
D-VAR VVO	AMSC	OK without transformer	1 to 4	SSBC	CONFIDENTIAL
ADF P700	COMSYS	OK with transformer	1 to 10	2-level	CONFIDENTIAL
General Electric STATCOM	General Electric	no information	no information	SDBC	no information
JEMA LV STATCOM	Jema Energy	Possible if transformer adapted	1 to 3	2-level	no information
JEMA MV STATCOM	Jema Energy	Possible if transformer adapted	10	no information	no information
Panel STATCOM	LS Electric	Possible if transformer adapted	2 to 10	3-level NPC	no information
M-STATCOM	Merus Power	Possible if transformer adapted	1.36 to 10	no information	no information
SILCOVAR D	Nidec	Possible if transformer adapted	0.5 to 10	3-level NPC	no information
SILCOVAR H	Nidec	OK without transformer	4.763 to 7.621	SSBC	no information
EASY STATCOM	Siemens	OK with transformer	2.5 to 10	3-level NPC	CONFIDENTIAL

Table 2: List of STATCOMs adapted to SIL case study, taken from [3]



4.3 Modular STATCOMs operating range: simulations and prototype validation tests

4.3.1 Purpose of this section

Different STATCOM topologies are possible to exchange reactive power with the electrical grid. From previous work (section 4.1 and [2]), three configurations have been chosen. They are: SSBC, SDBC and DSCC. According to literature review in section 4.1 and [2], these topologies are able to work on medium and high voltage balanced grid and to continue to operate during some grid imbalances. This interesting advantage compared to conventional topologies brought us to investigate their full potential.

To ensure that the topologies are able to work in every possible grid voltage state, control design and preliminary simulations via “Plecs blockset” (version 4.5.7) and Matlab/Simulink (version 2021b) softwares were realised in [4]. A summary of preliminary results is presented from section 4.3.2 to 4.3.5 of this report. Detailed explanations are available in [4].

Most promising STATCOM topologies (SSBC and DSCC) are deeply compared via simulations in this report. Furthermore, DSCC STATCOM prototype tests were realised confirming simulation results. The detailed comparison and test results are presented from section 4.3.6 to 4.3.10.

At the end of this section, the reader will know which STATCOM modular topologies are able to operate under every possible grid voltage state (including short-circuit condition).

4.3.2 Identification of worst-case grid voltage states STATCOM has to cope with

Firstly, to be sure that the topologies are able to work in every possible grid state, the worst grid state cases were found in section 4.1 and [2]. They correspond to 1 line-to-earth and 2 lines-to-earth short-circuits directly at the substation where the STATCOM is connected. These situations cause a high degree of imbalance in which voltage amplitudes and phase shift between phases are the main issues the STATCOM has to cope with. This point is confirmed by the simulations realised on SIL network case study during these faults in section 4.1, [2] and [4]. Worst case grid voltage parameters at STATCOM substation (which is Boisdavaux substation in SIL network) are presented again in Table 3.

STATCOM substation	Boisdavaux			
Network state	1 line-to-earth short-circuit directly at Boisdavaux substation		2 lines-to-earth short-circuit directly at Boisdavaux substation	
	Amplitude [pu]	Phase [rad]	Amplitude [pu]	Phase [rad]
Positive sequence: U^+	0.986	2.624	0.492	-2.094
Negative sequence: U^-	0.006	2.405	0.492	2.094
Homopolar sequence: U_z	0.992	-0.519	0.492	0.000
VUF: $\frac{U^-}{U^+} \cdot 100$	0.6 [%]		100 [%]	
Phase voltage: U_{L1}	0	0	0	0
Phase voltage: U_{L2}	1.710	0	0	0
Phase voltage: U_{L3}	1.714	-1.037 (shift with L2)	1.476	0

Table 3: Worst case grid voltage parameters at STATCOM substation

In Table 3, positive, negative and homopolar sequences allow calculation of the Voltage Unbalance Factor (VUF). This factor represents the degree of imbalance at this substation. For more information on these factors see [2].

It can be seen that for 1 line-to-earth short-circuit directly at Boisdavaux substation, the degree of imbalance is close to 0. However, in this case U_z is high. The importance of the homopolar sequence can be problematic if the STATCOM neutral is connected to ground. Fortunately, the neutral in this topology is floating (not connected to ground). Thanks to this, STATCOM is not affected by the high value of homopolar sequence. However, it is important to note that the voltage of the lines increase to



around 1.7 times the nominal value. According to all of this, 1 line-to-earth short-circuit is the second worst case the STATCOM has to cope with.

The worst case is then 2 lines-to-earth short-circuit directly at Boisdavaux substation. The degree of imbalance ($VUF = 100\%$) is very important as well as the contribution of homopolar sequence. Furthermore, the voltage of the last line still connected to the network increase to around 1.476 times the nominal value.

4.3.3 STATCOM control strategies and current operating ranges for the project

To perform simulations and verify the STATCOM can cope with these imbalances, as suitable control strategy of the converter has to be used. These control strategies for each topology are deeply explained in [4].

An important point to note is that the STATCOM is not able to restore grid voltage balance in an unbalanced network. However, the interesting point we study in this project is the ability of the modular topologies of STATCOM to operate even during these faults and can help the network to rebalance when fault is cleared. Indeed, with significant imbalance or in case of fault, conventional 2-level STATCOM converters have to disconnect from the grid. Then, they have to be restarted on a balanced network meaning it cannot help to restore balance.

Concerning the current exchanged between the STATCOM and the grid, the goal is to always exchange a certain amount of balanced current (positive sequence of current) whatever the grid voltage state. More precisely, the goal is to send positive sequence inductive or capacitive reactive power according to network needs and whatever the grid voltage imbalance. It is worth to keep in mind that a negligible amount of the current is mandatorily used as active power to compensate the losses in the STATCOM.

4.3.4 Pre-study elimination of topologies not suitable for 100% VUF

Each STATCOM topology studied works well on a balanced grid without any fault. So, evaluation of each STATCOM topology is done on its capability to operate properly when a fault occurs in the grid. Before deeply investigate the behaviour of these 3 topologies in simulations and tests, the three STATCOM structures operating range were evaluated in [4]. The conclusion of this pre-study is summarized hereunder:

- SSBC: as explained in [4], the ZSVC control strategy is sensitive to high degree of current unbalance ($\frac{I^-}{I^+}$ close to 100%) and support all kind of unbalanced voltage. In our study, there is no need to compensate unbalanced current. It means we always work imposing $\hat{I}_n = 0$. Then the ZSVC control strategy seems to allow the SSBC to continue its operation during network fault. On the contrary, the NSCC strategy cannot be used when it has a two-phase short-circuit directly at the STATCOM substation because $VUF = 100\%$. This topology controlled via ZSVC strategy is deeply investigated via simulations. The results are presented hereafter in this section 4.3.
- SDBC: as explained in [4], the ZSCC strategy control is sensitive to high degree of voltage unbalance ($\frac{V^-}{V^+}$ close to 100%) and support well unbalanced current. As previously mentioned, $VUF = 100\%$ in the case of two-phase short-circuit directly at STATCOM substation. Due to this, the ZSCC strategy cannot be used at this operating point. It is the same conclusion for the NSCC strategy as explain for the SSBC structure. This topology cannot fit for the operating range of the project. It will not be further investigated in this project however this topology is interesting for other applications where voltage imbalance is low but currents are highly unbalanced.
- DSCC: According to state of the art presented in [2], DSCC topology having more degree of freedom than SSBC and SDBC and with a suitable control, is able to work with every type of imbalance. The control strategy proposed in this project for unbalanced grid operation is presented in [4]. This topology is deeply investigated via simulations and results are also confirmed by prototype tests in the Relne laboratory. These results are presented hereafter in this section 4.3. As a remark, it is out of the scope of this project but we confirmed by simulation that DSCC is able to operate with 100% unbalanced currents with balanced voltages.

Thanks to this pre-study, we eliminated the SDBC topology unable to work properly in all network voltage states. Hereafter, a deep investigation is performed on the DSCC and SSBC topologies via their respective control in simulations. Experimental results on the reduced scale DSCC prototype designed by HEIG-VD team are also presented.



4.3.5 Preliminary simulations to verify correctness of internal control strategies

In [4], a first set of simulations were realised to prove the well operation of the internal control of both topologies. On a balanced grid voltage, the cluster voltages (sum of internal submodules voltage of the topologies) and the voltage of each submodule inside each leg were voluntarily unbalanced. Then the internal control was activated. It allowed to re-balance the cluster voltages and submodule voltages of each leg meaning internal control are operational. For more information, please refer to [4].

4.3.6 Method of STATCOM operation validation for all possible grid voltage states

The method proposed to validate the proper STATCOM operation in all possible grid voltage states is as follows. The STATCOM operation in both transient and steady-state is analysed in simulation with three different grid voltage states:

- Balanced voltages
- One line-to-earth short-circuit directly at STATCOM substation
- Two lines-to-earth short-circuit directly at STATCOM substation

Indeed, these 3 grid voltage states cover the nominal (balanced) and worst case (two lines-to-earth short-circuit directly at STATCOM substation). If STATCOM operation is validated for these 3 states, it means it works for every other unbalanced grid voltage state in between.

For each grid voltage state, the aim is to exchange the nominal positive sequence reactive powers between STATCOM and the grid. Indeed, if the nominal values are reached, values in between are reachable too.

As a reminder, STATCOM prototypes used in this project are designed for LV applications. Given that the COSTAM project study is focused on MV or HV grid operation, figures are given in per unit (pu). The base quantities used for these prototype tests are:

- $S_{baseTests3\phi} = 3 \text{ kVA}$
- $S_{baseTests1\phi} = \frac{S_{baseTests3\phi}}{3} = 1 \text{ kVA}$
- $V_{baseLineNeutralTests} = 200 V_{pk}$ (it corresponds to the peak voltage for easier reading on graphs but the base for RMS voltage values is: $\frac{200}{\sqrt{2}} = 141.42 V_{rms}$)
- $I_{baseTests} = \frac{S_{baseTests1\phi}}{\frac{V_{baseLineNeutralTests}}{\sqrt{2}}} \cdot \sqrt{2} = 10 A_{pk}$ (it corresponds to the peak current for easier reading on graphs but the base for RMS current values is: $\frac{10}{\sqrt{2}} = 7.07 A_{rms}$)

For the prototype testings, nominal voltage was chosen to $200 V_{pk}$ according to the voltage limit reachable by the grid simulator available in HEIG-VD Relne Laboratory. According to MV network case study analyses realised in [5] and [2], phase voltage can reach until 2.12 pu during short-circuits transient. It means 2.12 pu must stay under the maximum reachable voltage of the grid simulator ($431 V_{pk}$). Choosing $V_{baseLineNeutralTests} = 200 V_{pk}$ gives $V_{maxLineNeutralTests} = 200 * 2.12 = 424 V_{pk} < 431 V_{pk}$ grid simulator limit.

To reach reactive power management whatever the grid voltage state, the goal of our study is to provide the balanced base current ($I_{baseTests} = 10 A_{pk}$) to the grid whatever the voltage state. The reasons are the following:

- during balanced grid voltage operation, unbalanced current exchange would lead to grid voltage unbalance
- during unbalanced grid voltage operation, unbalanced current exchange would lead to deteriorate even more grid voltage unbalance

This methodology is realised in simulation for both SSBC and DSCC topologies in sections 4.3.7 and 4.3.8. These topologies are then compared in section 4.3.9. Even better, experimental results for the DSCC prototype are also presented validating simulations correctness in section 4.3.10. Due to hardware issues it was impossible to provide the SSBC prototype experimental results.



To lighten the report content and facilitate reading of the report, for each grid voltage state a deep analyse of inductive reactive power case is proposed while the capacitive case is only summarized. The detailed results for capacitive case are available in section 16 Appendices.

4.3.7 SSBC simulation results

Simulation results presented in this section confirm the ability of the SSBC with this control strategy to continue to operate permanently when grid voltage state is balanced, during one line-to-earth short-circuit and during two lines-to-earth short-circuit situations.

4.3.7.1. SSBC simulations with balanced grid voltages

The SSBC simulations use the electrical schematic presented in Figure 6.

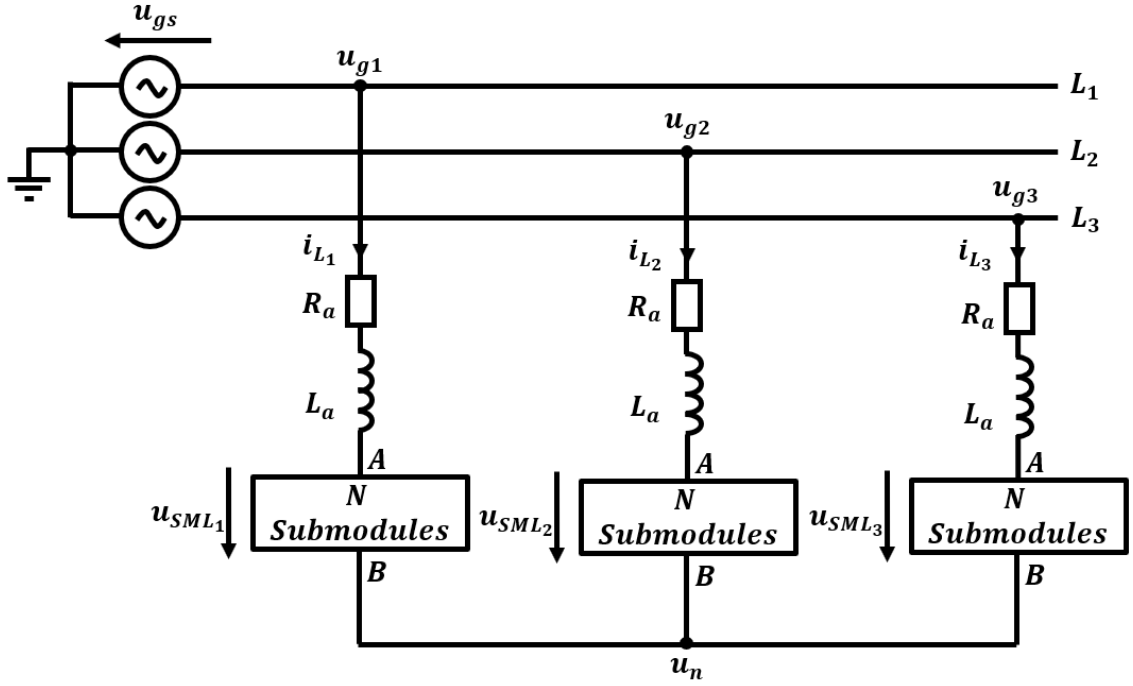


Figure 6: SSBC simulations electrical schematic

In the schematic in Figure 6, the SSBC converter is coupled with a 3-phase ideal electrical network via inductors and their intrinsic resistor. The submodules of SSBC are H-bridges with capacitance C_{sm} . The parameters of the simulations are given in Table 4.

Parameter	Value	Parameter	Value
$U_{gs \text{ balanced}}$	1 [pu] = 200 [V _{pk}]	$u_{SM_L}^{\Sigma*}$	343 [V] = 1.715 [pu]
f_g	50 [Hz]	f_{sw}	1 [kHz]
L_a	15 [mH]	$t_{deadband}$	1 [μs]
R_a	200 [mΩ]	f_{sample}	5 [kHz]
N_{sm}	5 [-] (SM by arm)		
C_{sm}	3.63 [mF]		
$S_{baseTestS3\phi}$	3 [kVA] = 1 [pu]		

Table 4: Simulation parameters for SSBC simulations

In Table 4, $u_{SM_L}^{\Sigma*}$ is the nominal value for the cluster voltage (by arm). Each submodule switches at a frequency of f_{sw} with a dead-band time of $t_{deadband}$. Finally, the sampling of each measure is done at $f_{sample} = f_{sw} * N$.



In this simulation, grid voltages (u_{gs}) are balanced 50 Hz sinusoidal waveforms with peak value of 1 pu. They are visible in Figure 7.

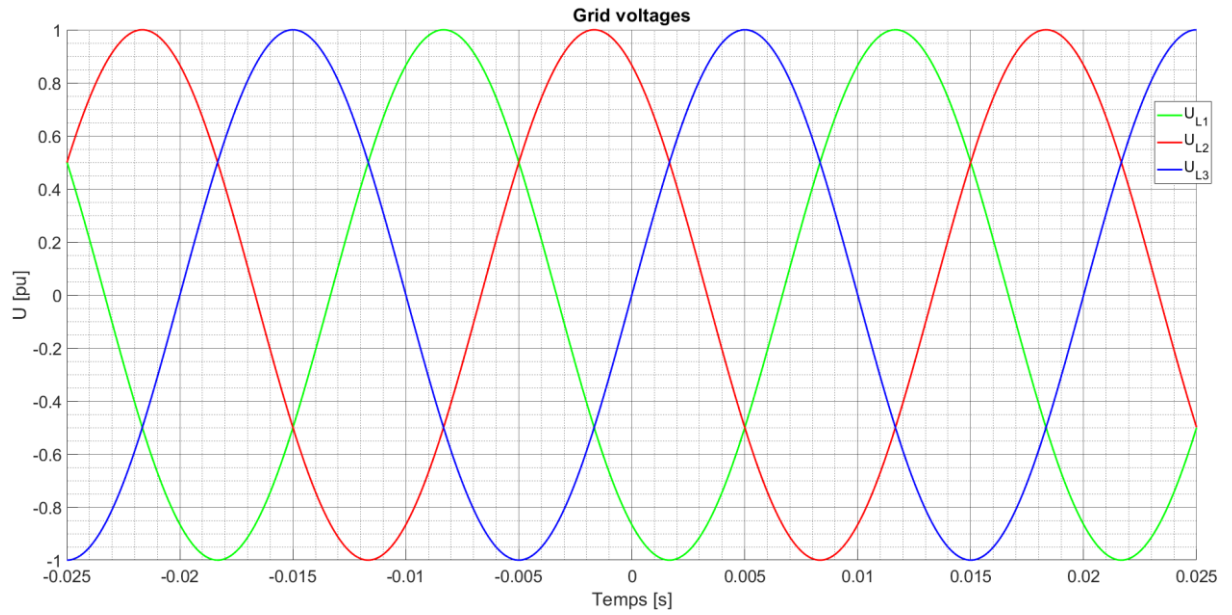


Figure 7: Grid voltages balanced in simulation

When reactive power reference is set to $Q_{STATCOM}^* = +1$ pu (inductive case), grid currents are well balanced with Current Unbalance Factor (CUF) = $\frac{I_-}{I_+}$ = of 0.0%. Their fundamental peak value are all of 1.000 pu. These three balanced currents exchanged between SSBC converter and grid are visible in Figure 8. THD of the currents of all phases are around 1.9% in the simulation for balanced grid voltages. As a remark, it should be noted that the current direction for measurement follows the direction of Figure 6.

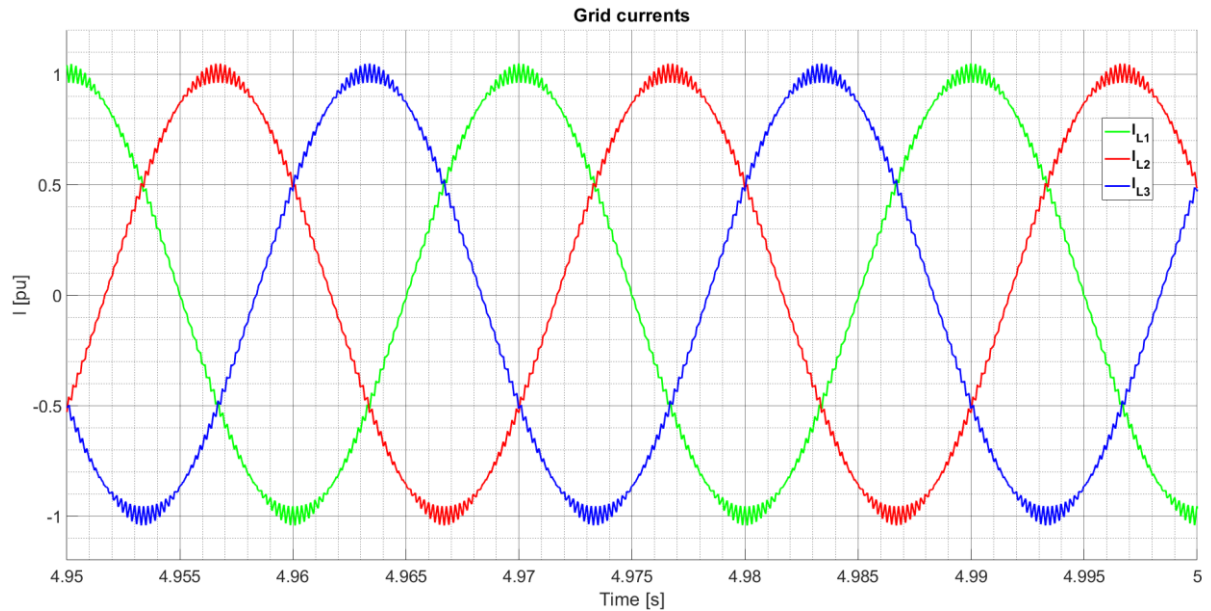


Figure 8: SSBC grid currents when $Q_{STATCOM}^* = +1$ pu and grid voltages are balanced in simulation

Due to their very low THD, currents and voltages are considered purely 50 Hz signals (without harmonics), active and reactive powers are calculated via the fundamental components (50Hz) of voltages and current. Furthermore, in this test, voltages and currents are balanced. It means active power and reactive power are expressed respectively in equation (1) and (2):



$$P_{h1} = \frac{3 * U_{rms_{h1}} * I_{rms_{h1}} * \cos(\theta_{h1})}{S_{baseTests_{3\phi}}} \quad (1)$$

$$Q_{h1} = \frac{3 * U_{rms_{h1}} * I_{rms_{h1}} * \sin(\theta_{h1})}{S_{baseTests_{3\phi}}} \quad (2)$$

Where:

- P_{h1} is the fundamental 3-phase active power (50Hz) [pu]
- $U_{rms_{h1}}$ is the rms value of fundamental voltage (50Hz) [V]
- $I_{rms_{h1}}$ is the rms value of fundamental current (50Hz) [A]
- θ_{h1} is the phase shift between u_{h1} (fundamental voltage) and i_{h1} (fundamental current) in [rad]
- Q_{h1} is the fundamental 3-phase reactive power (50Hz) [pu]

The calculation gives:

- $P_{h1}(Q^* = +1pu \text{ simulation balanced voltages}) = 0.006 pu$
- $Q_{h1}(Q^* = +1pu \text{ simulation balanced voltages}) = 1.000 pu$

(Powers are calculated with voltage and current accuracy taken at mA and mV.)

The relative deviation between reference value and measurement value is calculated via equation (3):

$$\Delta_X = \frac{|X_{meas} - X^*|}{X^*} \cdot 100 \quad (3)$$

Where:

- X_{meas} is the measurement value [pu]
- X^* is the reference value [pu]
- Δ_X is the relative deviation between reference and measurement [%]

The analytical result in the case of reactive power gives:

- $\Delta_Q(Q^* = +1pu \text{ simulation balanced voltages}) = 0.0 \%$.

Figure 9 allows to confirm that the STATCOM is used as a reactive power device. Indeed, fundamental grid voltage L3 is leading its fundamental grid current by 89.7°. A pure reactive power device would have 90° phase shift between current and voltage, but the converter includes also losses that must be compensated which correspond to active power P_{h1} . With the current convention chosen, a positive reactive power means the converter works as an inductor.

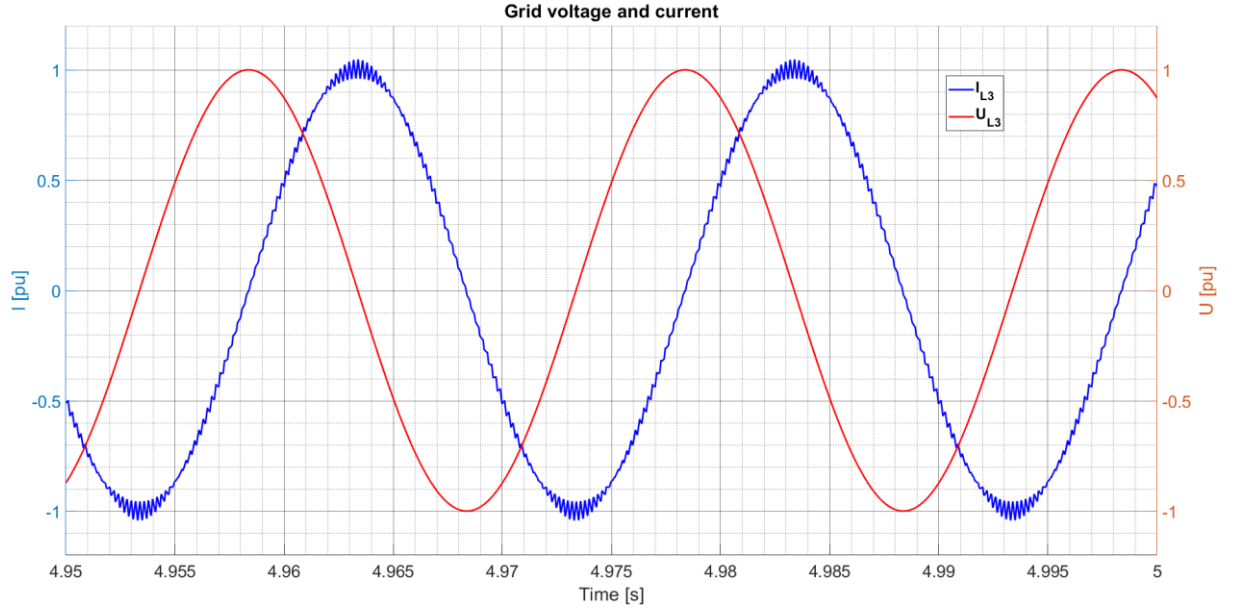


Figure 9: SSBC grid voltage and current of phase L3 when $Q_{STATCOM}^* = +1pu$ and grid voltages are balanced in simulation

Given that the 3 currents are 120° phase shifted as well as the voltages, only Figure 9 is shown to lighten the report. Indeed, in this case each voltage leads its proper current by around 90° .

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg at $Q_{STATCOM}^* = +1pu$ in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 10.

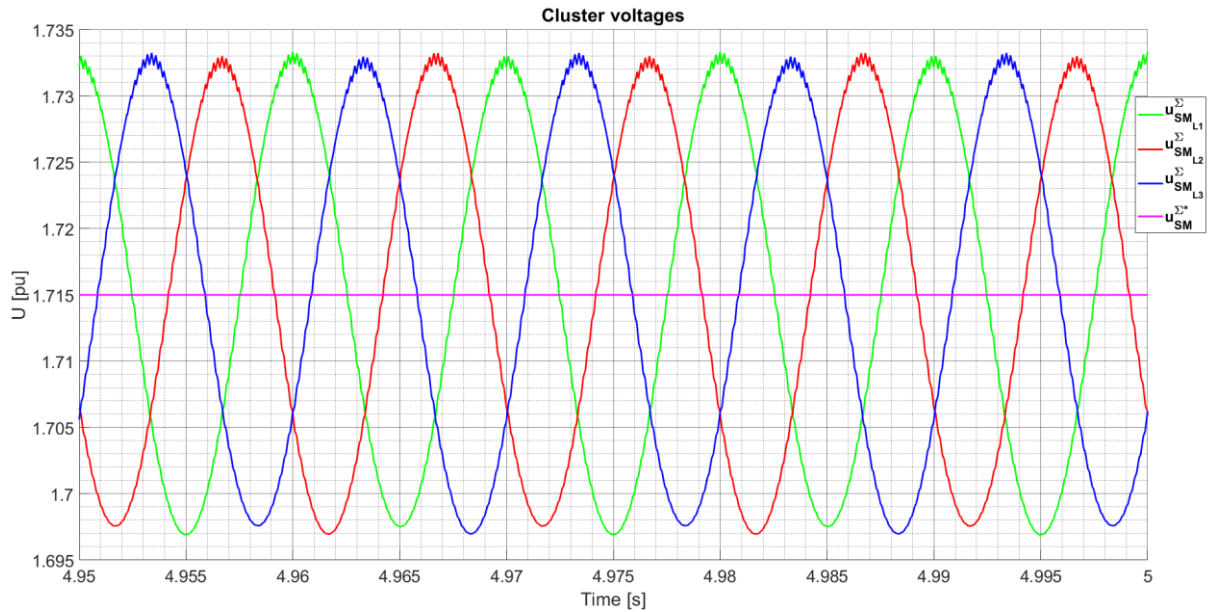


Figure 10: SSBC cluster voltage for each leg when $Q_{STATCOM}^* = +1pu$ and grid voltages are balanced in simulation

It can be seen that cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.035 pu in average. The mean value over one period of time is 1.715 pu which is equal to the reference $u_{SM_L}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_L}^{\Sigma*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = +1pu$ and grid voltages are balanced in simulation.

Finally, it is possible to validate the correct SSBC operation with $Q_{STATCOM}^* = +1pu$ in balanced grid voltage operation with the proposed control strategy.



A summary of SSBC simulation results with balanced grid voltages is given in Table 5. As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are presented to lighten the report content. The detailed results are available in 16.1 appendix.

SSBC simulation results with balanced grid voltages		
	$Q_{STATCOM}^* = +1$ pu (inductive)	$Q_{STATCOM}^* = -1$ pu (capacitive)
$\hat{I}_{h1}$ [pu] (all phases)	1.000	1.000
THDi [%] (all phases)	1.9	1.9
P_{h1} [pu]	0.006	0.007
Q_{h1} [pu]	1.000	1.000
$u_{SM_L}^{\Sigma}$ pk-pk amplitude [pu] (all legs)	0.035	0.048
$\overline{u_{SM_L}^{\Sigma}}$ average [pu] (all legs)	1.715	1.715

Table 5: SSBC simulation results summary with balanced grid voltages

As it can be seen in Table 5, capacitive and inductive results ($Q_{STATCOM}^* = \pm 1$ pu) are very close to each other. Furthermore, all results are precisely matching their setpoint. Only oscillations are 1.37 times higher in capacitive operation compared to inductive case. However, this oscillation is still low (around 3% of the setpoint value). Finally, the low THDi is beneficial for the network and is reached in majority thanks to the modular topology of the converter.

Based on these results, it is possible to confirm that SSBC STATCOM control strategy works correctly in balanced grid voltages state.



4.3.7.2. SSBC simulations with one line-to-earth short-circuit

SSBC simulations for one line-to-earth short-circuit use the electrical schematic presented in Figure 6.

The grid voltage in simulation is applied as in Figure 11. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 4. SSBC STATCOM exchanges $Q_{STATCOM}^* = +1\text{pu}$ (or $Q_{STATCOM}^* = -1\text{pu}$). Then, when time = 0.0484 s the one line-to-earth short-circuit appears on phase L1 meaning the grid voltage $u_{gSL1} = 0\text{ pu}$ and the other phase voltage amplitude increase. It can be seen a transient for around three periods. And then the one line-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gSL1}(\text{steady state}) = 0\text{ pu}$
- $u_{gSL2}(\text{steady state}) = 1.710\text{ pu}$
- $u_{gSL3}(\text{steady state}) = 1.714\text{ pu}$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

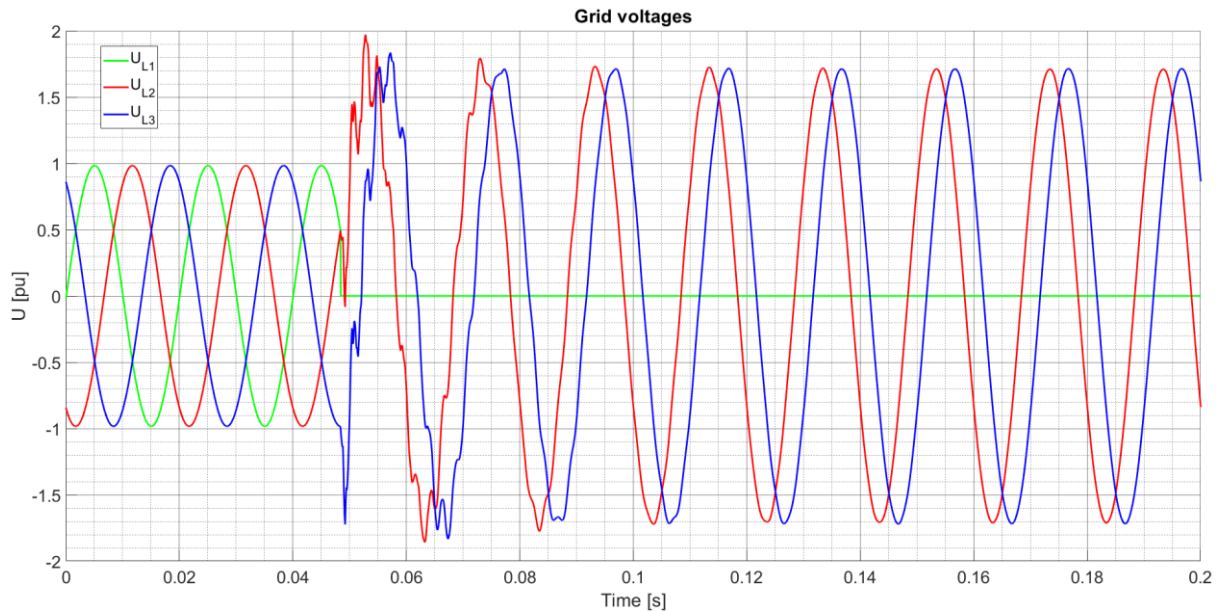


Figure 11: Overall grid voltages during one line-to-earth short-circuit simulation

When this one line-to-earth short-circuit occurs, the goal for SSBC STATCOM is to continue to exchange the same positive sequence current (inductive or capacitive) with the grid. However, during this fault, positive sequence voltage amplitude decreases. As a consequence, positive sequence reactive power exchanged is less important than during balanced grid operation. This choice was made not to overstress the STATCOM prototypes with high currents.

In this section, we focus only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 12 shows steady-state unbalanced grid voltages during one line-to-earth short-circuit applied on SSBC STATCOM in simulation.

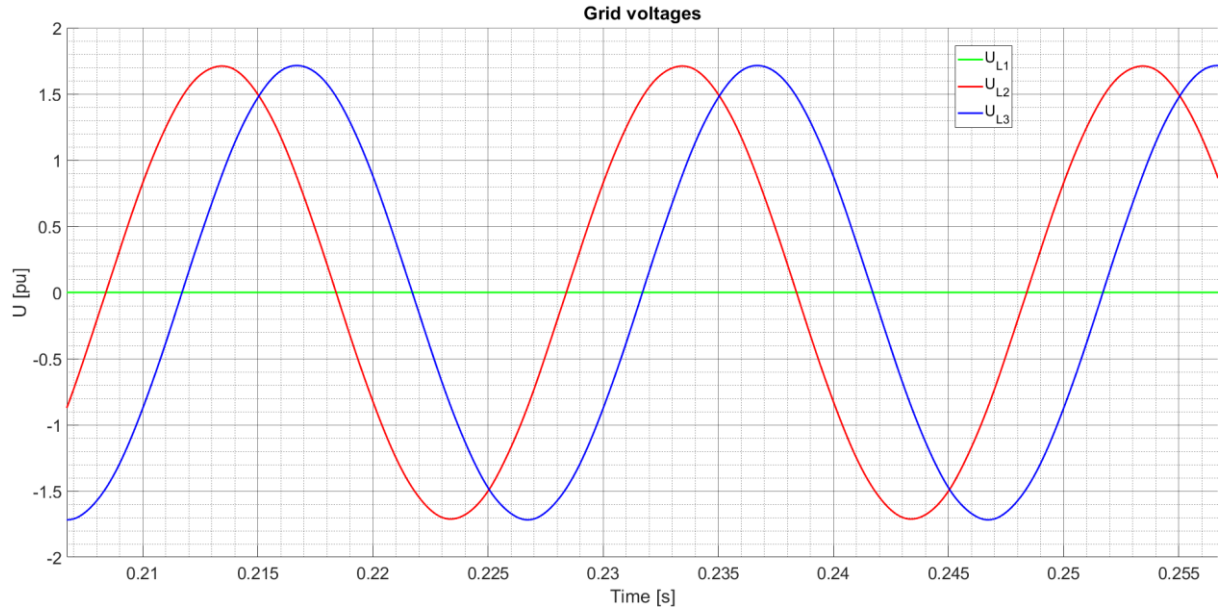


Figure 12: Steady-state unbalanced grid voltages during one line-to-earth short-circuit in simulation

As already mentioned, during one line-to-earth short-circuit steady state STATCOM goal is to exchange positive sequence current (inductive or capacitive) of 1pu with the grid.

Firstly, we present the results when positive sequence inductive current ($I_{h1}^{+}=1\text{pu}$ inductive) is exchanged between SSBC and grid. The currents exchanged are shown in Figure 13.

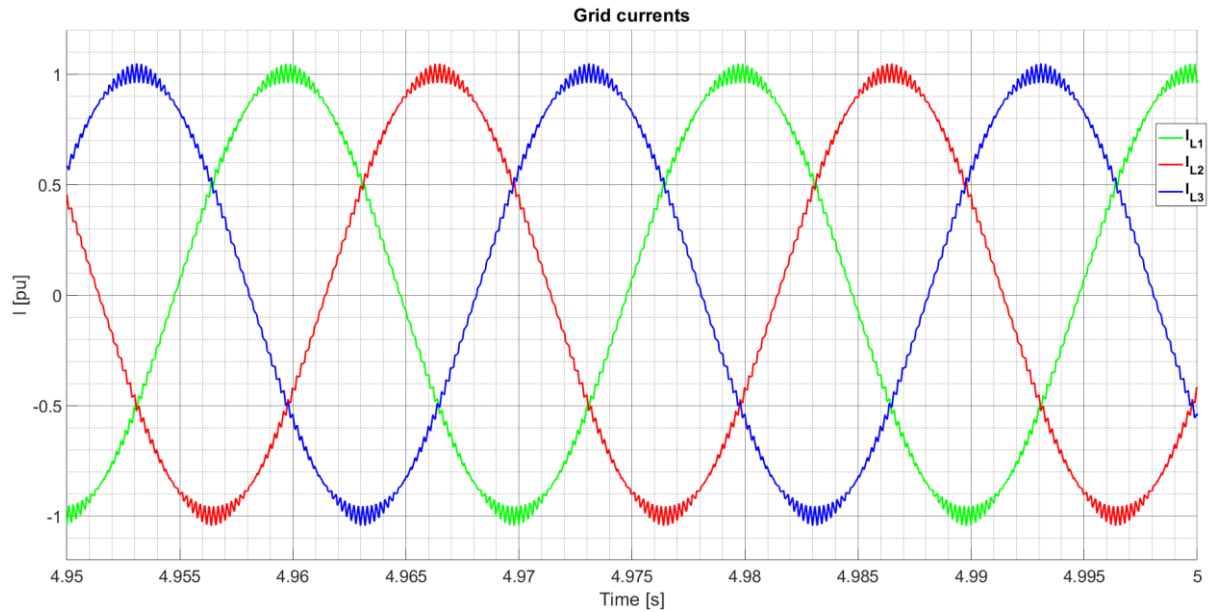


Figure 13: SSBC grid currents when $I_{h1}^{+}=1\text{ pu}$ inductive during one line-to-earth short-circuit steady-state in simulation

In Figure 13, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{+} = 1\text{pu inductive and } L1 \text{ in } SC) = 1.9 \%$
- $THDi_{L2}(I_{h1}^{+} = 1\text{pu inductive and } L1 \text{ in } SC) = 1.9 \%$
- $THDi_{L3}(I_{h1}^{+} = 1\text{pu inductive and } L1 \text{ in } SC) = 1.9 \%$

Compared to grid voltage balanced state, $THD(I_{h1}^{+} = 1\text{pu inductive and } L1 \text{ in } SC)$ remains globally the same. One line-to-earth short-circuit does not really affect the harmonics quality of the signal.



The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

- $\hat{I}_{h1}^+(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 1.000 pu$
- $\hat{I}_{h1}^-(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 0.000 pu$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.0\%$. It confirms that the currents provided by the SSBC prototype are well balanced with the setpoint $I_{h1}^{+*}=1 pu$ inductive during one line-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the SSBC exchanges fundamental positive sequence inductive reactive power with the grid. To verify this in simulation, positive sequence voltages and currents are used. Indeed, thanks to them, fundamental positive sequence active and reactive powers can be calculated thanks to (4) and (6), taken from [7]:

$$Q_{h1}^+ = \frac{3 * U_{rms_{h1}}^+ * I_{rms_{h1}}^+ * \sin(\theta_{h1}^+)}{S_{baseTests_{3\Phi}}} \quad (4)$$

$$P = \frac{P_{L1} + P_{L2} + P_{L3}}{S_{baseTests_{3\Phi}}} \quad (5)$$

$$P_{h1}^+ = \frac{3 * U_{rms_{h1}}^+ * I_{rms_{h1}}^+ * \cos(\theta_{h1}^+)}{S_{baseTests_{3\Phi}}} \quad (6)$$

Where:

- Q_{h1}^+ is the fundamental 3-phase reactive power (50 Hz) [pu]
- $U_{rms_{h1}}^+$ is the rms value of fundamental positive sequence of voltage (50Hz) [V]
- $I_{rms_{h1}}^+$ is the rms value of fundamental positive sequence of current (50Hz) [V]
- θ_{h1}^+ is the phase shift between U_{h1}^+ (fundamental positive sequence of voltage) and I_{h1}^+ (fundamental positive sequence of current) in [rad]: $\theta_{h1}^+ = \varphi_{U_{h1}^+} - \varphi_{I_{h1}^+}$
- P is the 3-phase active power [pu]
- P_{Lx} is the phase x active power [W]
- P_{h1}^+ is the fundamental 3-phase active power (50 Hz) [pu]

During one line-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^+$) is equal to 0.986 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^+ = 89.6^\circ$. It is then possible to calculate the powers:

- $P_{h1}^+(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 0.006 pu$
- $Q_{h1}^+(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 0.987 pu$

SSBC converter exchanges Q_{h1}^+ in great majority meaning that it continues to operate as a balanced STATCOM. In addition, Q_{h1}^+ is very close to the base power value because positive sequence of voltage and current are dominant on their negative sequence.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg with $I_{h1}^{+*}=1pu$ inductive in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 14.

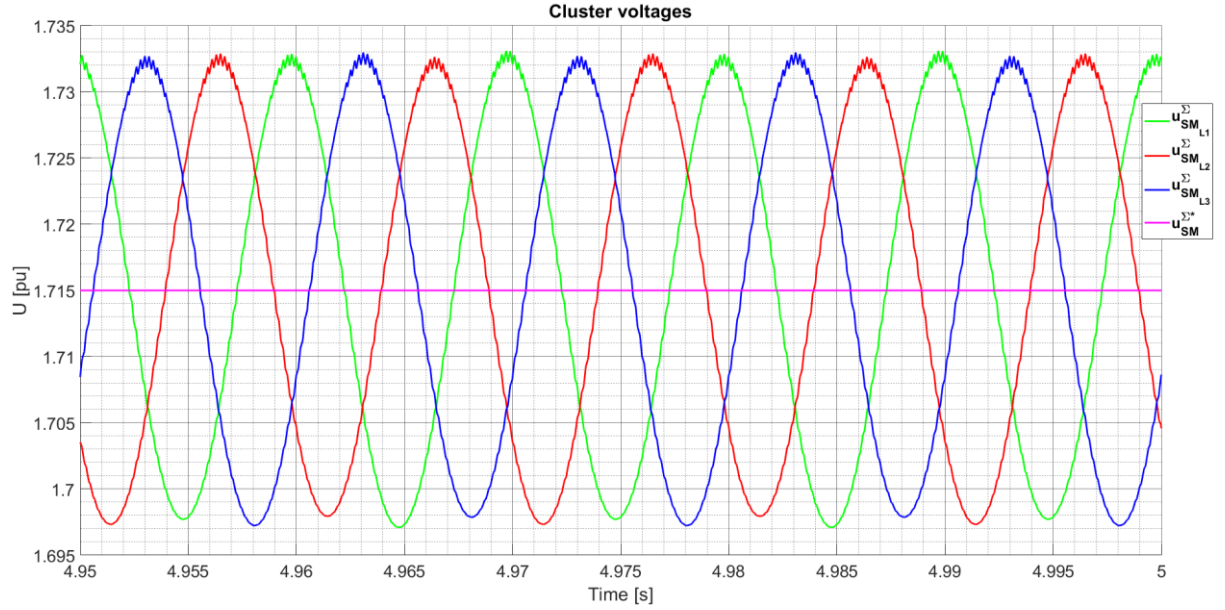


Figure 14: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit steady-state in simulation

It can be seen that cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.035 pu in average. The mean value over one period of time is 1.715 pu which is equal to the reference $u_{SM, L}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SM, L}^{\Sigma*}$ and so that internal stability is guaranteed when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit steady-state in simulation.

It is important also to verify the STATCOM is able to withstand the transient of one line-to-earth short-circuit. Grid currents during this transient are shown in Figure 15.

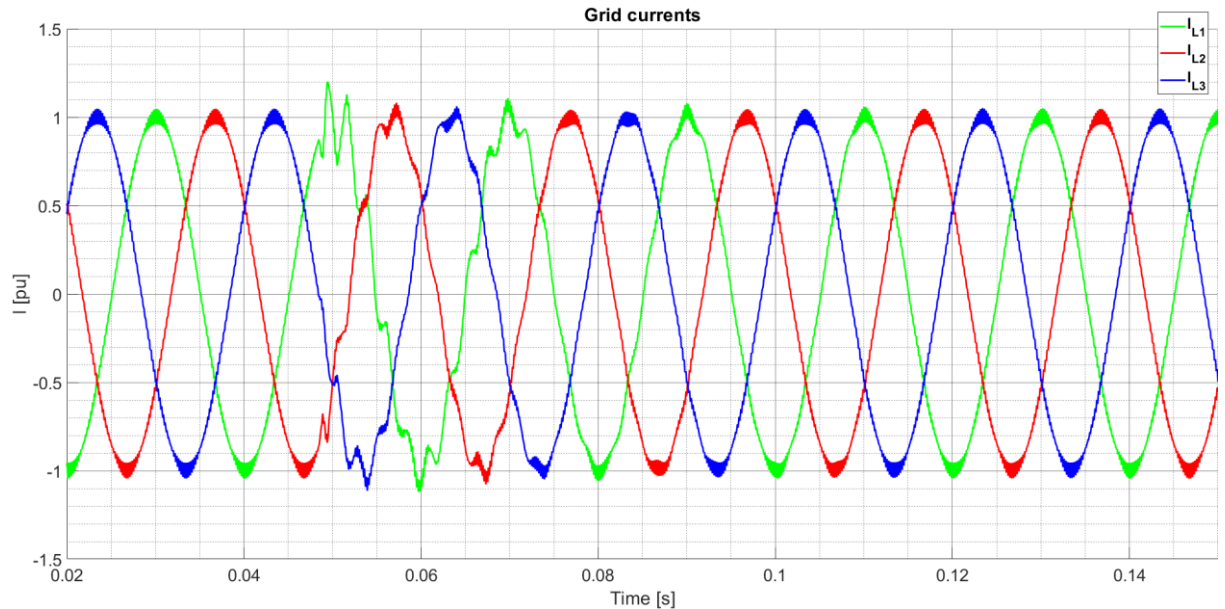


Figure 15: SSBC grid currents when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit transient in simulation

As it can be seen in Figure 15, grid currents continue to follow the $I_{h1}^{+*} = 1\text{ pu}$ inductive reference during the transient. However, at the beginning of the transient (at 0.0484 s), oscillations occur going until 1.201 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.



Figure 16 shows the internal cluster voltages during this transient.

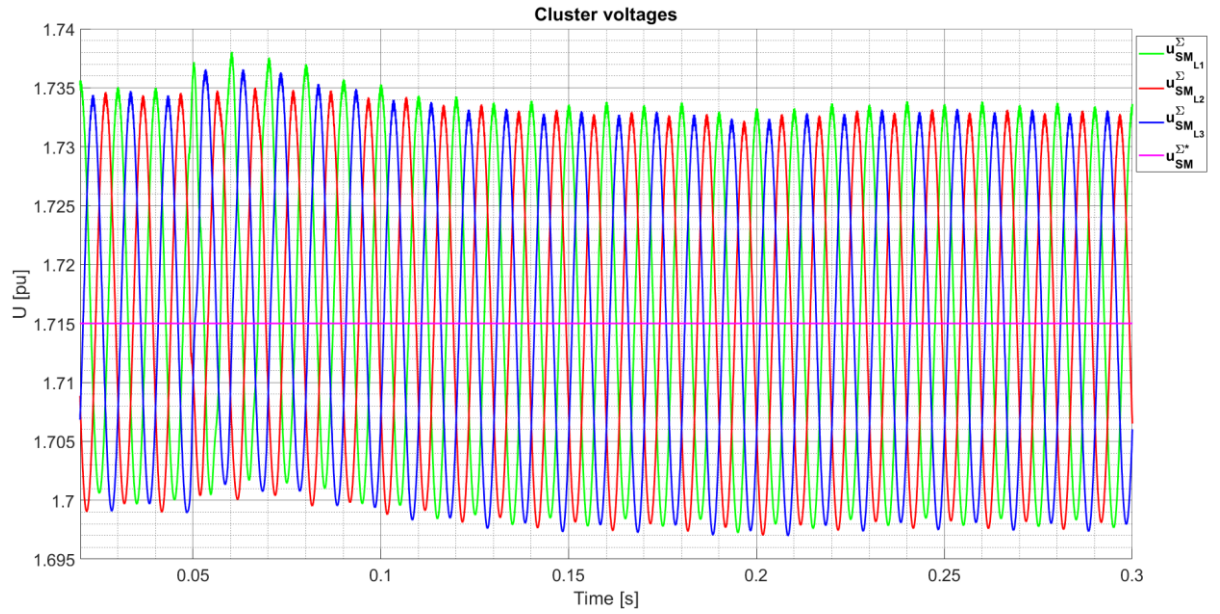


Figure 16: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1$ pu inductive during one line-to-earth short-circuit transient in simulation

Cluster voltages contain also an additional oscillation but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 1.738 pu. Cluster voltages are weakly impacted during this transient and remain stable. These results imply that the SSBC STATCOM with this control strategy is also able to withstand the transient of one line-to-earth short-circuit.

Finally, it is possible to validate the correct SSBC operation when $I_{h1}^{+*}=1$ pu inductive during one line-to-earth short-circuit with the proposed control strategy.

A summary of SSBC simulation results when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit in steady state is given in Table 6. As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are also presented to lighten the report content. The detailed results are available in 16.2 appendix.



SSBC simulation results at the end of one line-to-earth short-circuit		
	$I_{h1}^{+*} = 1$ pu inductive	$I_{h1}^{+*} = 1$ pu capacitive
I_{h1}^{+*} [pu] (all phases)	1.000	1.000
THDi phase L1 [%]	1.9	1.9
THDi phase L2 [%]	1.9	1.9
THDi phase L3 [%]	1.9	1.9
THDi maximum increase compared to balanced grid voltages case [%]	0.0	0.0
Current Unbalance Factor [%]: $\frac{\hat{i}_{h1}^-}{\hat{i}_{h1}^+}$	0.0	0.0
P_{h1}^+ [pu]	0.006	0.007
Q_{h1}^+ [pu]	0.987	-0.987
$u_{SM_L}^\Sigma$ pk-pk amplitude [pu] (all arms)	0.035	0.048
$\overline{u_{SM_L}^\Sigma}$ average [pu] (all arms)	1.715	1.715

Table 6: SSBC simulation results at the end of one line-to-earth short-circuit

As it can be seen in Table 6, capacitive and inductive results are very close to each other. Furthermore, all results are precisely matching their setpoint. Finally, the low THDi is beneficial for the network and is reached in majority thanks to the modular topology of the converter.

Based on these results, it is possible to confirm that SSBC STATCOM control strategy works correctly during one line-to-earth short-circuit. SSBC STATCOM is able to exchange $I_{h1}^{+*} = 1$ pu capacitive and inductive during one line-to-earth short-circuit permanently.



4.3.7.3. SSBC simulations with two lines-to-earth short-circuit

It is important to remind that two lines-to-earth short-circuit directly at STATCOM input is the worst voltage grid unbalanced state for the STATCOM and converters in general. SSBC simulations for two lines-to-earth short-circuit use the electrical schematic presented in Figure 6.

The grid voltage in simulation is applied as in Figure 17. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 4. SSBC STATCOM exchanges $Q_{STATCOM}^* = +1$ pu or $Q_{STATCOM}^* = -1$ pu. Then, when time = 0.0484 s the two lines-to-earth short-circuit appears on phases L1 and L2 meaning the grid voltages $u_{gsL1} = 0$ pu as well as $u_{gsL2} = 0$ pu. In the same time, phase voltage L3 amplitude increases. It can be seen a transient for around three periods. Then the two lines-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(\text{steady state}) = 0$ pu
- $u_{gsL2}(\text{steady state}) = 0$ pu
- $u_{gsL3}(\text{steady state}) = 1.476$ pu

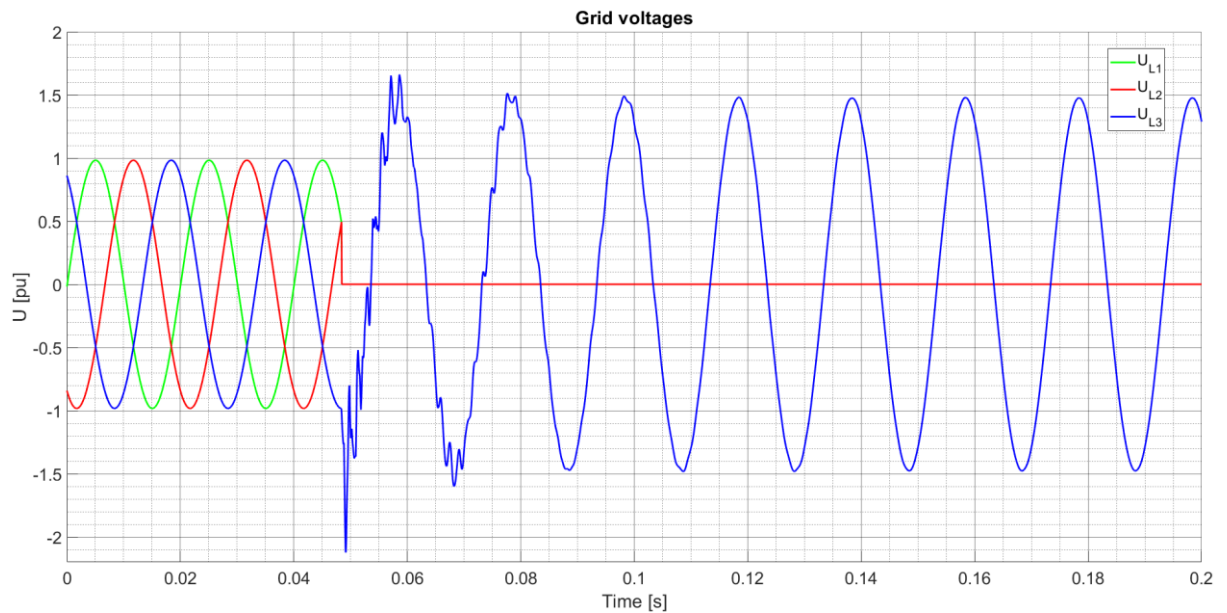


Figure 17: Overall grid voltages during two lines-to-earth short-circuit in simulation

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

When this two lines-to-earth short-circuit occurs, the goal for SSBC STATCOM is to continue to exchange the same positive sequence current (inductive or capacitive) with the grid (for the same reason as for one line-to-earth short-circuit).

This section focuses only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 18 shows steady-state unbalanced grid voltages during two lines-to-earth short-circuit applied on SSBC STATCOM in simulation.

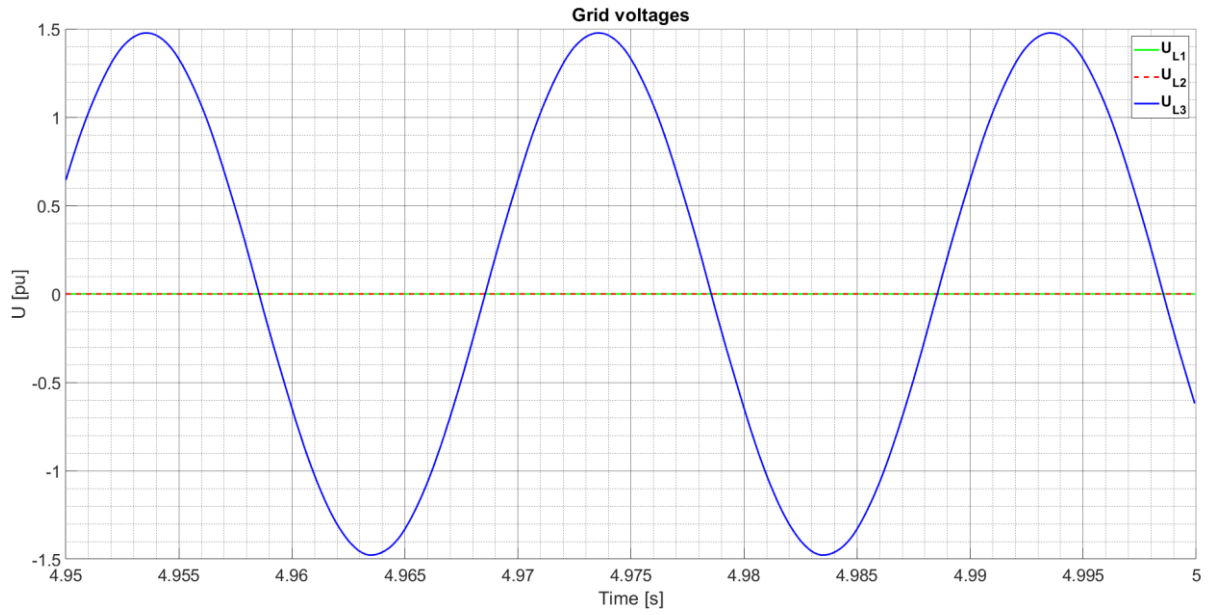


Figure 18: Steady-state unbalanced grid voltages during two lines-to-earth short-circuit in simulation

Firstly, we present the results when positive sequence inductive current ($I_{h1}^{+*} = 1$ pu inductive) is exchanged between SSBC and grid. The currents exchanged at the end of short-circuit are shown in Figure 19.

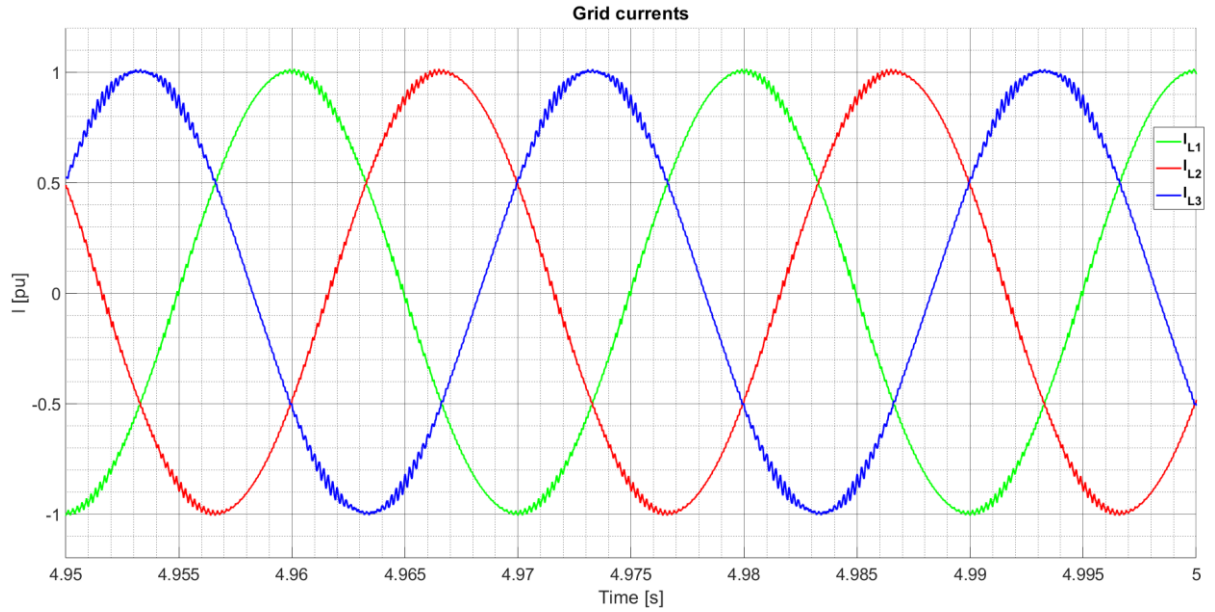


Figure 19: SSBC grid currents when $I_{h1}^{+*}=1$ pu inductive at the end of two lines-to-earth short-circuit in simulation

In Figure 19, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 1.9 \%$
- $THDi_{L2}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 1.9 \%$
- $THDi_{L3}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 1.9 \%$

Compared to grid voltage balanced state, $THD(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC})$ remains globally the same. Two lines-to-earth short-circuit does not really affect the harmonics quality of the signal.



The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

- $\hat{I}_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 1.000 \text{ pu}$
- $\hat{I}_{h1}^-(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.000 \text{ pu}$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.0\%$. It confirms that the currents provided by the SSBC prototype are well balanced with the setpoint $I_{h1}^{+*} = 1 \text{ pu}$ inductive during two lines-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the SSBC exchanges fundamental positive sequence inductive reactive power with the grid. During two lines-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^+$) is equal to 0.492 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^+ = 89.2^\circ$. It is then possible to calculate the powers:

- $P_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.007 \text{ pu}$
- $Q_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.492 \text{ pu}$

SSBC converter exchanges Q_{h1}^+ in great majority meaning that it continues to operate as a balanced STATCOM. Power losses (P_{h1}^+) are slightly higher than in the balanced case but remain low compared to Q_{h1}^+ . However, as mentioned earlier in the report, Q_{h1}^+ is half of the base power value because positive sequence of voltage is half of the base value and positive sequence of current is voluntarily kept to 1 pu inductive to avoid high currents in the converter during this short-circuit state.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg with $I_{h1}^{+*}=1\text{pu}$ inductive in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 20.

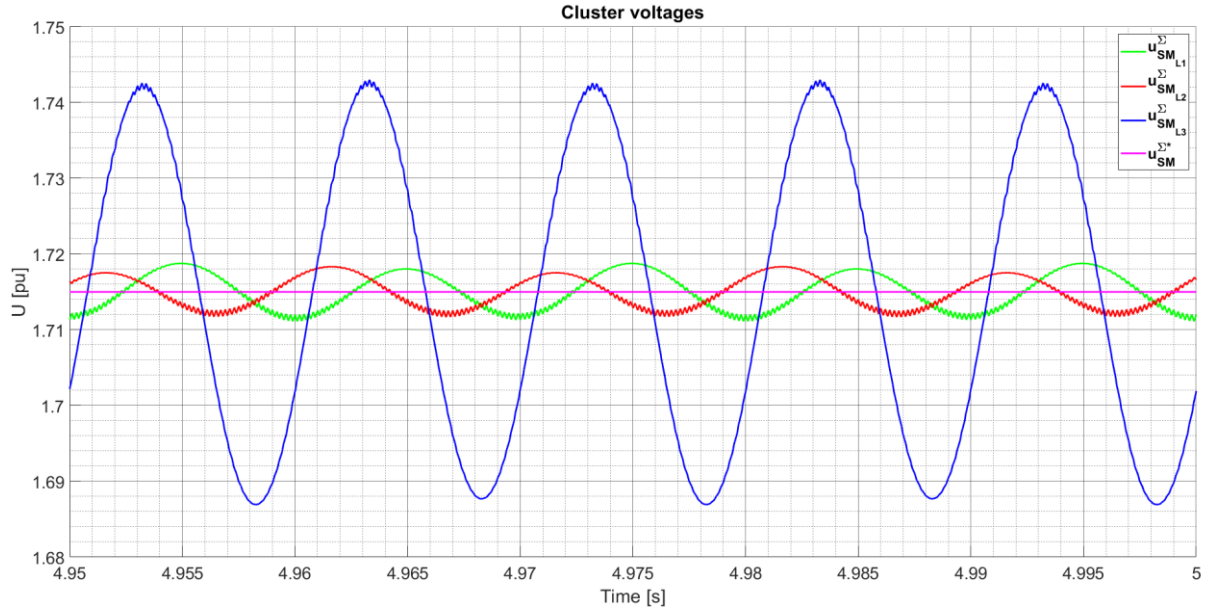


Figure 20: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ inductive at the end of two lines-to-earth short-circuit in simulation

It can be seen that the average value over the last period of time is still 1.715 pu for each leg which is equal to the reference $u_{SM_L}^{\Sigma*}$. So, cluster voltages remain stable at the end of the 5s short circuit. Even better, this state could be hold permanently.



It is important to mention that peak-to-peak amplitudes are unbalanced between legs. The with peak-to-peak amplitude of each leg is:

- $u_{SML1pk-pk}^{\Sigma} = 0.007 \text{ pu}$
- $u_{SML2pk-pk}^{\Sigma} = 0.007 \text{ pu}$
- $u_{SML3pk-pk}^{\Sigma} = 0.055 \text{ pu}$

The peak-to-peak amplitude of L3 leg is 1.57 times higher than the balanced case. It has to be taken in consideration during the design phase of the converter. It is worth to mention that peak-to-peak amplitude of other legs are 5 times lower than the balanced case which is a positive behaviour for the converter.

We can conclude that cluster voltages are balanced around the reference value u_{SML}^{+*} with reasonable ripples amplitude. It means internal stability is guaranteed when $I_{h1}^{+*} = 1 \text{ pu}$ inductive during two lines-to-earth short-circuit steady-state in simulation.

It is important also to verify the STATCOM is able to withstand the transient of two lines-to-earth short-circuit. Grid currents during this transient are shown in Figure 21.

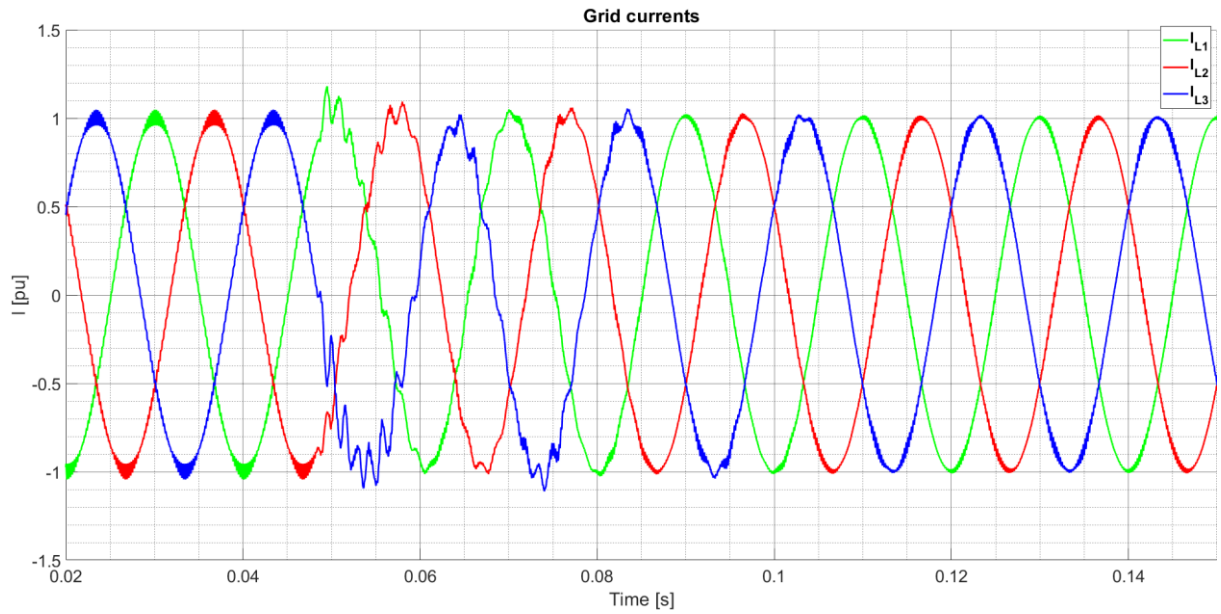


Figure 21: SSBC grid currents when $I_{h1}^{+*}=1\text{pu}$ inductive during two lines-to-earth short-circuit transient in simulation

As it can be seen in Figure 21, grid currents continue to follow the $I_{h1}^{+*}=1 \text{ pu}$ inductive reference during the transient. However, at the beginning of the transient (at 0.0484 s), oscillations occur going until 1.180 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.

Figure 22 shows the internal cluster voltages during this transient.

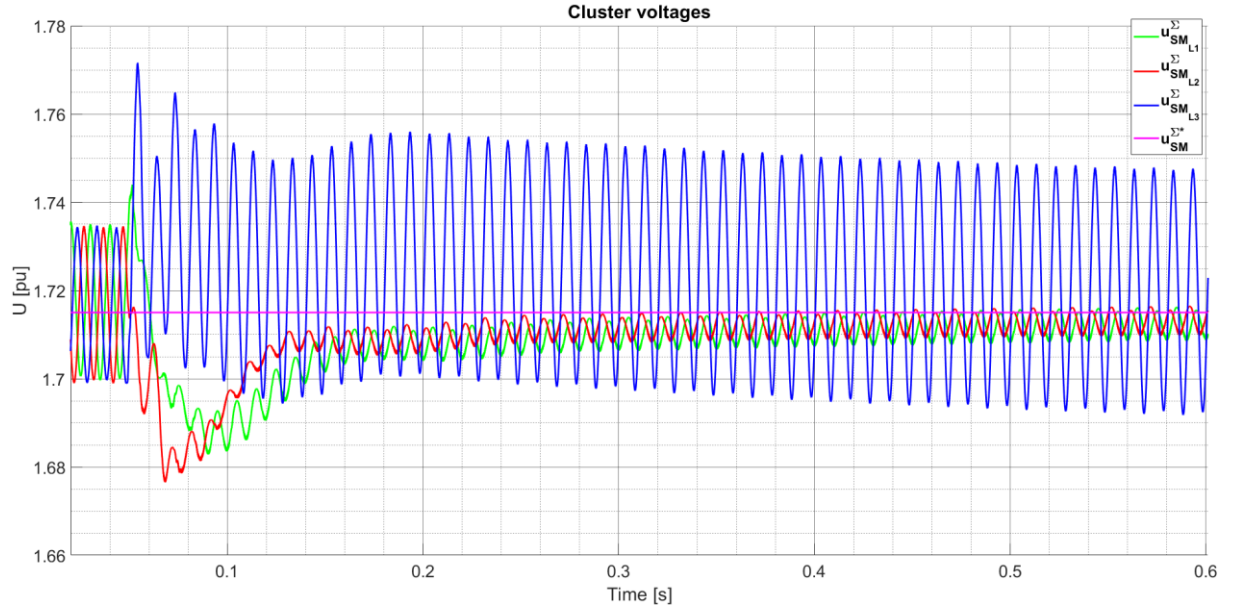


Figure 22: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ inductive during two lines-to-earth short-circuit transient in simulation

Cluster voltages contain also an additional oscillation but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 1.772 pu. Cluster voltages are notably impacted during the first 50ms of the transient and then return to stable state. These results imply that the SSBC STATCOM with this control strategy is also able to withstand the transient of two lines-to-earth short-circuit. However, the voltages reached during the transient has to be considered in the converter design stage.

Finally, it is possible to validate the correct SSBC operation when $I_{h1}^{+*}=1\text{pu}$ inductive during two lines-to-earth short-circuit with the proposed control strategy.

A summary of SSBC simulation results when $I_{h1}^{+*}=1\text{pu}$ inductive at the end of two lines-to-earth short-circuit is given in Table 7. As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are also presented to lighten the report content. The detailed results are available in 16.3 appendix.



SSBC simulation results at the end of two lines-to-earth short-circuit		
	$I_{h1}^{+*} = 1$ pu inductive	$I_{h1}^{+*} = 1$ pu capacitive
I_{h1}^{+*} [pu] (all phases)	1.000	1.000
THDi phase L1 [%]	1.9	1.9
THDi phase L2 [%]	1.9	1.9
THDi phase L3 [%]	1.9	2.0
THDi maximum increase compared to balanced grid voltages case [%]	0.0	0.1
Current Unbalance Factor [%]: $\frac{\hat{i}_{rms}^-}{\hat{i}_{rms}^+}$	0.0	0.0
P_{h1}^+ [pu]	0.007	0.007
Q_{h1}^+ [pu]	0.492	-0.492
$u_{SM_L}^\Sigma$ maximum pk-pk amplitude [pu]	0.055	0.069
$\overline{u_{SM_L}^\Sigma}$ average [pu] (all arms)	1.715	1.715

Table 7: SSBC simulation results at the end of two lines-to-earth short-circuit

As it can be seen in Table 7, capacitive and inductive results are very close to each other. Furthermore, all results are precisely matching their setpoint. Finally, the low THDi is beneficial for the network and is reached in majority thanks to the modular topology of the converter. It is important to note the notable increase of maximum $u_{SM_L}^\Sigma$ in this case of short circuit until 1.6 times the maximum of the grid voltage balanced case.

Based on these results, it is possible to confirm that SSBC STATCOM control strategy works correctly during two lines-to-earth short-circuit. SSBC STATCOM is able to exchange $I_{h1}^{+*} = 1$ pu capacitive and inductive during two lines-to-earth short-circuit permanently.



Parameter	Value	Parameter	Value
$U_{gs \text{ balanced}}$	1 [pu] = 200 [V_{pk}]	C_{sm}	3.3 [mF]
f_g	50 [Hz]	$S_{baseTests3\phi}$	3 [kVA] = 1 [pu]
L_g	3 [mH]	$u_{SMu,l}^*$	490 [V] = 2.45 [pu]
R_g	100 [m Ω]	f_{sw}	1 [kHz]
L_a	6 [mH]	$t_{deadband}$	1 [μ s]
R_a	200 [m Ω]	f_{sample}	5 [kHz]
N	5 [-] (SM by arm)		

Table 8: Simulation parameters for DSCC simulations

In Table 8, $u_{SMu,l}^*$ is the nominal value for the cluster voltage (by arm). Each submodule switches at a frequency of f_{sw} with a dead-band time of $t_{deadband}$. Finally, the sampling of each measure is done at $f_{sample} = f_{sw} * N$.

In this simulation, grid voltages (u_{gs}) are balanced 50 Hz sinusoidal waveforms with peak value of 1 pu. They are visible in Figure 7.

When reactive power reference is set to $Q_{STATCOM}^* = +1$ pu (inductive case), grid currents are well balanced with Current Unbalance Factor (CUF) = $\frac{I_-}{I_+} =$ of 0.0%. Their fundamental peak value are all of 1.000 pu. These three balanced currents exchanged between DSCC converter and grid are visible in Figure 24. THD of the currents of all phases are around 0.9% in the simulation for balanced grid voltages. As a remark, it should be noted that the current direction for measurement follows the direction of Figure 23.

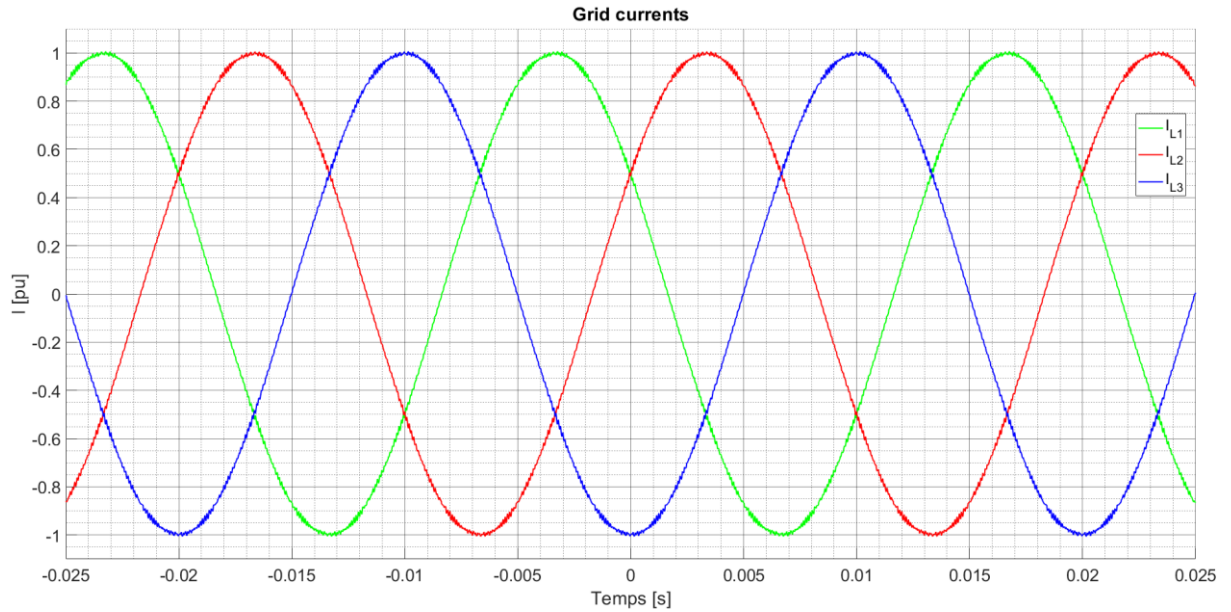


Figure 24: DSCC grid currents when $Q_{STATCOM}^* = +1$ pu and grid voltages are balanced in simulation

Due to their very low THD, currents and voltages are considered purely 50 Hz signals (without harmonics), active and reactive powers are calculated via equations (1) and (2):

- $P_{h1}(Q^* = +1 \text{ pu simulation balanced voltages}) = 0.006 \text{ pu}$
- $Q_{h1}(Q^* = +1 \text{ pu simulation balanced voltages}) = 1.000 \text{ pu}.$

(Powers are calculated with voltage and current accuracy taken at mA and mV.)

The relative deviation between reference value and measurement value is:

- $\Delta_Q(Q^* = +1 \text{ pu simulation balanced voltages}) = 0.0 \text{ \%}.$



Figure 25 allows to confirm that the STATCOM is used as a reactive power device. Indeed, fundamental grid voltage L3 is leading its fundamental grid current by 89.6° . A pure reactive power device would have 90° phase shift between current and voltage but the converter includes also losses which correspond to active power P_{h1} . With the current convention chosen, a positive reactive power means the converter works as an inductor.

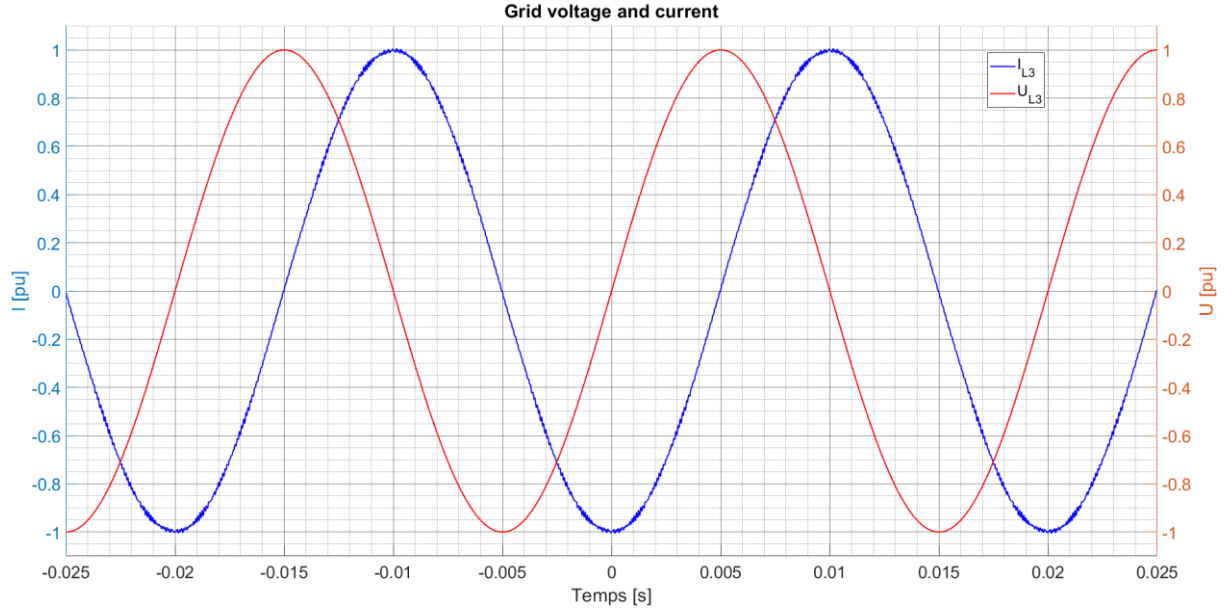


Figure 25: DSCC grid voltage and current of phase L3 when $Q_{STATCOM}^* = +1pu$ and grid voltages are balanced in simulation

Given that the 3 currents are 120° phase shifted as well as the voltages, only Figure 25 is shown to lighten the report. Indeed, in this case each voltage leads its proper current by around 90° too.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SMu,l}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SMu,l}^{\Sigma*}$) equal to 2.45 pu. The upper arm cluster voltage for each leg at $Q_{STATCOM}^* = +1pu$ in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 26.

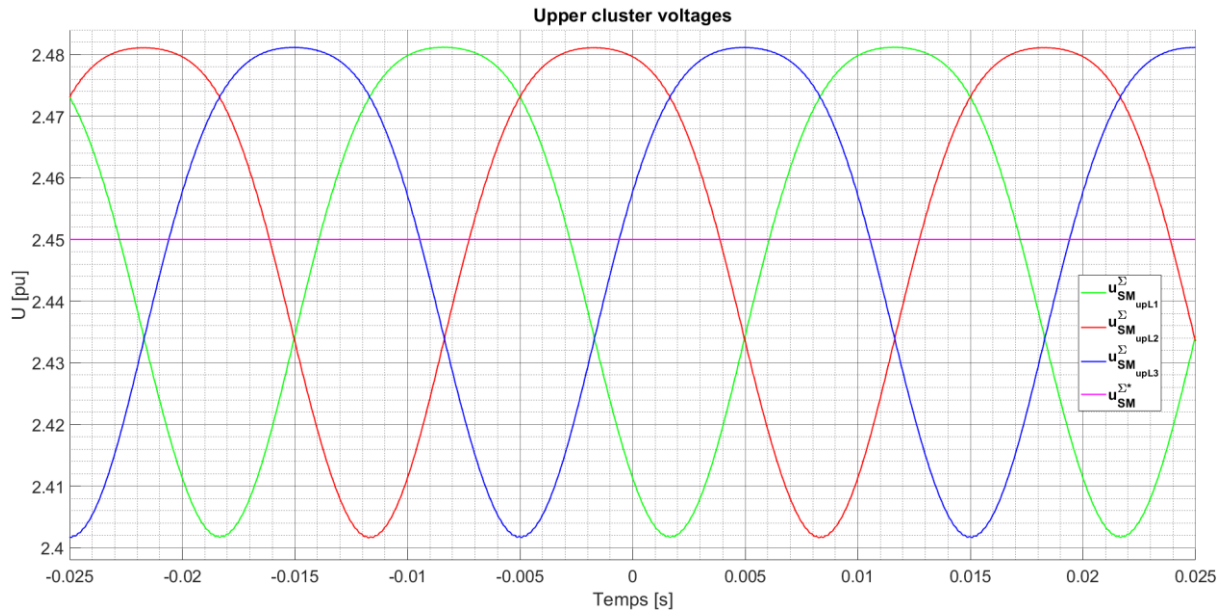


Figure 26: DSCC upper arm cluster voltage for each leg when $Q_{STATCOM}^* = +1 pu$ and grid voltages are balanced in simulation



It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu as well. The mean value over one period of time is 2.450 pu which is also equal to the reference $u_{SMu,l}^{\Sigma*}$.

As well, the lower arm cluster voltage for each leg at $Q_{STATCOM}^* = +1pu$ in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 27.

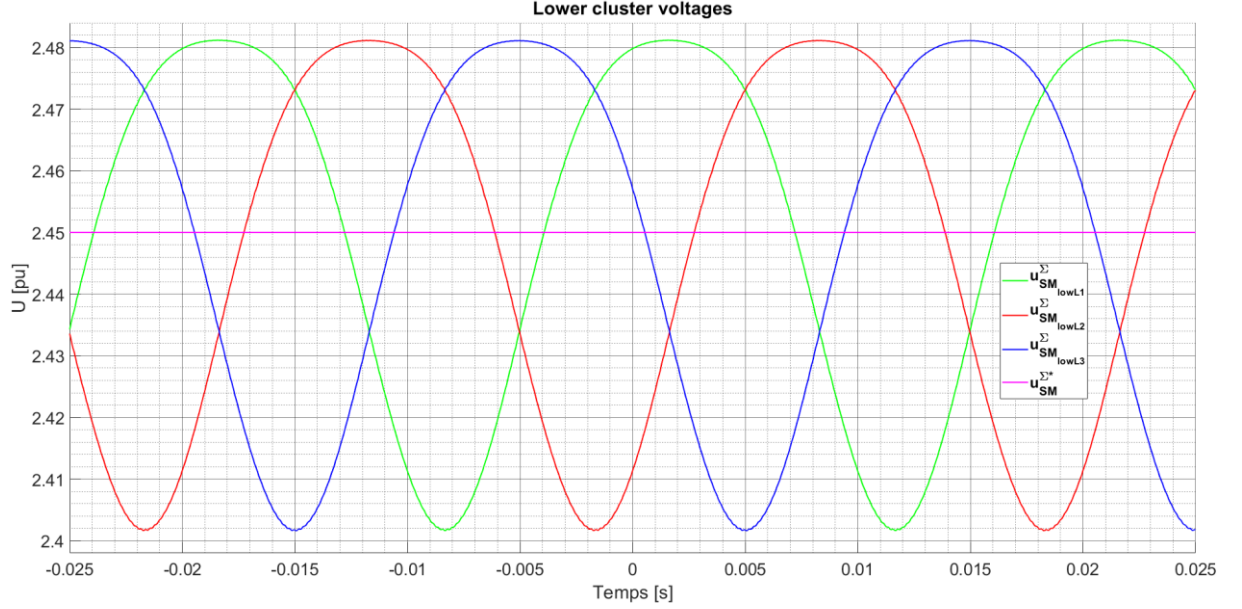


Figure 27: DSCC lower arm cluster voltage for each leg when $Q_{STATCOM}^* = +1pu$ and grid voltages are balanced in simulation

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu as well. The mean value over one period of time is 2.450 pu which is also equal to the reference $u_{SMu,l}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SMu,l}^{\Sigma*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = +1 pu$ and grid voltages are balanced in simulation.

Finally, it is possible to validate the correct DSCC operation with $Q_{STATCOM}^* = +1 pu$ in balanced grid voltage operation with the proposed control strategy.

A summary of DSCC simulation results with balanced grid voltages is given in Table 9. As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are presented to lighten the report content. The detailed results are available in 16.4 appendix.



DSCC simulation results with balanced grid voltages		
	$Q_{STATCOM}^* = +1$ pu (inductive)	$Q_{STATCOM}^* = -1$ pu (capacitive)
$\hat{I}_{h1}$ [pu] (all phases)	1.000	1.000
THDi [%] (all phases)	0.9	1.0
P_{h1} [pu]	0.006	0.007
Q_{h1} [pu]	1.000	-1.000
$u_{SM_u}^{\Sigma}$ pk-pk amplitude [pu] (all arms)	0.079	0.079
$\overline{u_{SM_u}^{\Sigma}}$ average [pu] (all arms)	2.450	2.450
$u_{SM_l}^{\Sigma}$ pk-pk amplitude [pu] (all arms)	0.079	0.079
$\overline{u_{SM_l}^{\Sigma}}$ average [pu] (all arms)	2.450	2.450

Table 9: DSCC simulation results summary with balanced grid voltages

As it can be seen in Table 9, capacitive and inductive results ($Q_{STATCOM}^* = \pm 1$ pu) are very close to each other. Furthermore, all results are precisely matching their setpoint. Finally, the low THDi is beneficial for the network and is reached in majority thanks to the modular topology of the converter.

Based on these results, it is possible to confirm that DSCC STATCOM control strategy works correctly in balanced grid voltages state.



4.3.8.2. DSCC simulations with one line-to-earth short-circuit

DSCC simulations for one line-to-earth short-circuit use the electrical schematic presented in Figure 23.

The grid voltage in simulation is applied as in Figure 11. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 8. DSCC STATCOM exchanges $Q_{STATCOM}^* = +1\text{pu}$ (or $Q_{STATCOM}^* = -1\text{pu}$). Then, when time = 0.0484 s the one line-to-earth short-circuit appears on phase L1 meaning the grid voltage $u_{gsL1} = 0\text{ pu}$ and the other phase voltage amplitude increase. It can be seen a transient for around three periods. And then the one line-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(\text{steady state}) = 0\text{ pu}$
- $u_{gsL2}(\text{steady state}) = 1.710\text{ pu}$
- $u_{gsL3}(\text{steady state}) = 1.714\text{ pu}$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. In our study, to go further, the one line-to-earth short-circuit is maintained for 1 minute to evaluate STATCOM behaviour in this operating point. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

When this one line-to-earth short-circuit occurs, the goal for DSCC STATCOM is to continue to exchange the same positive sequence current (inductive or capacitive) with the grid.

In this section, we focus only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 12 shows steady-state unbalanced grid voltages during one line-to-earth short-circuit applied on DSCC STATCOM in simulation.

Firstly, we present the results when positive sequence inductive current ($I_{h1}^{++} = 1\text{ pu}$ inductive) is exchanged between DSCC and grid. The currents exchanged are shown in Figure 28.

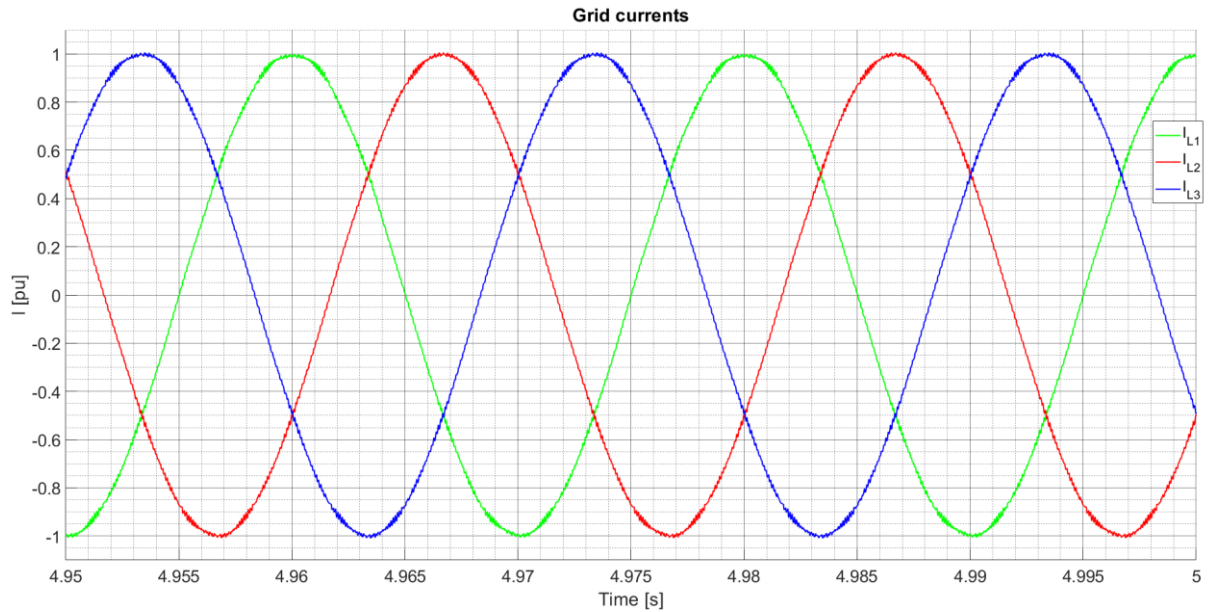


Figure 28: DSCC grid currents when $I_{h1}^{++} = 1\text{ pu}$ inductive during one line-to-earth short-circuit steady-state in simulation

In Figure 28, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1\text{ pu inductive and L1 in SC}) = 1.0\%$
- $THDi_{L2}(I_{h1}^{++} = 1\text{ pu inductive and L1 in SC}) = 0.9\%$
- $THDi_{L3}(I_{h1}^{++} = 1\text{ pu inductive and L1 in SC}) = 0.9\%$



Compared to grid voltage balanced state, THD($I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}$) remains globally the same. One line-to-earth short-circuit does not really affect the harmonics quality of the signal.

The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

- $\hat{I}_{h1}^{+}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 1.000 \text{ pu}$
- $\hat{I}_{h1}^{-}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 0.000 \text{ pu}$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 0.0\%$. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*} = 1 \text{ pu inductive}$ during one line-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the DSCC exchanges fundamental positive sequence inductive reactive power with the grid. During one line-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^{+}$) is equal to 0.986 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^{+} = 89.6^{\circ}$. It is then possible to calculate the powers thanks to (4) and (6):

- $P_{h1}^{+}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 0.007 \text{ pu}$
- $Q_{h1}^{+}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 0.987 \text{ pu}$

DSCC converter exchanges Q_{h1}^{+} in great majority meaning that it continues to operate as a balanced STATCOM. In addition, Q_{h1}^{+} is very close to the base power value because positive sequence of voltage and current are dominant on their negative sequence.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SM_{u,l}}^{\Sigma}$) are regulated to oscillate around the cluster voltage reference ($u_{SM_{u,l}}^{\Sigma*}$) equal to 2.45 pu. The upper arm cluster voltage for each leg with $I_{h1}^{+*} = 1 \text{ pu inductive}$ in simulation and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 29.

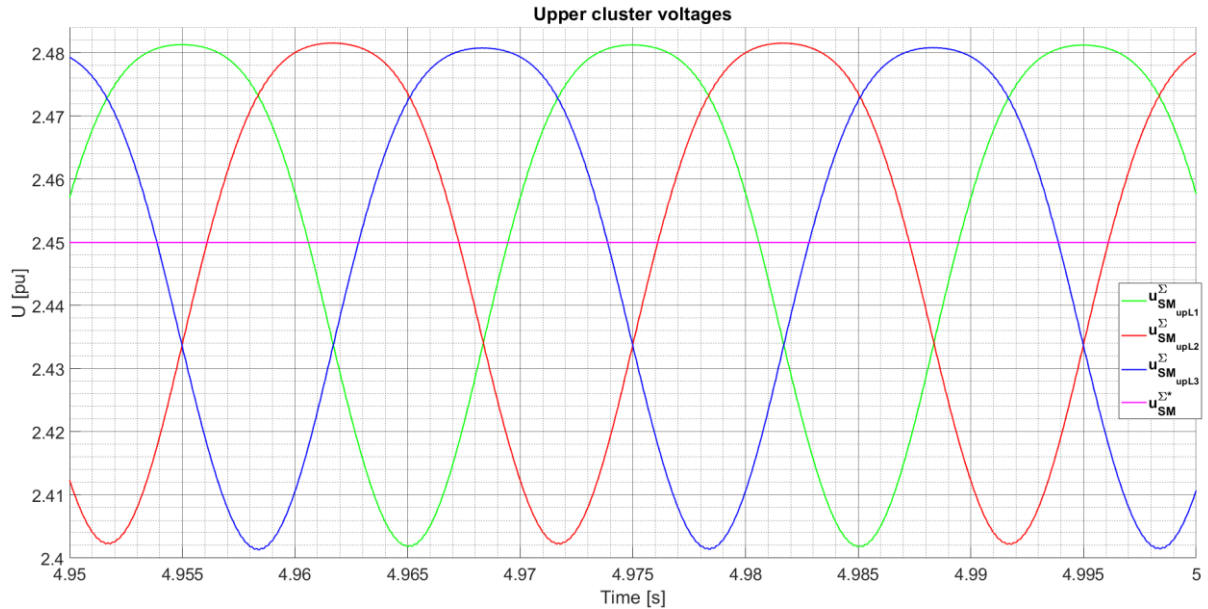


Figure 29: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*} = 1 \text{ pu inductive}$ during one line-to-earth short-circuit steady-state in simulation

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu. The mean value over one period of time is 2.450 pu which is equal to the reference $u_{SM_{u,l}}^{\Sigma*}$.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*} = 1 \text{ pu inductive}$ in simulation and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 30.

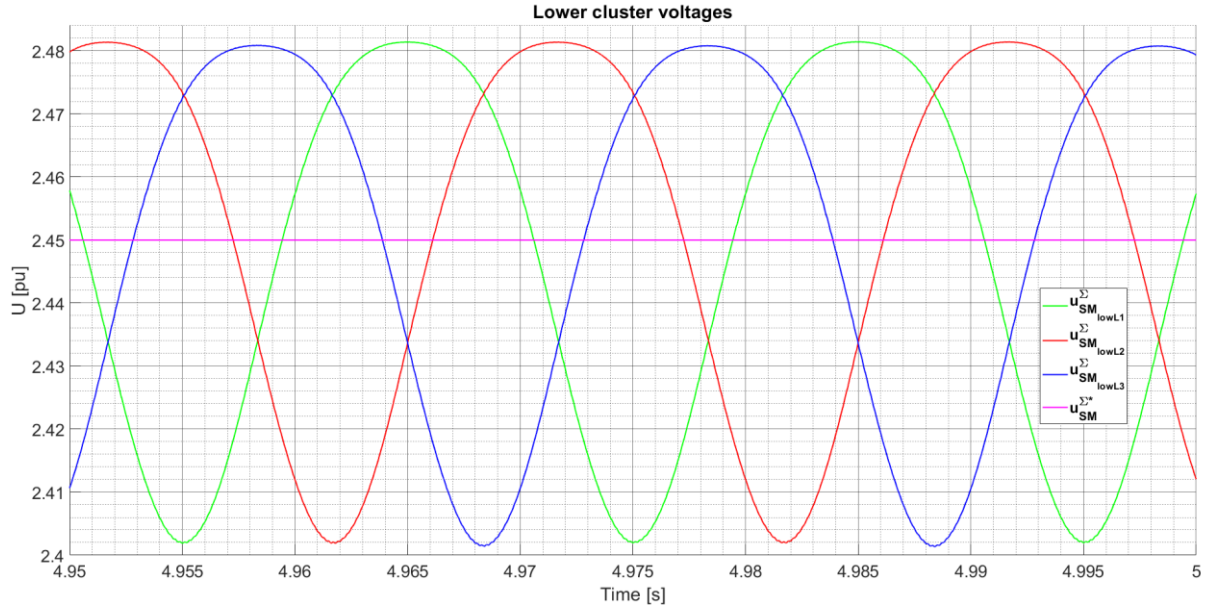


Figure 30: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit steady-state in simulation

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu. The mean value over one period of time is 2.450 pu which is equal to the reference $u_{SMu,l}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SMu,l}^{\Sigma*}$ and so that internal stability is guaranteed when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit steady-state in simulation.

It is important also to verify the STATCOM is able to withstand the transient of one line-to-earth short-circuit. Grid currents during this transient are shown in Figure 31.

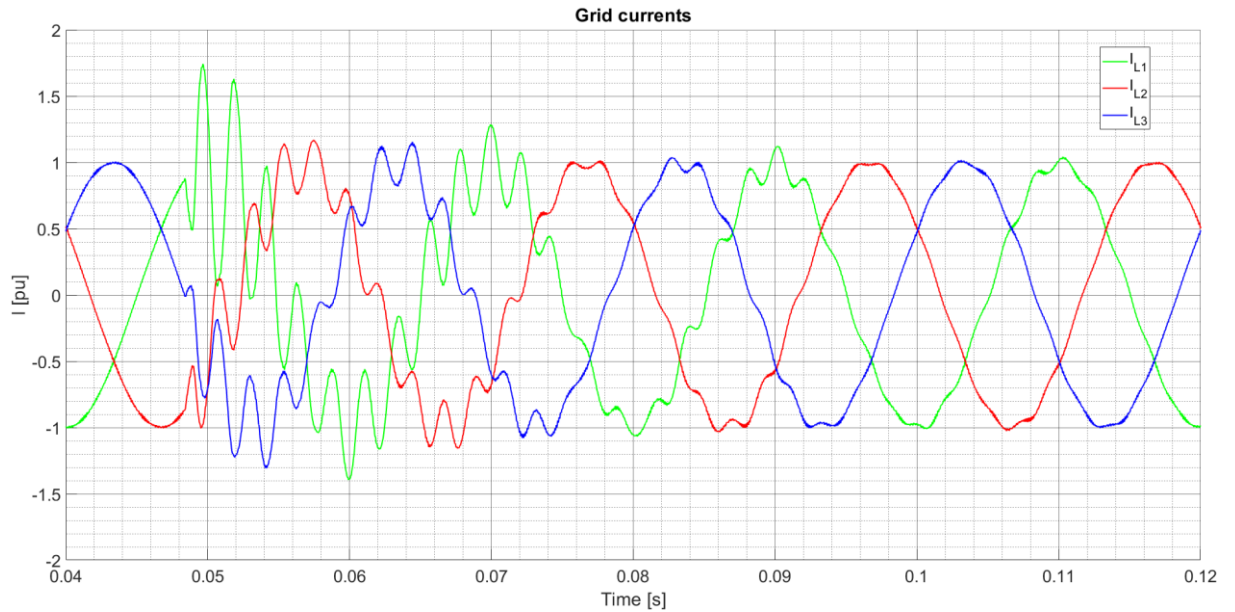


Figure 31: DSCC grid currents when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit transient in simulation

As it can be seen in Figure 31, grid currents continue to follow the $I_{h1}^{+*} = 1$ pu inductive reference during the transient. However, at the beginning of the transient (at 0.0484 s), important oscillations occur going until 1.742 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.



Figure 32 and Figure 33 show the internal cluster voltages during this transient.

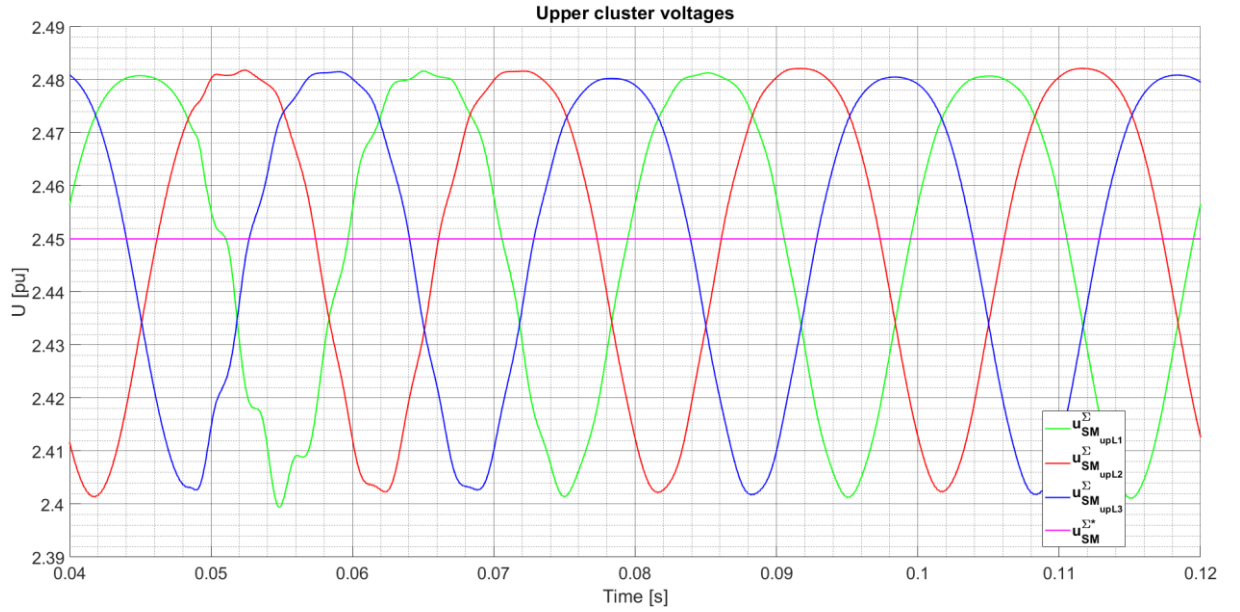


Figure 32: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit transient in simulation

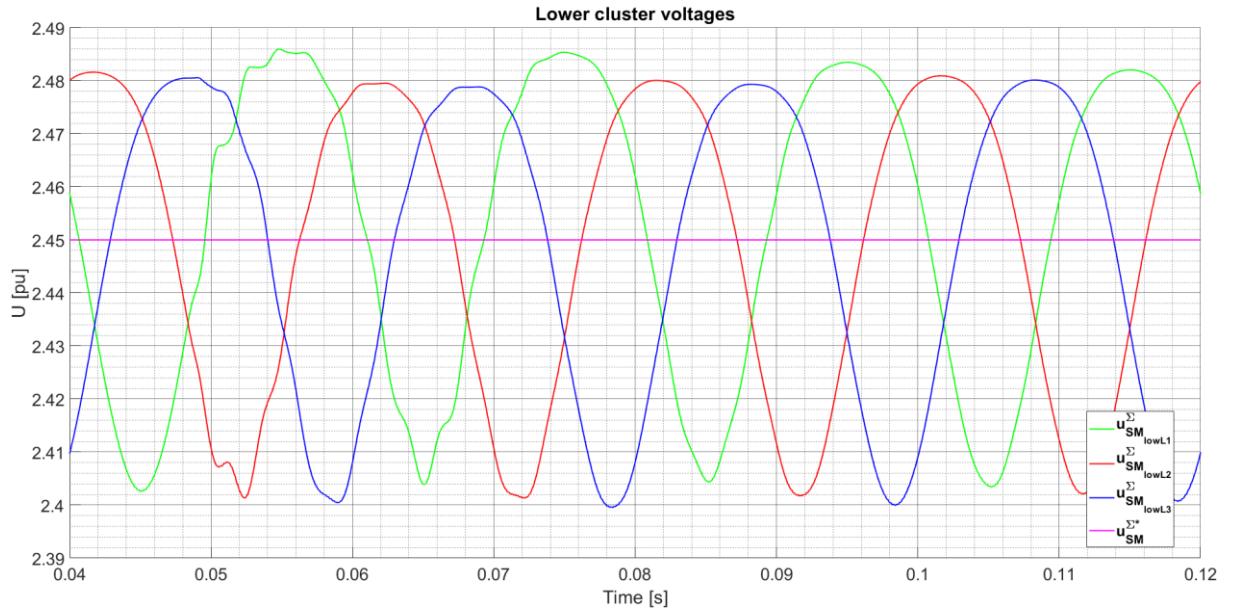


Figure 33 : DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit transient in simulation

Cluster voltages contain also additional oscillations but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 2.486 pu. Cluster voltages are less impacted than current during this transient and remain stable. These results imply that the DSCC STATCOM with this control strategy is also able to withstand the transient of one line-to-earth short-circuit.

Finally, it is possible to validate the correct DSCC operation when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit with the proposed control strategy.

A summary of DSCC simulation results when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit in steady state is given in Table 10. As already mentioned in section 4.3.6, only the summarized results



for STATCOM capacitive operation are presented to lighten the report content. The detailed results are available in 16.5 appendix.

DSCC simulation results at the end of one line-to-earth short-circuit		
	$I_{h1}^{++}=1\text{pu}$ inductive	$I_{h1}^{++}=1\text{pu}$ capacitive
I_{h1}^{++} [pu] (all phases)	1.000	1.000
THDi phase L1 [%]	1.0	1.0
THDi phase L2 [%]	0.9	1.0
THDi phase L3 [%]	0.9	1.0
THDi maximum increase compared to balanced grid voltages case [%]	0.1	0.0
Current Unbalance Factor [%]: $\frac{\hat{i}_{h1}^-}{\hat{i}_{h1}^+}$	0.0	0.0
P_{h1}^+ [pu]	0.007	0.007
Q_{h1}^+ [pu]	0.987	-0.987
$u_{SM_u}^\Sigma$ pk-pk amplitude [pu] (all arms)	0.079	0.079
$\overline{u_{SM_u}^\Sigma}$ average [pu] (all arms)	2.450	2.450
$u_{SM_l}^\Sigma$ pk-pk amplitude [pu] (all arms)	0.079	0.079
$\overline{u_{SM_l}^\Sigma}$ average [pu] (all arms)	2.450	2.450

Table 10: DSCC simulation results at the end of one line-to-earth short-circuit

As it can be seen in Table 10, capacitive and inductive results are very close to each other. Furthermore, all results are precisely matching their setpoint. Finally, the low THDi is beneficial for the network and is reached in majority thanks to the modular topology of the converter.

Based on these results, it is possible to confirm that DSCC STATCOM control strategy works correctly during one line-to-earth short-circuit. DSCC STATCOM is able to exchange $I_{h1}^{++} = 1$ pu capacitive and inductive during one line-to-earth short-circuit permanently.

In addition, displacement angles between voltage and current for each remaining phase are taken from simulation for DSCC because they are used as references for the comparison with experimental measurements. Indeed, the power quality analyser measures this displacement angle. Figure 34 and Figure 35 present the current and its respective voltage for L2 and L3.

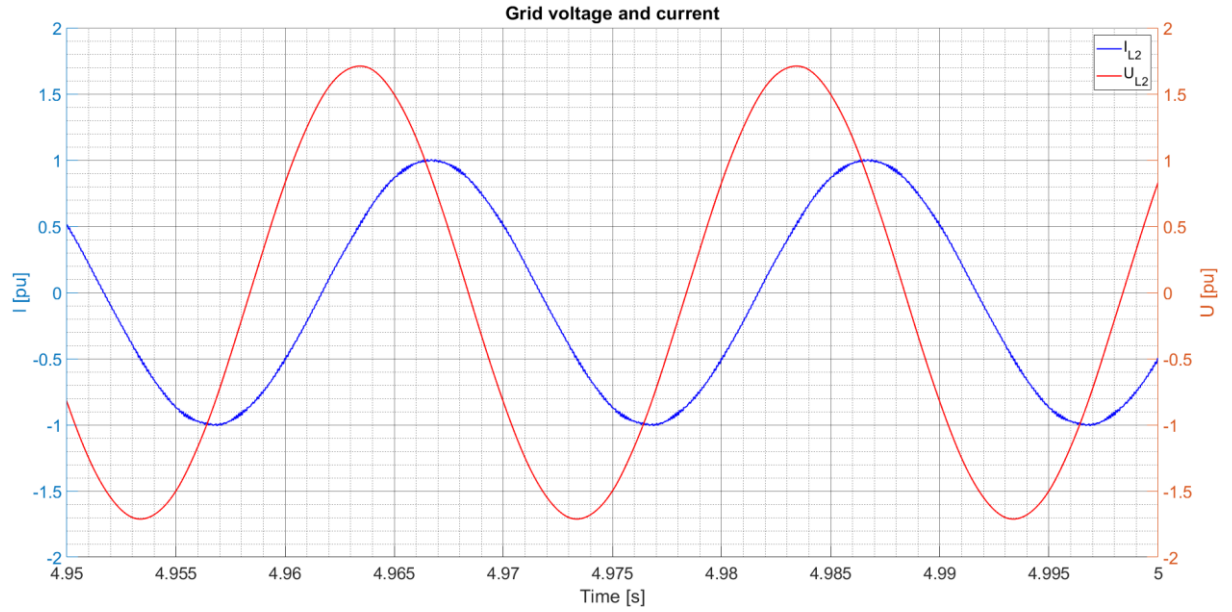


Figure 34: DSCC grid voltage and current of phase L2 when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit steady-state in simulation

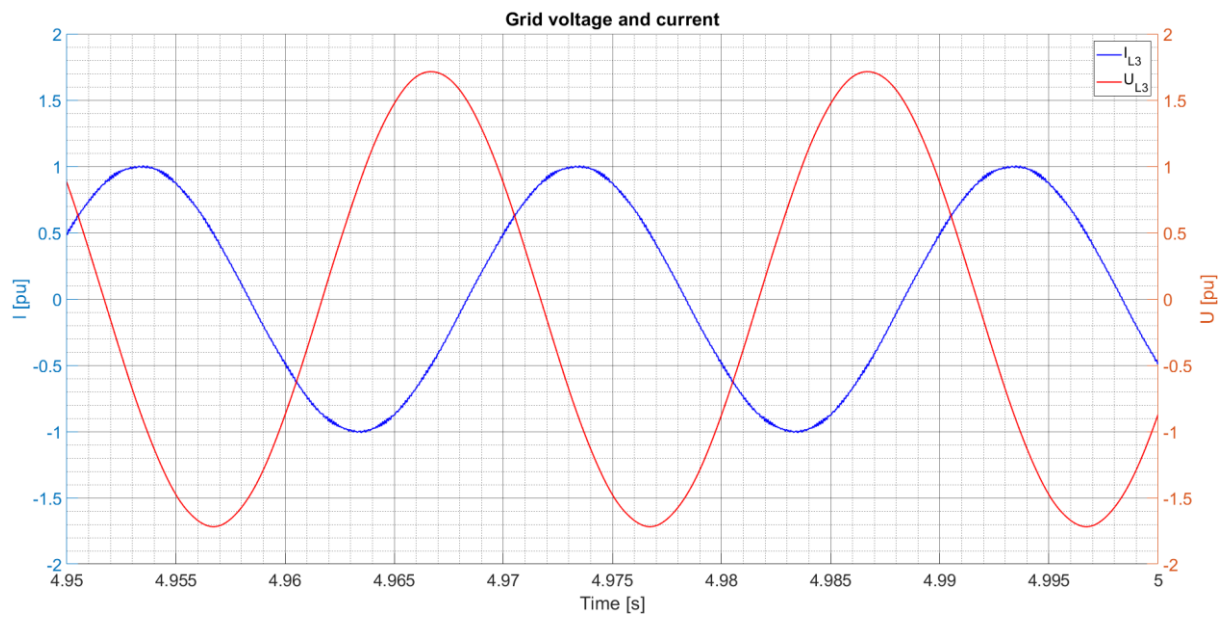


Figure 35: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*} = 1$ pu inductive during one line-to-earth short-circuit steady-state in simulation

Simulation gives us the displacement angle between voltage and current for each phase:

- $\theta_{h1L2}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 59.4^\circ$
- $\theta_{h1L3}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 119.8^\circ$

As a remark, the current is lagging the voltage meaning an inductive operation.



4.3.8.3. DSCC simulations with two lines-to-earth short-circuit

It is important to remind that two lines-to-earth short-circuit directly at STATCOM input is the worst voltage grid unbalanced state for the STATCOM and converters in general. DSCC simulations for two lines-to-earth short-circuit use the electrical schematic presented in Figure 23.

The grid voltage in simulation is applied as in Figure 17. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 8. DSCC STATCOM exchanges $Q_{STATCOM}^* = +1pu$ or $Q_{STATCOM}^* = -1pu$. Then, when time = 0.0484 s the two lines-to-earth short-circuit appears on phases L1 and L2 meaning the grid voltages $u_{gsL1} = 0 pu$ as well as $u_{gsL2} = 0 pu$. In the same time, phase voltage L3 amplitude increases. It can be seen a transient for around three periods. Then the two lines-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(steady\ state) = 0 pu$
- $u_{gsL2}(steady\ state) = 0 pu$
- $u_{gsL3}(steady\ state) = 1.476 pu$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

When this two lines-to-earth short-circuit occurs, the goal for DSCC STATCOM is to continue to exchange the same positive sequence current (inductive or capacitive) with the grid (for the same reason as for one line-to-earth short-circuit).

This section focuses only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 18 shows steady-state unbalanced grid voltages during two lines-to-earth short-circuit applied on DSCC STATCOM in simulation.

In the extreme case of two lines-to-earth short-circuit at STATCOM input, the control strategy proposed in this project does not allow to maintain a permanent internal stability of the cluster voltages. It is confirmed by calculation in [8]. The arm energy balancing controller of each leg cannot be regulated to zero. As a consequence, the upper and lower cluster voltage of each arm are respectively increasing and decreasing. After a certain amount of time, the current exchanged with grid would be too distorted and the high voltages for submodule capacitors would lead to component failure. Before it happens, internal safety program disconnects the STATCOM from the grid.

However, as already mentioned, the maximum duration time of a short-circuit in MV or HV grid is around 5 seconds (for grid lines conductor safety). Then, the internal behaviour of the DSCC do not need to remain stable permanently in short-circuit conditions. It only needs to continue to operate during these 5 seconds without safety disconnection. This section will show that even if the internal control is not stable, it is sufficient to maintain cluster voltages in a safety operating state during 5 seconds of two lines-to-earth short-circuit.

To go further, [8] proposes different control strategies that could possibly improve internal stability of the STATCOM DSCC topology. But the lack of time in the project did not allow us to explore a new control strategy. This point is still opened and would need more time to investigate.

The grid currents results when positive sequence inductive current ($I_{h1}^{+*} = 1 pu$ inductive) is exchanged between DSCC and grid at the end of short circuit are shown in Figure 36.

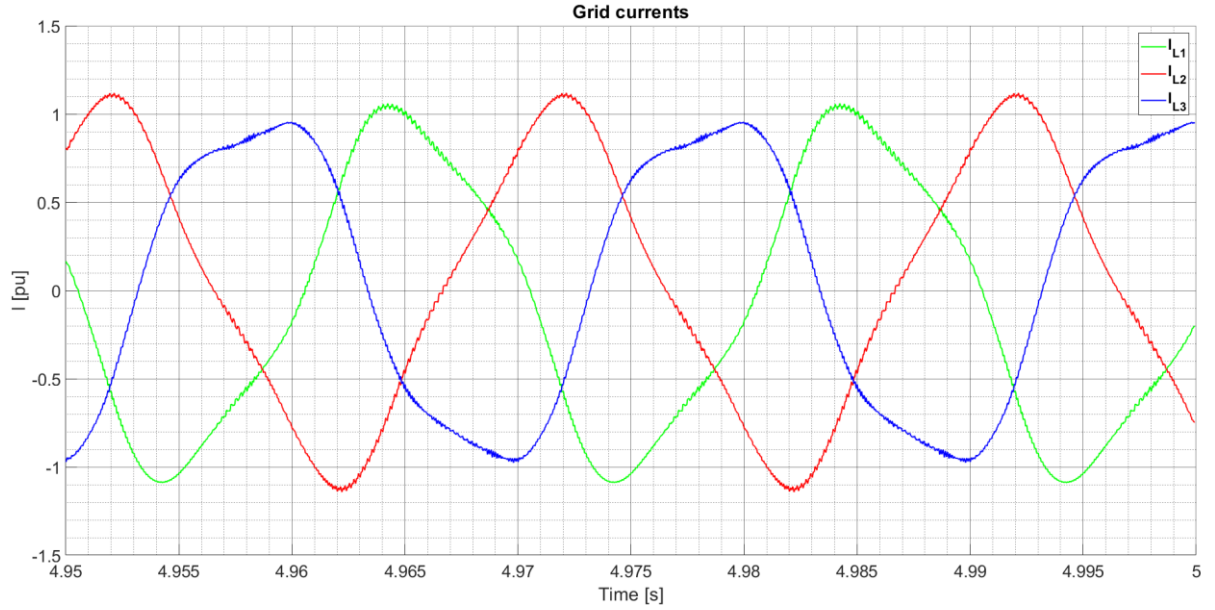


Figure 36: DSCC grid currents when $I_{h1}^{+*} = 1$ pu inductive at the end of two lines-to-earth short-circuit in simulation

In Figure 36, it can be seen that the currents are 50 Hz distorted sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 14.5 \%$
- $THDi_{L2}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 13.4 \%$
- $THDi_{L3}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 15.7 \%$

Contrary to grid voltage balanced state, $THDi(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC)$ is quite high. The third harmonic (150 Hz) is the most important with around 14% of the fundamental value followed by the fifth harmonic (250 Hz) with around 0.8% of the fundamental value. Other harmonics are negligible with less than 0.5% of the fundamental value. Two lines-to-earth short-circuit has a quite important impact on the quality of the currents. This is due to converter topology and internal control. To solve this issue, additional techniques in the control or filters could be used to attenuate the harmonics. However, given that two lines-to-earth short-circuit are uncommon and do not last more than few seconds, it does not bring any significant added value for the overall STATCOM operation (mainly balanced network operation). As a remark, the internal instability is not responsible for this amount of THDi because the internal state in this case is far from instability.

The fundamental RMS value of positive and negative sequence grid currents given by simulation are:

- $\hat{I}_{h1}^{+}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 1.000 \text{ pu}$
- $\hat{I}_{h1}^{-}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.000 \text{ pu}$

This implies no imbalance is seen at fundamental frequency. The converter regulates well the current to provide only 50 Hz positive sequence current. But the third harmonic brings notable negative sequence. The overall Current Unbalance Factor (CUF) is:

$$CUF(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = \frac{I_{rms}^{-}}{I_{rms}^{+}} = \frac{0.062}{1.003} \cdot 100 = 6.2 \%$$

This value is negligible considering the grid voltage short-circuit state ($VUF = 100\%$).

All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*} = 1$ pu inductive in spite of the distortion which is notable during two lines-to-earth short-circuit steady-state in simulation.

The second goal is to verify the DSCC exchanges fundamental positive sequence inductive reactive power with the grid. During two lines-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^{+}$) is equal to 0.492 pu (see Table 3). Simulation results give the



fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^+ = 90.8^\circ$. It is then possible to calculate the powers:

- $P_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 0.007 \text{ pu}$
- $Q_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 0.492 \text{ pu}$

DSCC converter exchanges Q_{h1}^+ in great majority meaning that it continues to operate mainly as a balanced inductive STATCOM. However, as mentioned earlier in the report, Q_{h1}^+ is half of the base power value because positive sequence of voltage is half of the base value and positive sequence of current is voluntarily kept to 1 pu inductive to avoid high current value in the converter. Other components of active and reactive powers are not the point of interest in our application. But it is important to mention that these components add notable ripples to the overall powers which are not desired in normal operation.

It is also important to verify the STATCOM is able to withstand the transient of two lines-to-earth short-circuit. Grid currents during this transient are shown in Figure 37.

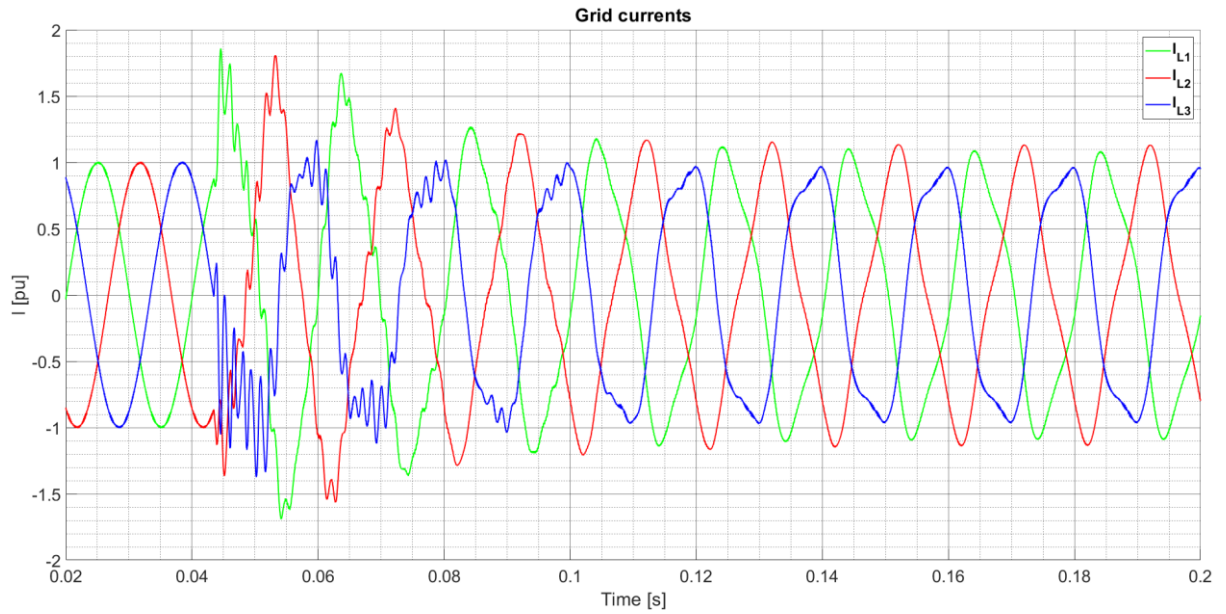


Figure 37: DSCC grid currents when $I_{h1}^{+*} = 1 \text{ pu inductive}$ during two lines-to-earth short-circuit transient in simulation

As it can be seen in Figure 37, grid currents continue to follow the $I_{h1}^{+*} = 1 \text{ pu inductive}$ reference during the transient. However, at the beginning of the transient (at 0.0484 s), important oscillations occur going until 1.859 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods. The transient is managed correctly for the currents.

During the 5 seconds of two lines-to-earth short-circuit, the transient and steady-state currents exchanged with the grid in simulation confirm correct inductive operation of the STATCOM.

However, as explained above, cluster voltages are slowly moving away from their reference ($u_{SMu,l}^{\Sigma*} = 2.45 \text{ pu}$). The upper arm cluster voltage for each leg with $I_{h1}^{+*} = 1 \text{ pu inductive}$ in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 38.

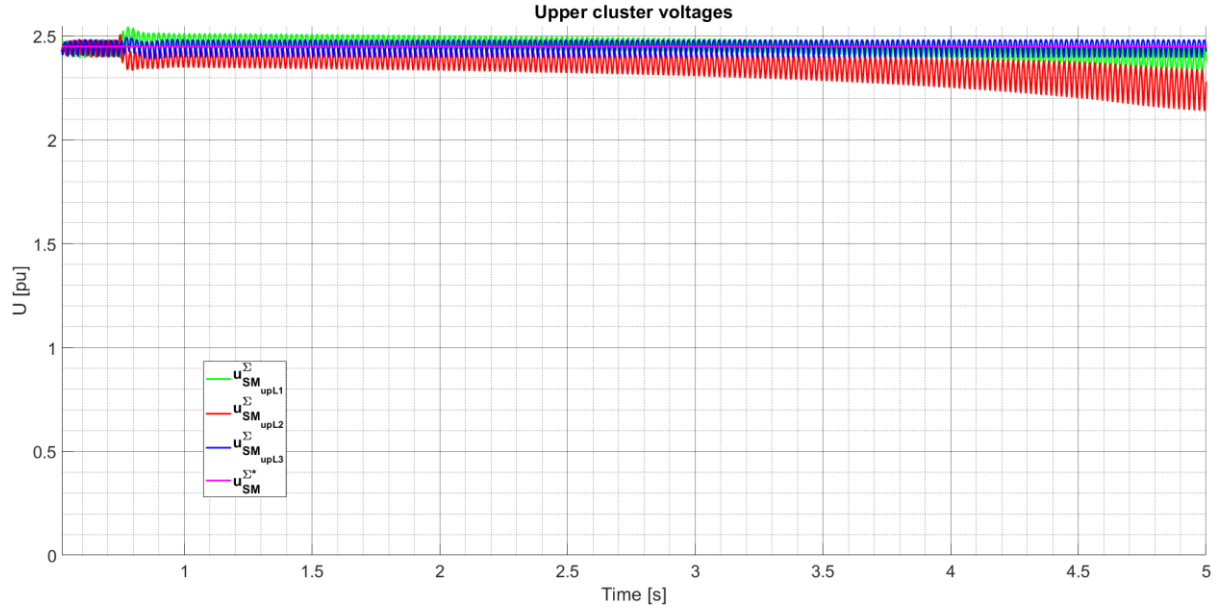


Figure 38: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive during two lines-to-earth short-circuit in simulation

In Figure 38, L1 and L2 upper cluster voltages are slowly decreasing from the 2.45 pu setpoint while L3 is decreasing even more slowly.

The final value before 5s of short-circuit are shown in Figure 39.

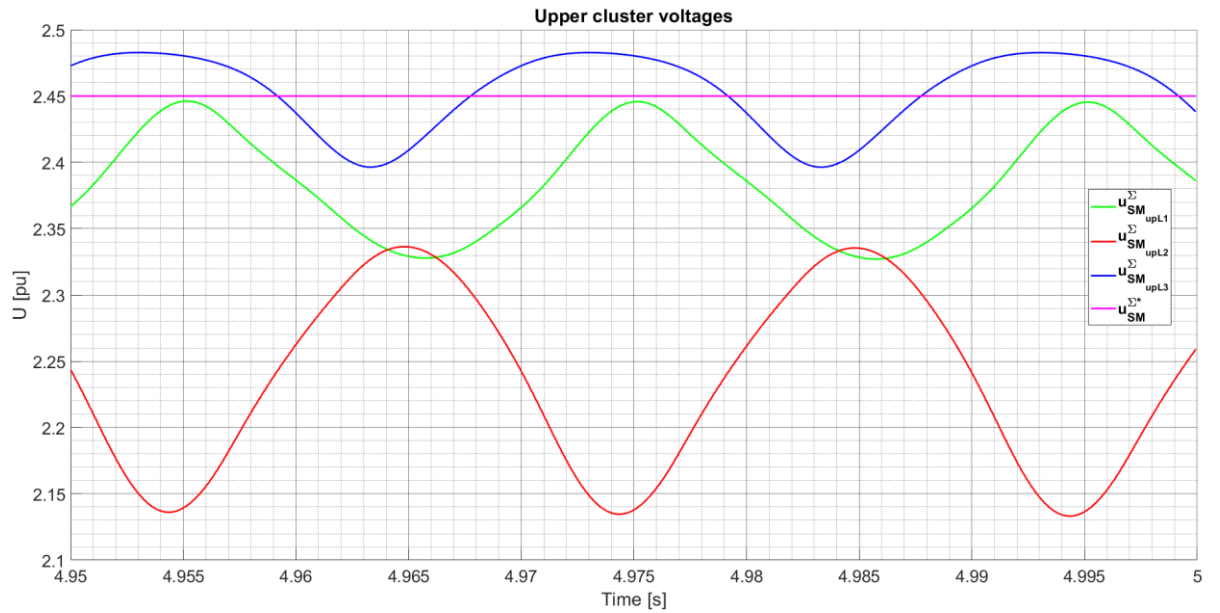


Figure 39: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive at the end of two lines-to-earth short-circuit in simulation

As it can be seen, after 5 seconds of short-circuit, their peak-to-peak amplitudes are:

- $u_{SMupL1pp}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 0.118 \text{ pu}$
- $u_{SMupL2pp}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 0.200 \text{ pu}$
- $u_{SMupL3pp}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 0.086 \text{ pu}$



Ripple amplitudes are maximum 2.5 times higher than the balanced case (phase L2) but stay reasonable for STATCOM hardware safety operation.

It can also be noted that L3 phase stay around the setpoint value but L2 and L1 phases do not have the same average value. This internal unbalance between phases is not an issue for the overall internal operation.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*} = 1$ pu inductive in simulation and the reference $u_{SM,u,l}^{+*}$ are shown in Figure 40.

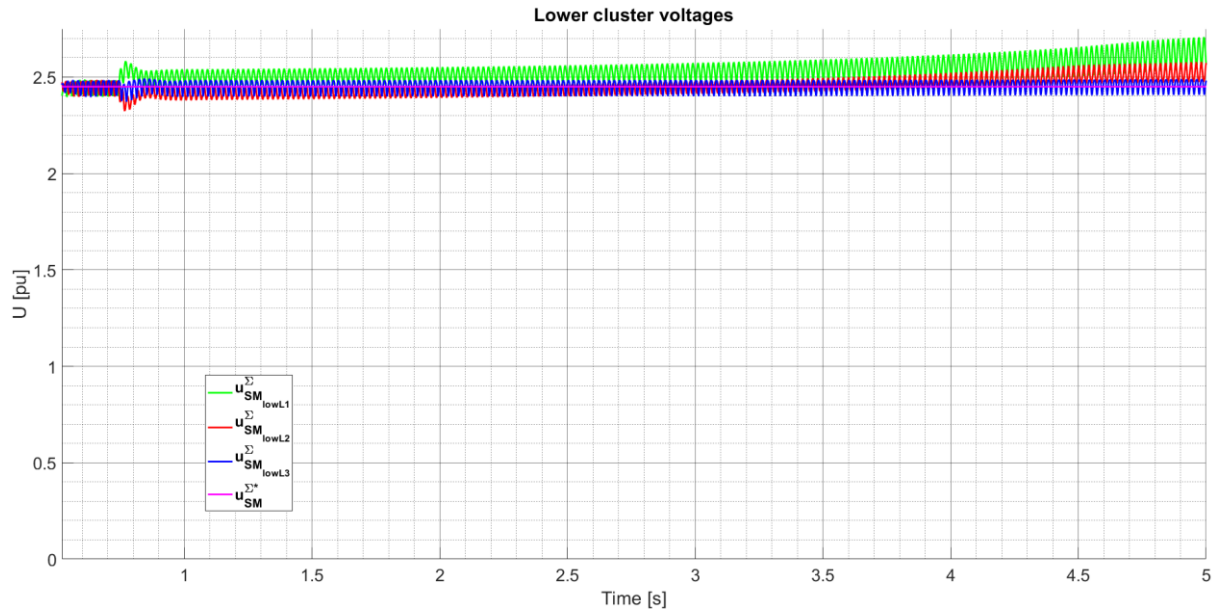


Figure 40: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive during two lines-to-earth short-circuit in simulation

In Figure 40, L1 and L2 lower cluster voltages are slowly increasing from the 2.45 pu setpoint while L3 is increasing even more slowly.

The final value before 5s of short-circuit are shown in Figure 41.

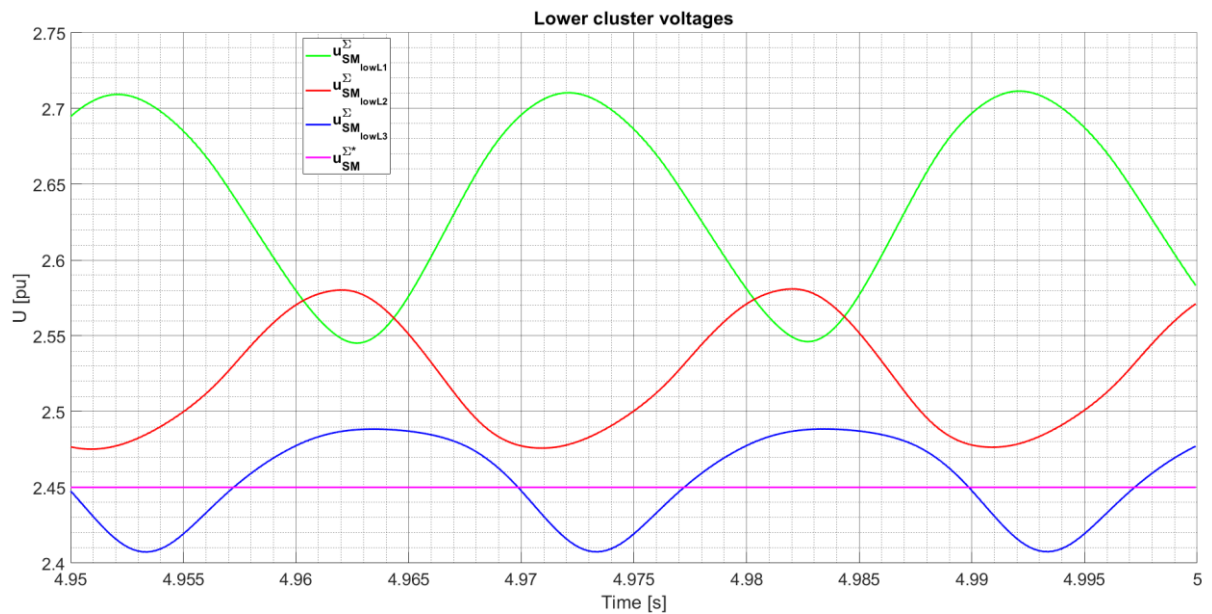


Figure 41: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive at the end of two lines-to-earth short-circuit in simulation



As it can be seen, after 5 seconds of short-circuit, their peak-to-peak amplitudes are:

- $u_{SM_{upL1pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.165 \text{ pu}$
- $u_{SM_{upL2pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.105 \text{ pu}$
- $u_{SM_{upL3pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.081 \text{ pu}$

Ripple amplitudes are maximum 2.1 times higher than the balanced case (phase L1) but stay reasonable for STATCOM hardware safety operation.

It can also be noted that L3 phase stay around the setpoint value but L2 and L1 phases do not have the same average value. This internal unbalance between phases is not an issue for the overall internal operation.

As already mentioned earlier in this section, in the extreme case of two lines-to-earth short-circuit at STATCOM input, the control strategy proposed in this project does not allow to maintain a permanent internal stability of the cluster voltages. The arm energy balancing controller of each leg cannot be regulated to zero. As a consequence, the upper and lower cluster voltage of each arm are respectively increasing and decreasing. However, after 5 seconds of short-circuit (very high time duration in power systems), simulation results show that internal unbalance is reasonable to continue to exchange correct currents with the grid while insuring the internal safety of the DSCC. Indeed, maximum cluster voltage reached (phase L1) is 2.712 pu which is 0.262 pu over the reference value. Dividing this value by 5 gives maximum voltage increase for each capacitor in the arm: 0.052 pu. This small increase compared to the nominal voltage value (10.7% of relative deviation) means the DSCC do not need to be disconnected for safety reason. Indeed, this increase do not impact significantly the design of the capacitors of the DSCC.

Finally, all simulation results of this section confirm DSCC correct operation of the converter to exchange positive sequence inductive current ($I_{h1}^{+*} = 1 \text{ pu inductive}$) during 5s of two lines-to-earth short-circuit with the proposed control strategy.

A summary of DSCC simulation results when $I_{h1}^{+*} = 1 \text{ pu inductive}$ during two lines-to-earth short-circuit in steady state is given in Table 11. As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are also presented to lighten the report content. The detailed results are available in 16.6 appendix.



DSCC simulation results at the end of two lines-to-earth short-circuit		
	$I_{h1}^{+*} = 1$ pu inductive	$I_{h1}^{+*} = 1$ pu capacitive
I_{h1}^{+*} [pu] (all phases)	1.000	1.000
THDi phase L1 [%]	14.5	12.7
THDi phase L2 [%]	13.4	12.6
THDi phase L3 [%]	15.7	13.2
THDi maximum increase compared to balanced grid voltages case [%]	14.8	12.2
Current Unbalance Factor h1 [%]: $\frac{\hat{i}_{h1}^-}{\hat{i}_{h1}^+}$	0.0	0.0
Current Unbalance Factor [%]: $\frac{\hat{i}_{rms}^-}{\hat{i}_{rms}^+}$	6.2	5.6
P_{h1}^+ [pu]	0.007	0.012
Q_{h1}^+ [pu]	0.492	-0.492
$u_{SM_u}^{\Sigma}$ maximum pk-pk amplitude [pu]	0.200 (phase L2)	0.087 (phase L3)
$u_{SM_u}^{\Sigma}$ minimum value [pu]	2.133 (phase L2)	2.363 (phase L1)
$u_{SM_u}^{\Sigma}$ maximum relative deviation compared to 2.45pu setpoint [%]	12.9	3.6
$u_{SM_l}^{\Sigma}$ maximum pk-pk amplitude [pu]	0.165 (phase L1)	0.084 (phase L3)
$u_{SM_l}^{\Sigma}$ maximum value [pu]	2.712 (phase L1)	2.541 (phase L2)
$u_{SM_l}^{\Sigma}$ maximum relative deviation compared to 2.45pu setpoint [%]	10.7	3.7

Table 11: DSCC simulation results at the end of two lines-to-earth short-circuit

As it can be seen in Table 11, currents exchanged with grid (capacitive or inductive) follow their setpoint even if THDi is quite important. The divergence of cluster voltages are slow enough to insure correct overall operation of DSCC during 5s of two lines-to-earth short circuit. It can be noted that capacitive operation keeps internal stability for a longer period of time than inductive operation. Based on these results, it is possible to confirm that DSCC STATCOM control strategy works correctly (exchange $I_{h1}^{+*}=1$ pu capacitive and inductive) during two lines-to-earth short-circuit without damaging the converter.

In addition, displacement angles between voltage and current for each remaining phase are taken from simulation for DSCC because they are used as references for the comparison with experimental measurements. Indeed, the power quality analyser measures this displacement angle. Figure 42 presents current and its respective voltage for L3.

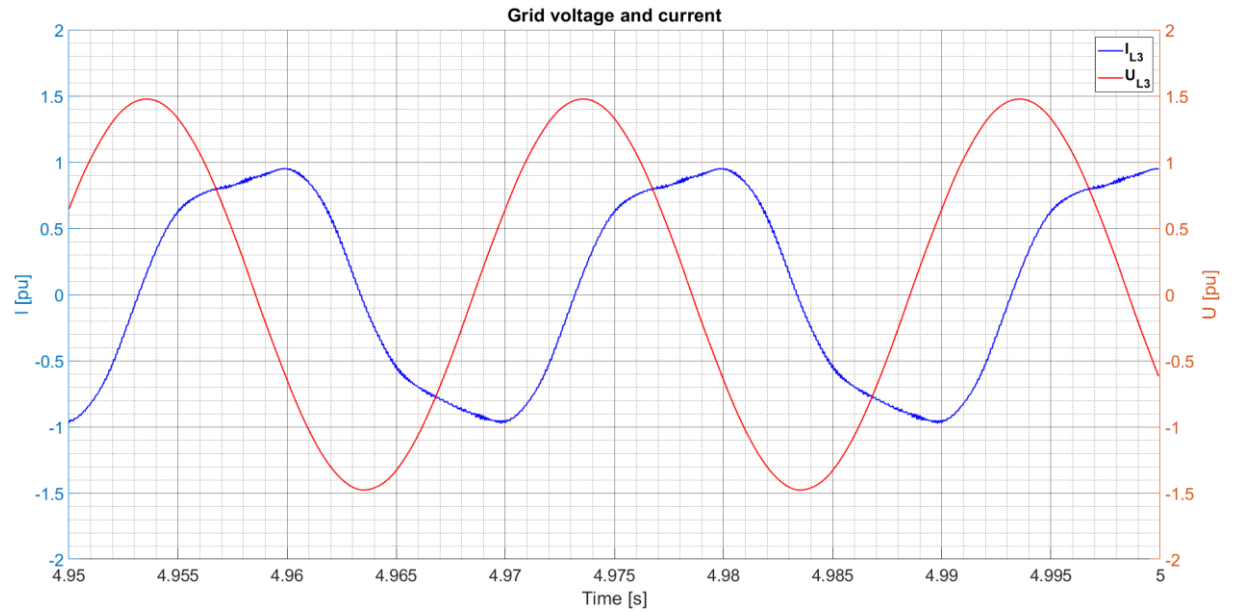


Figure 42: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*}=1$ pu inductive during two lines-to-earth short-circuit steady-state in simulation

Simulation gives us the displacement angle between voltage and current for phase L3:

$$- \theta_{h1_{L3}}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in SC}) = 92.6^\circ$$

This Figure 42 confirms the current is lagging the voltage meaning an inductive operation.



4.3.9 SSBC and DSCC comparison

The results presented in sections 4.3.7 and 4.3.8 confirm that SSBC and DSCC topologies (with the control strategies proposed) are able to continue to operate even if a short-circuit less than 5s happens. In this section, both topologies results are compared according to the currents exchanged with the grid and their internal behaviour.

4.3.9.1. Grid currents exchanged comparison

The first element to mention is that both topologies are able to exchange 1 pu positive sequence inductive (or capacitive) currents at 50Hz with grid whatever the grid voltage state. It means even if grid voltages are highly unbalanced, both topologies are able to exchange 50Hz balanced currents (which is beneficial for the grid).

The overall current unbalance (including all harmonics) are the same for both topologies in case the grid voltages are balanced or during one line-to-earth short-circuit (0%). However, during two lines-to-earth short-circuit (grid voltages with the highest unbalance), SSBC topology is better than the DSCC with the control strategies proposed. Indeed, the control strategy proposed for DSCC introduces negative sequence through the third harmonic (150Hz) increasing the total current unbalance exchanged (including all harmonics) until maximum 6% (in inductive operation) while SSBC with the control proposed do not inject negative sequence in any harmonics (0%).

In terms of power exchanged between converters and the grid, both topologies are able to perfectly follow their fundamental (50Hz) positive sequence reactive power in any grid voltages state. No difference is visible in terms of reactive power. The low amount of active power (due to converter losses) is equal for every cases except for the capacitive operation during two lines-to-earth short-circuit. DSCC power losses are almost doubled in this case while SSBC power losses remain the same as in balanced grid case. In overall, from the power point of view, SSBC seems better than DSCC with the control strategies proposed.

In terms of currents harmonic distortion, both topologies do not have the same submodules architecture and the same inductor parameters. It is then impossible to compare THDi directly. However, the THDi increase in short-circuits compared to balanced grid voltages case is compared. THDi of SSBC topology with the control used stays the same as balanced grid voltages case for both short-circuits. On the contrary, THDi of DSCC topology is importantly impacted in case of two lines-to-earth short-circuit. It means, SSBC topology with control proposed is better in terms of THDi during short-circuits.

A summary of the best topology (with control proposed) according to comparison indicators of grid currents exchanged is presented in Table 12.

Comparison indicators of grid currents exchanged	Best topology during balanced grid voltage	Best topology during 1 line-to-earth short-circuit	Best topology during 2 lines-to-earth short-circuit
Positive sequence currents at 50 Hz (capacitive or inductive)	Equals	Equals	Equals
Overall current unbalance (including all harmonics)	Equals	Equals	SSBC
Fundamental (50Hz) positive sequence reactive power	Equals	Equals	Equals
Power losses	Equals	Equals	SSBC
THDi increase during short-circuit conditions		Equals	SSBC

Table 12: Summary of the best topology (with control proposed) according to comparison indicators of grid currents exchanged

In conclusion, with the controls proposed, SSBC topology is more efficient in term of currents exchanged with the grid during short-circuit than the DSCC topology. However, for balanced grid voltages case, there is no significant difference between the topologies.



4.3.9.2. Converters internal behaviour comparison

It is also important to compare internal behaviour of converters.

The first point of comparison is the permanent stability of the internal behaviour. In balanced grid voltages operation as well as in one line-to-earth short-circuit, both topologies are permanently stable. The cluster voltages follow their setpoint for each arm. But in case of two lines-to-earth short-circuit, only SSBC is able to stay permanently stable with the control proposed while DSCC can operate only several seconds before stopping. DSCC could possibly do the same with an improved control strategy but it was impossible to do it before the end of the project.

Another point could be the comparison of minimum amplitude of voltage needed in submodule capacitors to keep internal stability. The lower the amplitude is, the better the costs are. However, SSBC submodules are made of bridge-cells while DSCC submodules are made of chopper cells. It leads intrinsically to lower amplitudes in SSBC case. This is why this comparison is not relevant.

The last point is the fact that in case of two lines-to-earth short-circuit, the internal control of DSCC is responsible of important grid current THDi increase while SSBC internal control does not affect significantly the grid currents quality.

In conclusion, with the controls proposed, SSBC topology internal behaviour is better than the DSCC topology during 2 lines-to-earth short-circuit. In balanced grid voltage operation and one line-to-earth short-circuit, there is no important difference between topologies.

4.3.9.3. Conclusion of comparison

In overall for balanced grid voltage operation and one line-to-earth short-circuit, DSCC and SSBC are similar in terms of grid currents exchanged and internal behaviour.

However, considering 2 lines-to-earth short-circuits and with the control proposed, SSBC works better than DSCC in terms of quality of currents exchanged with grid and internal behaviour.

As already mentioned, possible improvements in the control strategy of the DSCC could possibly lead to the same results as for the SSBC but with the timeline of the project, it was impossible to go further on this point.



4.3.10 DSCC experimental results

The DSCC prototype designed by HEIG-VD team (presented in section 2) was tested in Relne laboratory to validate simulation results. Experimental results are presented in this section.

4.3.10.1. DSCC prototype experimental results with balanced grid voltages

DSCC prototype was tested under balanced grid voltages for $Q_{STATCOM}^* = +1 pu$ and $Q_{STATCOM}^* = -1 pu$. A grid simulator is used to provide 200 V_{pk} and 50 Hz balanced grid voltage to the STATCOM. Coupling inductors with the same L_g and R_g values as in the simulation are added in series between STATCOM and grid simulator. Other STATCOM prototype parameters are the same as the simulation parameters presented in Table 8. The physical connections of components are presented in Figure 43.

For each STATCOM nominal power, the same test is performed 3 times, each one with a different measurement. They are necessary to confirm correct STATCOM operation.

The test protocols for $Q_{STATCOM}^* = +1 pu$ are as follows:

- First test: DSCC prototype is connected as presented in Figure 43. In this configuration, the power quality analyser allows to measure the STATCOM active and reactive power exchanged between STATCOM and grid simulator. Furthermore, it allows to measure voltages and currents quality in terms of RMS value, phases, harmonics, frequency and imbalance. The values are recorded with a sampling rate of 250ms for the complete test duration. In the same time, the three grid currents and L3 phase voltage waveforms are measured via the oscilloscope during steady state operation. Once the material is connected as presented in Figure 43, the grid simulator is parametrised to provide 200 V_{pk} and 50 Hz balanced grid voltage indefinitely. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) to be able to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The test operator then launches the STATCOM prototype operation. The first phase of the test is the preload of STATCOM submodules to their nominal voltage value as well as the synchronisation to network frequency. The STATCOM is considered as correctly preloaded when the average value of all $u_{SM_{u,l}}^\Sigma$ is equal to $u_{SM_{u,l}}^{\Sigma*}$ ($\overline{u_{SM_{u,l}}^\Sigma} = u_{SM_{u,l}}^{\Sigma*}$). Then the STATCOM starts to exchange $Q = +1 pu$ with the grid simulator. When the steady state is reached, the operator saves oscilloscope waveform measurements in CSV format. The test lasts 1 minute to $Q = +1 pu$ operation. At the end of this time duration, STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the first test at $Q_{STATCOM}^* = +1 pu$.

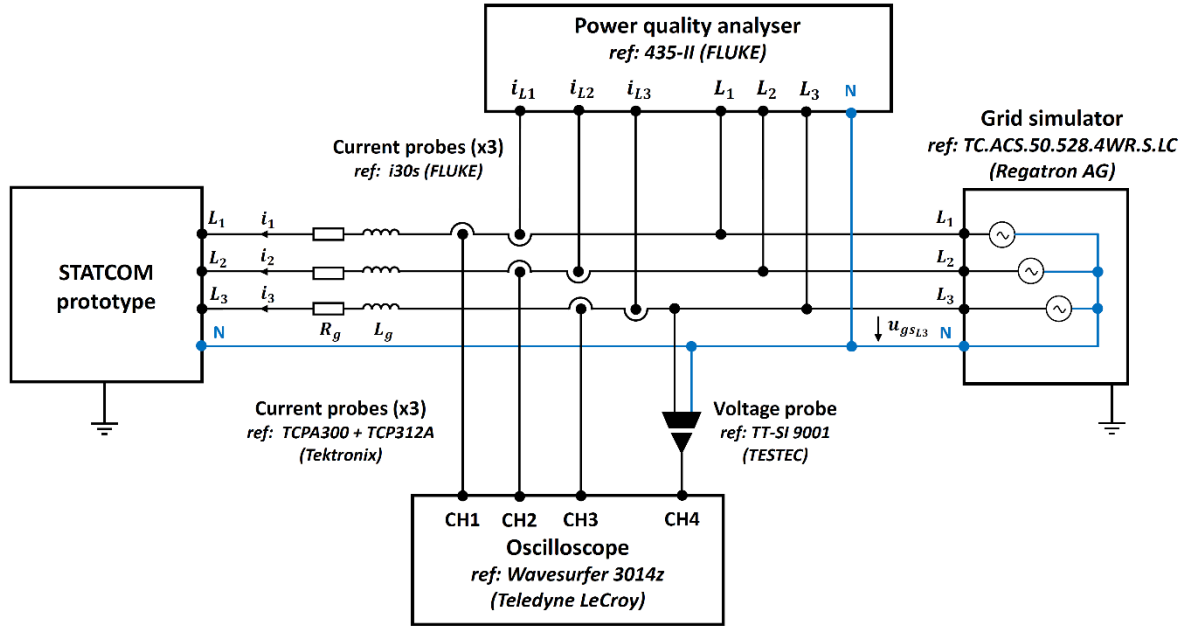


Figure 43: Schematic diagram for power quality, grid currents and L3 phase voltage measurement

- Second test: DSCC prototype is connected as presented in Figure 44. In this configuration, the power quality analyser is used like in the first test. Now oscilloscope measures grid currents i_1 and i_2 as well as grid phase voltages u_{gsL1} and u_{gsL2} during steady state operation. Once the material is connected as presented in Figure 44, the test procedure is the same as the first test. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage indefinitely. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) to be able to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The test operator then launches the STATCOM prototype operation. The first phase of the test is the preload of STATCOM SM to their nominal voltage value as well as the synchronisation to network frequency. The STATCOM is considered as correctly preloaded when the average value of all $u_{SMu,l}^{\Sigma}$ is equal to $u_{SMu,l}^{\Sigma*}$ ($u_{SMu,l}^{\Sigma} = u_{SMu,l}^{\Sigma*}$). Then the STATCOM starts to exchange $Q = +1 pu$ with the grid simulator. When the steady state is reached, the operator saves oscilloscope waveform measurements in CSV format. The test lasts 1 minute to $Q = +1 pu$ operation. At the end of this time duration, STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the second test at $Q_{STATCOM}^* = +1 pu$.

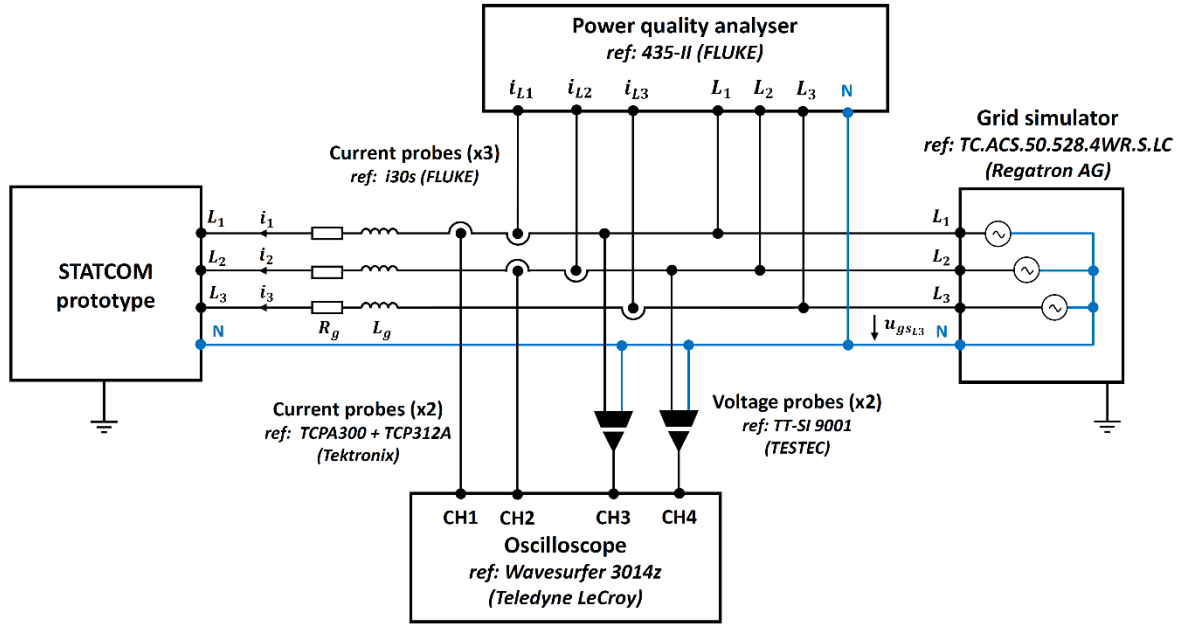


Figure 44: Schematic diagram for power quality, grid currents i_1 and i_2 and grid phase voltages u_{gsL1} and u_{gsL2} measurement

- Third test: DSCC prototype is connected as presented in Figure 45. In this configuration, the power quality analyser is used like in the first and second test. Now oscilloscope measures grid current i_1 as well as all grid phase voltages during steady state operation. Once the material is connected as presented in Figure 45, the test procedure is the same as the first and second test. The grid simulator is parametrised to provide 200 V_{pk} and 50 Hz balanced grid voltage indefinitely. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) to be able to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The test operator then launches the STATCOM prototype operation. The first phase of the test is the preload of STATCOM SM to their nominal voltage value as well as the synchronisation to network frequency. The STATCOM is considered as correctly preloaded when the average value of all $u_{SMu,l}^{\Sigma}$ is equal to $u_{SMu,l}^{\Sigma*}$ ($u_{SMu,l}^{\Sigma} = u_{SMu,l}^{\Sigma*}$). Then the STATCOM starts to exchange $Q = +1 pu$ with the grid simulator. When the steady state is reached, the operator saves oscilloscope waveform measurements in CSV format. The test lasts 1 minute to $Q = +1 pu$ operation. At the end of this time duration, STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the third and last test at $Q_{STATCOM}^* = +1 pu$.

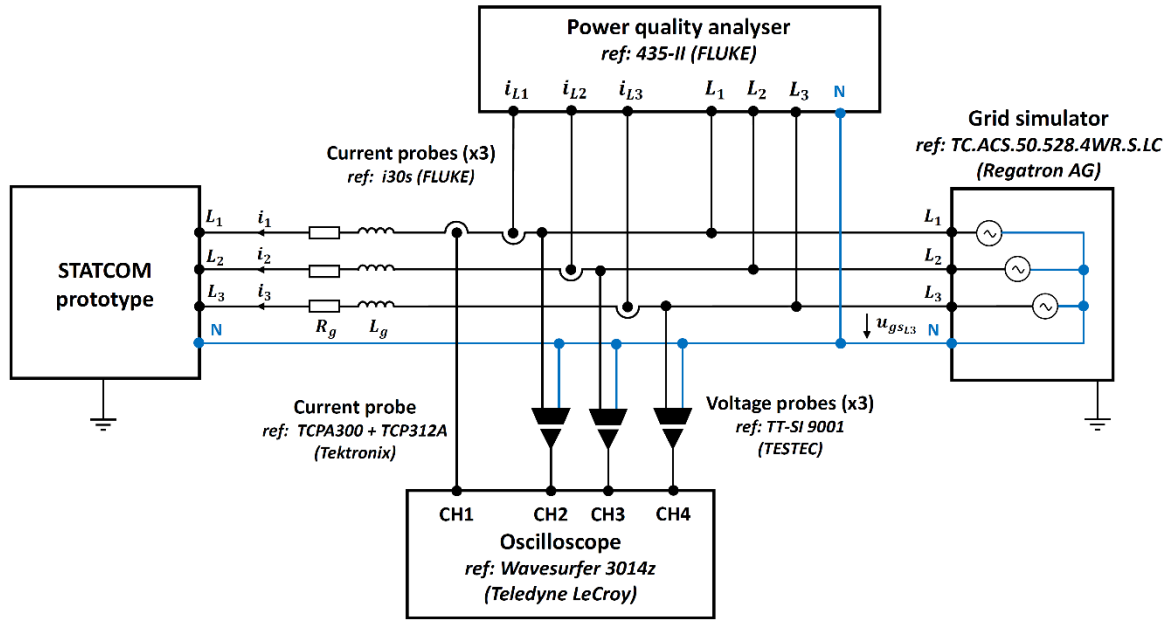


Figure 45: Schematic diagram for power quality, grid current i_1 and grid phase voltages measurement

To completely test DSCC STATCOM prototype under balanced grid voltages, the same three test protocols are also performed for $Q_{STATCOM}^* = -1 pu$.

Thanks to $Q_{STATCOM}^* = +1 pu$ (inductive operation) tests realised, it is possible to fully analyse the DSCC prototype results and to compare it with the simulation results.

The grid simulator voltages during $Q_{STATCOM}^* = +1 pu$ are visible in Figure 46.

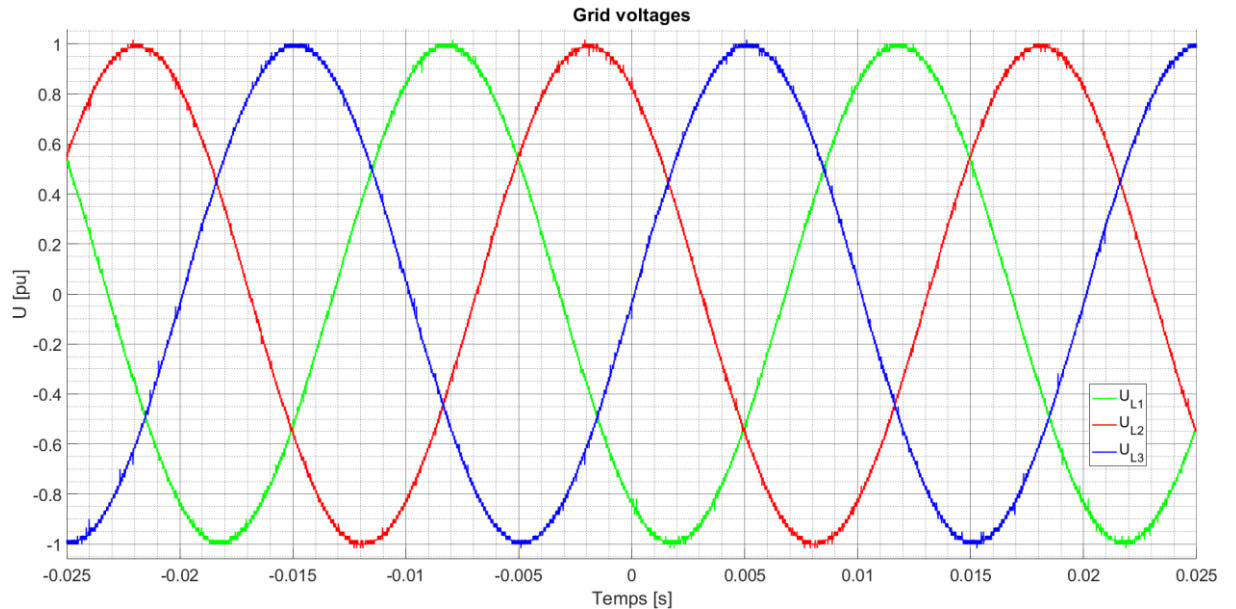


Figure 46: Balanced grid voltages of grid simulator during $Q_{STATCOM}^* = +1 pu$ tests

On Figure 46, it can be seen that the voltages are 50 Hz sinusoids. The 50 Hz frequency average over one-minute test is confirmed by power quality analyser measurements. The power quality analyser gives the same voltage THD for each phase: 0.4%. The fundamental RMS value of grid voltages (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values are given in pu:



- $\hat{U}_{L1h1}(Q^* = +1pu \text{ test balanced voltages}) = 0.996 \text{ pu}$
- $\hat{U}_{L2h1}(Q^* = +1pu \text{ test balanced voltages}) = 0.996 \text{ pu}$
- $\hat{U}_{L3h1}(Q^* = +1pu \text{ test balanced voltages}) = 0.996 \text{ pu}$

The fundamental displacement angles between phase voltages are given below (power quality analyser precision of 1°):

- $\varphi_{uL1 \rightarrow uL2}(Q^* = +1pu \text{ test balanced voltages}) = -120^\circ$
- $\varphi_{uL1 \rightarrow uL3}(Q^* = +1pu \text{ test balanced voltages}) = +120^\circ$

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 0.05%. These results confirm that the grid simulator provides balanced voltages to the DSCC prototype when $Q_{STATCOM}^* = +1 \text{ pu}$. Voltages are smaller than 1 pu because the STATCOM operates as an inductor, reducing the RMS grid voltage of only 0.4%.

With $Q_{STATCOM}^* = +1 \text{ pu}$, grid currents waveforms are shown in Figure 47.

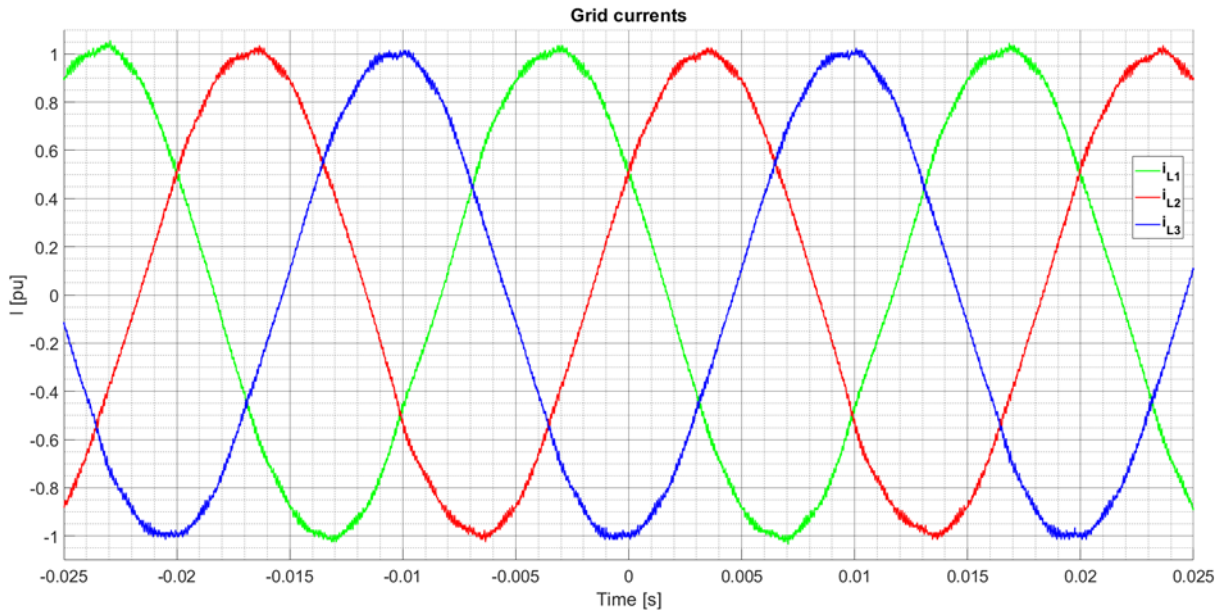


Figure 47: DSCC grid currents when grid voltages are balanced during $Q_{STATCOM}^* = +1pu$ test

On Figure 47, it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD in one-minute average for each phase:

- $THDi_{L1}(Q^* = +1pu \text{ test balanced voltages}) = 1.3\%$
- $THDi_{L2}(Q^* = +1pu \text{ test balanced voltages}) = 1.3\%$
- $THDi_{L3}(Q^* = +1pu \text{ test balanced voltages}) = 1.2\%$

Compared to simulation results, THD maximum increase is of 0.4%. This difference is negligible. This is mainly due to measurement noise and non-ideal components characteristics.

The fundamental RMS value of grid currents (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values in one-minute average are given in pu:

- $\hat{I}_{L1h1}(Q^* = +1pu \text{ test balanced voltages}) = 1.020 \text{ pu}$
- $\hat{I}_{L2h1}(Q^* = +1pu \text{ test balanced voltages}) = 1.015 \text{ pu}$
- $\hat{I}_{L3h1}(Q^* = +1pu \text{ test balanced voltages}) = 1.001 \text{ pu}$



The fundamental displacement angles are given below (power quality analyser precision of 1°):

- $\varphi_{iL1 \rightarrow iL2}(Q^* = +1pu \text{ test balanced voltages}) = -120^\circ$
- $\varphi_{iL1 \rightarrow iL3}(Q^* = +1pu \text{ test balanced voltages}) = +120^\circ$

A relative deviation of 0% compared to 120° is measured which confirm currents are balanced.

Furthermore, power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^+(Q^* = +1pu \text{ test balanced voltages}) = 1.011 pu$
- $\hat{I}_{h1}^-(Q^* = +1pu \text{ test balanced voltages}) = 0.008 pu$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.8\%$ which is negligible. These second elements confirm again that the current provided by the DSCC prototype is well balanced in case of grid voltages balanced when $Q_{STATCOM}^* = +1 pu$ which is one of the two goals needed to validate the correct STATCOM operation.

It is also important to verify that the reactive power is exchanged correctly. The power quality analyser measures the fundamental 3-phase reactive power (Q_{h1}^+) as well as the 3-phase active power (P) and the 3-phase fundamental active power (P_{h1}^+) according to relations (4), (5) and (6), all taken from [7].

During the one-minute test where $Q_{STATCOM}^* = +1 pu$, the average power values measured via the power quality analyser over this period in steady state are:

- $Q_{h1}^+(Q^* = +1pu \text{ test balanced voltages}) = 1.006 pu$
- $P_{h1}^+(Q^* = +1pu \text{ test balanced voltages}) = 0.017 pu$
- $P(Q^* = +1pu \text{ test balanced voltages}) = 0.017 pu$

The relative deviation between reactive power reference and measurement is equal to $\Delta_Q(Q^* = +1pu \text{ test balanced voltages}) = 0.6\%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator.

Active powers (equal losses for STATCOM) are negligible compared to reactive power exchanged with the grid. Given that the currents and voltages are well balanced, it can be noted that $P_{h1}^+ = P$ is a good approximation. It is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(Q^* = +1pu \text{ test balanced voltages}) = 183\%$. This is because, the simulation was not performed to precisely represent the prototype losses (cables, losses of components, components imperfection). It would have required an important additional work that was impossible to fulfil in the timeline of the project. However, the aim of the simulation was to design a STATCOM control strategy able to follow a reactive power reference as well as maintaining the internal behaviour stable. The results shown in this section confirm the correct operation of the converter to follow a reactive power setpoint. It means the simulation reached its goal which was to provide an operational control strategy for the STATCOM.

To confirm STATCOM inductive reactive power exchanged, Figure 48, Figure 49 and Figure 50 show each corresponding phase current and voltage.

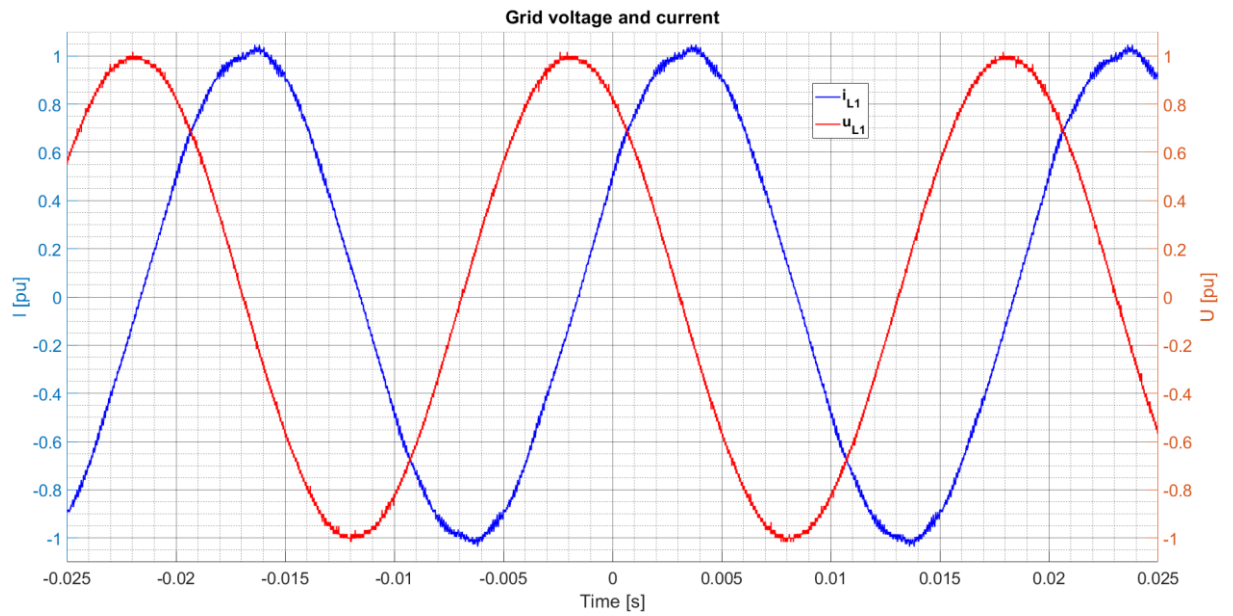


Figure 48: DSCC grid voltage and current of phase L1 when grid voltages are balanced during $Q_{STATCOM}^* = +1\text{pu}$ test (second test configuration)

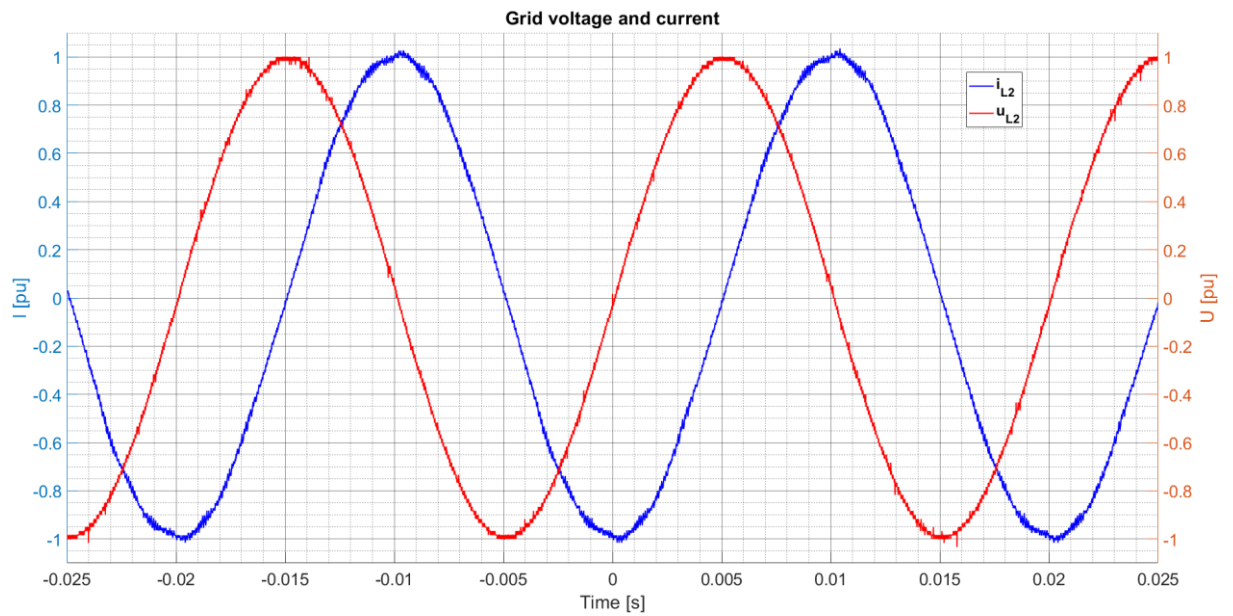


Figure 49: DSCC grid voltage and current of phase L2 when grid voltages are balanced during $Q_{STATCOM}^* = +1\text{pu}$ test (second test configuration)

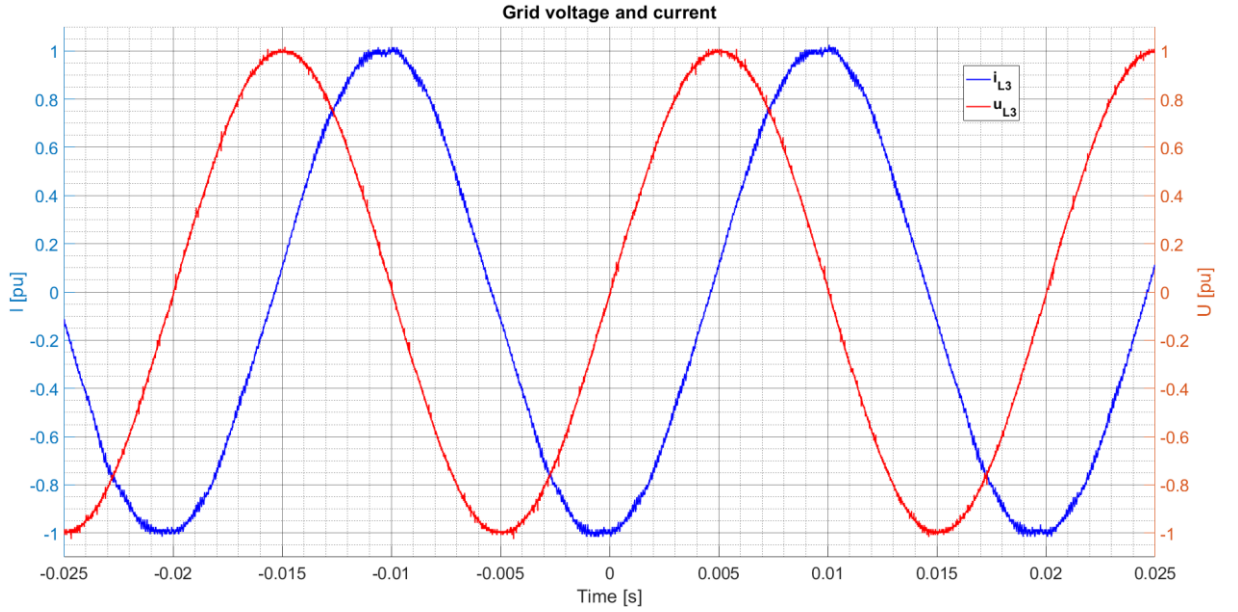


Figure 50: DSCC grid voltage and current of phase L3 when grid voltages are balanced during $Q_{STATCOM}^* = +1pu$ test (first test configuration)

It can be seen that the currents are lagging their respective voltage by nearly 90° as an inductor. The phase shift difference between the measurements and 90° corresponds to the active power losses of the DSCC STATCOM. Again, the phase shift difference compared to 90° is higher than in simulations due to higher losses of the real prototype.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SMu,l}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SMu,l}^{\Sigma*}$) equal to 2.45 pu (as in simulation). The upper arm cluster voltage for each leg at $Q_{STATCOM}^* = +1 pu$ recorded by the DSCC prototype and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 51.

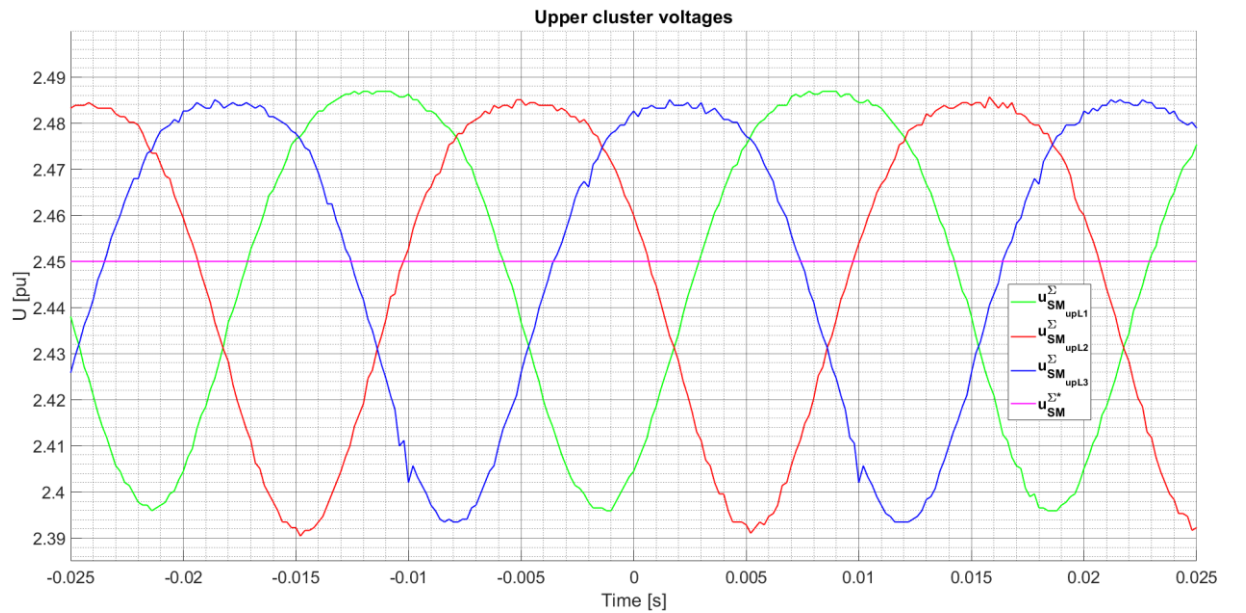


Figure 51: DSCC upper arm cluster voltage for each leg when grid voltages are balanced during $Q_{STATCOM}^* = +1pu$ test

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.091 pu in average. The peak-to-peak amplitude of prototype is 1.15 times higher than in simulation.



This difference is acceptable. It is mainly due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{upL1}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.451 \text{ pu}$
- $\overline{u_{SM_{upL2}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.448 \text{ pu}$
- $\overline{u_{SM_{upL3}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.448 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{*}$ and the three $\overline{u_{SM_{up}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{up}}^{\Sigma}}}(Q^* = +1 \text{ pu test balanced voltages}) = 0.1\%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference. Small differences between phases are due to small inequalities of physical components between phases (principally SM capacitances, arm inductance and overall arm resistance) and hardware measurement accuracy.

As well, the lower arm cluster voltage for each leg at $Q_{STATCOM}^* = +1 \text{ pu}$ recorded by the DSCC prototype and the reference $u_{SM_{u,l}}^{*}$ are shown in Figure 52.

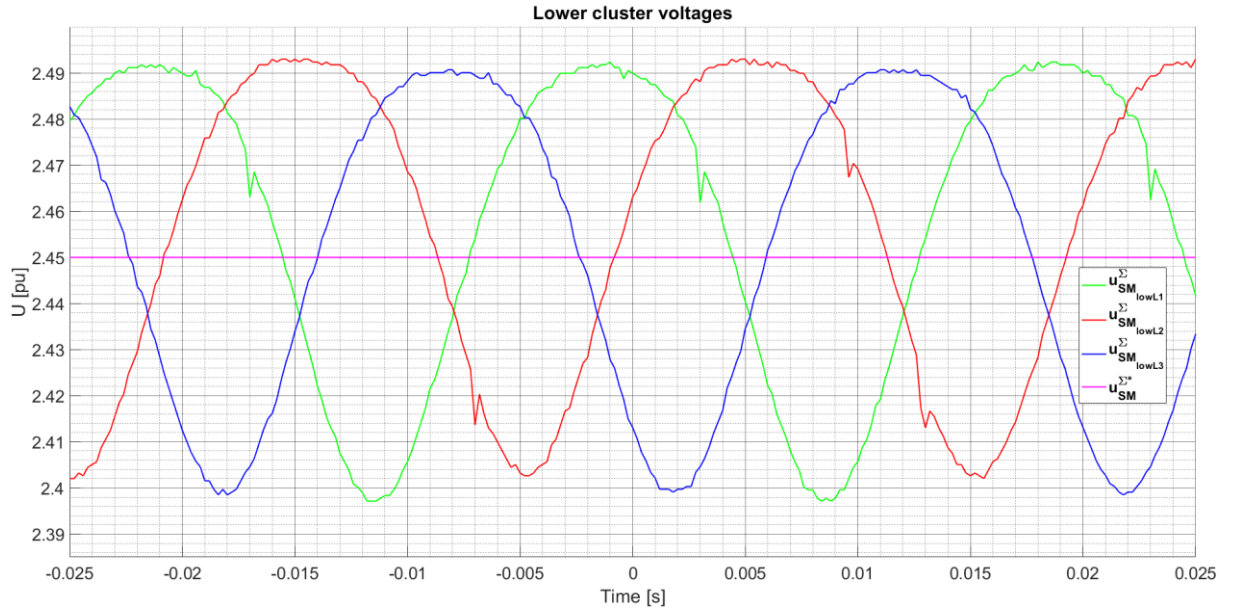


Figure 52: DSCC lower arm cluster voltage for each leg when grid voltages are balanced during $Q_{STATCOM}^* = +1 \text{ pu}$ test

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.092 pu in average. The peak-to-peak amplitude of prototype is 1.16 times higher than in simulation. This difference is acceptable. It is due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{lowL1}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.454 \text{ pu}$
- $\overline{u_{SM_{lowL2}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.457 \text{ pu}$
- $\overline{u_{SM_{lowL3}}^{\Sigma}}(Q^* = +1 \text{ pu test balanced voltages}) = 2.454 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{*}$ and the three $\overline{u_{SM_{low}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{low}}^{\Sigma}}}(Q^* = +1 \text{ pu test balanced voltages}) = 0.3\%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference. Small differences between phases are also due



to small inequalities of physical components between phases (principally SM capacitances, arm inductance and overall arm resistance).

We can conclude that cluster voltages are balanced around the reference value $u_{SMu,l}^{\Sigma*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = +1 pu$ and grid voltages are balanced. Furthermore, the test results confirm the simulation correctness.

A summary of DSCC test results with balanced grid voltages during $Q_{STATCOM}^* = +1 pu$ (inductive operation) is given in Table 13. This table also contain simulation results as a comparison.



DSCC test and simulation results with balanced grid voltages during $Q_{STATCOM}^* = +1$ pu (inductive operation)			
	Tests results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.020	1.000	2.0
$\hat{I}_{h1}$ phase L2 [pu]	1.015	1.000	1.5
$\hat{I}_{h1}$ phase L3 [pu]	1.001	1.000	0.1
THDi phase L1 [%]	1.3	0.9	44.4 (not relevant for low values)
THDi phase L2 [%]	1.3	0.9	44.4 (not relevant for low values)
THDi phase L3 [%]	1.2	0.9	33.3 (not relevant for low values)
Current Unbalance Factor [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	0.8	0.0	Impossible to calculate
P_{h1}^+ [pu]	0.017	0.006	183.3 (explained above)
Q_{h1}^+ [pu]	1.000	0.998	0.2
$u_{SM_{upL1}}^\Sigma$ pk-pk amplitude [pu]	0.090	0.079	13.9
$u_{SM_{upL2}}^\Sigma$ pk-pk amplitude [pu]	0.092	0.079	16.5
$u_{SM_{upL3}}^\Sigma$ pk-pk amplitude [pu]	0.090	0.079	13.9
$\overline{u_{SM_{upL1}}^\Sigma}$ average [pu]	2.451	2.450	0.0
$\overline{u_{SM_{upL2}}^\Sigma}$ average [pu]	2.448	2.450	0.1
$\overline{u_{SM_{upL3}}^\Sigma}$ average [pu]	2.448	2.450	0.1
$u_{SM_{lowL1}}^\Sigma$ pk-pk amplitude [pu]	0.095	0.079	20.2
$u_{SM_{lowL2}}^\Sigma$ pk-pk amplitude [pu]	0.089	0.079	12.7
$u_{SM_{lowL3}}^\Sigma$ pk-pk amplitude [pu]	0.091	0.079	15.2
$\overline{u_{SM_{lowL1}}^\Sigma}$ average [pu]	2.454	2.450	0.2
$\overline{u_{SM_{lowL2}}^\Sigma}$ average [pu]	2.457	2.450	0.3
$\overline{u_{SM_{lowL3}}^\Sigma}$ average [pu]	2.454	2.450	0.2

Table 13: DSCC test and simulation results with balanced grid voltages during $Q_{STATCOM}^* = +1$ pu (inductive operation)

In case of grid voltage balanced, test results above mentioned confirm that DSCC STATCOM prototype is able to exchange +1 pu positive sequence reactive power with the grid simulator while maintaining



the internal behaviour stable. In addition, except for DSCC converter losses (see above in this section) test results precisely match the simulation results and THD of the currents are small enough not to disturb correct grid operations.

As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are presented and compared to simulation in Table 14. The detailed results are available in 16.7 appendix.

DSCC test and simulation results with balanced grid voltages during $Q_{STATCOM}^* = -1$ pu (capacitive operation)			
	Tests results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.022	1.000	2.2
$\hat{I}_{h1}$ phase L2 [pu]	1.018	1.000	1.8
$\hat{I}_{h1}$ phase L3 [pu]	1.002	1.000	0.2
THDi phase L1 [%]	1.2	1.0	20.0
THDi phase L2 [%]	1.3	1.0	30.0
THDi phase L3 [%]	1.3	1.0	30.0
Current Unbalance Factor [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	0.7	0.0	Impossible to calculate
P_{h1}^+ [pu]	0.022	0.007	214.3 (explained above)
Q_{h1}^+ [pu]	-1.013	-1.000	1.3
$u_{SM_{upL1}}^\Sigma$ pk-pk amplitude [pu]	0.093	0.079	17.7
$u_{SM_{upL2}}^\Sigma$ pk-pk amplitude [pu]	0.086	0.079	8.9
$u_{SM_{upL3}}^\Sigma$ pk-pk amplitude [pu]	0.092	0.079	16.5
$\overline{u_{SM_{upL1}}^\Sigma}$ average [pu]	2.451	2.450	0.0
$\overline{u_{SM_{upL2}}^\Sigma}$ average [pu]	2.454	2.450	0.2
$\overline{u_{SM_{upL3}}^\Sigma}$ average [pu]	2.459	2.450	0.4
$u_{SM_{lowL1}}^\Sigma$ pk-pk amplitude [pu]	0.089	0.079	12.7
$u_{SM_{lowL2}}^\Sigma$ pk-pk amplitude [pu]	0.094	0.079	19.0
$u_{SM_{lowL3}}^\Sigma$ pk-pk amplitude [pu]	0.088	0.079	11.4
$\overline{u_{SM_{lowL1}}^\Sigma}$ average [pu]	2.451	2.450	0.0
$\overline{u_{SM_{lowL2}}^\Sigma}$ average [pu]	2.448	2.450	0.1
$\overline{u_{SM_{lowL3}}^\Sigma}$ average [pu]	2.443	2.450	0.3

Table 14: DSCC test and simulation results with balanced grid voltages during $Q_{STATCOM}^* = -1$ pu (capacitive operation)

In case of grid voltage balanced, test results above mentioned confirm DSCC STATCOM prototype is able to exchange -1 pu positive sequence reactive power with the grid simulator while maintaining the



internal behaviour stable. In addition, except for DSCC converter losses (see above in this section), test results precisely match the simulation results and THD of the currents are small enough not to disturb correct grid operations.

All experimental test results presented in section 4.3.10.1 confirm that DSCC prototype is able to exchange positive sequence reactive power in the range of $\pm 1 \text{ pu}$ ($Q_{STATCOM} \in [-1 \text{ pu}; +1 \text{ pu}]$) with grid voltages balanced and stable internal behaviour. In addition, apart from active power, experimental results confirm with good accuracy the simulation results.



4.3.10.2. DSCC prototype measurements with one line-to-earth short-circuit directly at STATCOM input

DSCC prototype was tested in one line-to-earth short-circuit voltages conditions. A grid simulator is used to provide one line-to-earth short-circuit voltage at the input of the DSCC STATCOM prototype. The base voltage is still $200 V_{pk}$ and frequency is kept at 50 Hz. Coupling inductors with the same L_g and R_g values as in the simulation are added in series between STATCOM and grid simulator. Other STATCOM prototype parameters are the same as the simulation parameters presented in Table 8. The connections are presented in Figure 43.

For each STATCOM nominal power, the same test is performed 3 times, each one with a different measurement. They are necessary to confirm correct STATCOM operation.

The test protocols for $I_{h1}^{+*}=1\text{pu}$ inductive are as follows:

- First test: DSCC prototype is connected as presented in Figure 43. In this configuration, the power quality analyser allows to measure the STATCOM positive sequence active and reactive power exchanged between STATCOM and grid simulator. Furthermore, it allows to measure voltages and currents quality in terms of RMS value, phases, harmonics, frequency and imbalance. The values are recorded with a sampling rate of 250ms for the complete test duration. In the same time, the three grid currents and L3 phase voltage waveforms are measured via the oscilloscope during transient and steady state operation. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) in order to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage for 2 minutes. This time duration allows the STATCOM prototype to preload and work at $I_{h1}^{+*}=1\text{pu}$ inductive under balanced voltage conditions as during tests of section 4.3.10.1. Then the same one line-to-earth short-circuit grid voltage as in simulation (including transient) is provided to the STATCOM prototype while positive sequence current setpoint is still $I_{h1}^{+*}=1\text{pu}$ inductive. The operator saves oscilloscope waveform measurements in CSV format during the transient and after 1 minute in steady-state. After 2 minutes of one line-to-earth short-circuit grid voltage, DSCC STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the first test at $I_{h1}^{+*}=1\text{pu}$ inductive.
- Second test: DSCC prototype is connected as presented in Figure 44. In this configuration, the power quality analyser is used like in the first test. Now oscilloscope measures grid currents i_1 and i_2 as well as grid phase voltages u_{gsL1} and u_{gsL2} . Once the material is connected as presented in Figure 44, the test procedure is the same as the first test. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) in order to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage for 2 minutes. This time duration allows the STATCOM prototype to preload and work at $I_{h1}^{+*}=1\text{pu}$ inductive under balanced voltage conditions as during tests of section 4.3.10.1. Then the same one line-to-earth short-circuit grid voltage as in simulation (including transient) is provided to the STATCOM prototype while positive sequence current setpoint is still $I_{h1}^{+*}=1\text{pu}$ inductive. The operator saves oscilloscope waveform measurements in CSV format during the transient and after 1 minute in steady-state. After 2 minutes of one line-to-earth short-circuit grid voltage, DSCC STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the second test at $I_{h1}^{+*}=1\text{pu}$ inductive.
- Third test: DSCC prototype is connected as presented in Figure 45. In this configuration, the power quality analyser is used like in the first and second test. Now oscilloscope measures grid current i_1 as well as all grid phase voltages. Once the material is connected as presented in Figure 45, the test procedure is the same as the first and second test. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) in order to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage for 2 minutes. This time duration allows the STATCOM prototype to preload and work at $I_{h1}^{+*}=1\text{pu}$ inductive under balanced voltage conditions as during tests of section 4.3.10.1. Then the same one line-to-earth short-circuit grid voltage as in simulation (including transient) is provided to the



STATCOM prototype while positive sequence current setpoint is still $I_{h1}^{+*}=1\text{pu}$ inductive. The operator saves oscilloscope waveform measurements in CSV format during the transient and after 1 minute in steady-state. After 2 minutes of one line-to-earth short-circuit grid voltage, STATCOM stops automatically. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in “.dat” format. And finally, the grid simulator is stopped as well. This marks the end of the third test at $I_{h1}^{+*}=1\text{pu}$ inductive.

To completely test DSCC STATCOM prototype under one line-to-earth short-circuit grid voltages, the same three test protocols are also performed for $I_{h1}^{+*} = 1\text{ pu}$ capacitive.

The results for $I_{h1}^{+*} = 1\text{ pu}$ inductive operation under one line-to-earth short-circuit grid voltages are presented below. The grid simulator voltage sequence was extracted from the simulation signal and imported directly in the grid simulator software “ACS Control” (version 2.3.0.13737). It means the grid simulator voltages are the same as presented in Figure 11. One line-to-earth short-circuit steady-state results are presented first.

The grid simulator voltages during $I_{h1}^{+*}=1\text{pu}$ inductive operation are visible in Figure 53.

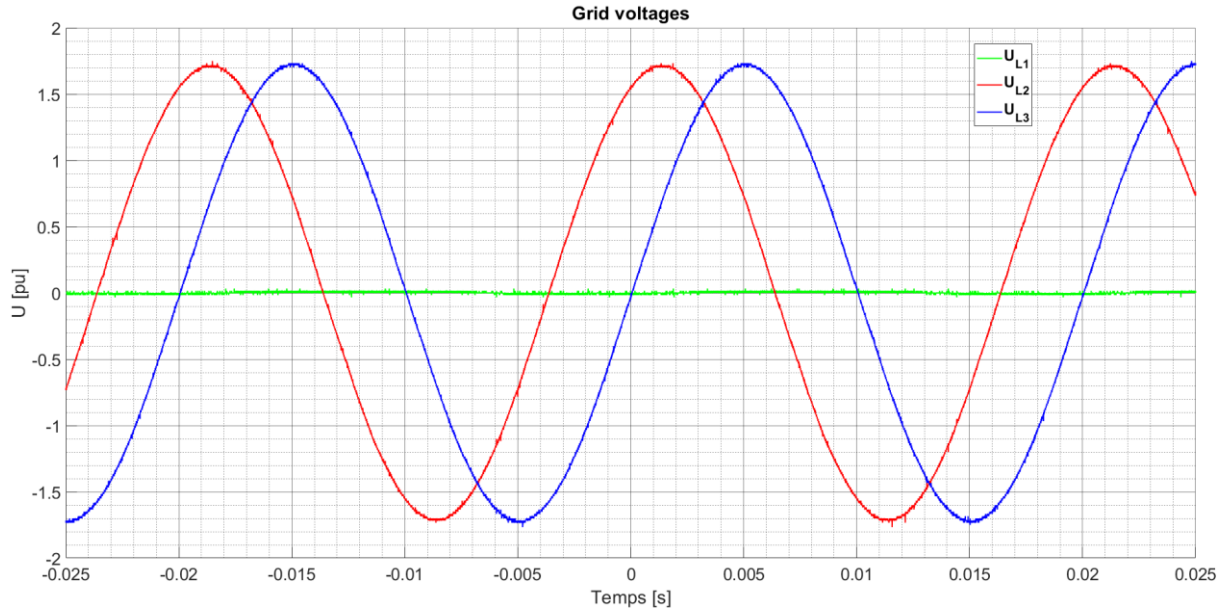


Figure 53: Steady-state unbalanced one line-to-earth short-circuit grid voltages during $I_{h1}^{+*} = 1\text{ pu}$ inductive test

On Figure 53, it can be seen that the voltages are 50 Hz sinusoids unbalanced. The 50 Hz frequency average over one-minute test is confirmed by power quality analyser measurements. The power quality analyser gives the voltage THD in steady-state for each phase:

- $THDu_{L1}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 18.8\%$
- $THDu_{L2}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 0.2\%$
- $THDu_{L3}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 0.2\%$

The high THDu of phase L1 is due to the very low voltage amplitude which is not a constant zero. However, with important amplitudes, THDu of L2 and L3 are very low.

The fundamental RMS value of grid voltages are given by the power quality analyser. The corresponding peak values are given in pu:

- $\hat{U}_{L1h1}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 0.006\text{ pu}$
- $\hat{U}_{L2h1}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 1.715\text{ pu}$
- $\hat{U}_{L3h1}(I_{h1}^{+*} = 1\text{ pu inductive and } L1 \text{ in } SC) = 1.726\text{ pu}$



Compared to simulation, it can be seen that $\hat{U}_{L1h1}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC})$ is not completely null. This is due to the fact the grid simulator is not a perfect device. It has an internal impedance which is never null. Given that current is still exchanged, it creates a residual voltage. The 0.006 pu value is considered negligible. Relative deviation compared to simulation value are given for phase L2 and L3:

- $\Delta \hat{U}_{L2h1}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = 0.3\%$
- $\Delta \hat{U}_{L3h1}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = 0.7\%$

These relative deviations confirm the correct operation of the grid simulator to provide the correct amplitude for phase L2 and L3.

The fundamental displacement angles between phase voltages are given below:

- $\varphi_{uL1 \rightarrow uL2}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = -252^\circ$
- $\varphi_{uL1 \rightarrow uL3}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = -311^\circ$
- $\varphi_{uL2 \rightarrow uL3}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = -60^\circ$

Displacement angle between L2 and L3 is the only one comparable with value of Table 3, because L1 is considered null in theory. The relative deviation is 0.9%. This small difference with theory is mainly explained by the precision of grid simulator and power quality analyser accuracy.

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 0.5%. The relative deviation with the value in Table 3 is equal to 17%. This deviation stays reasonable for small values like this.

The correct operation of the grid simulator to provide the one line-to-earth short-circuit with $I_{h1}^{++} = 1 \text{ pu inductive}$ is confirmed.

Grid currents waveforms during $I_{h1}^{++} = 1 \text{ pu inductive}$ operation are visible in Figure 54.

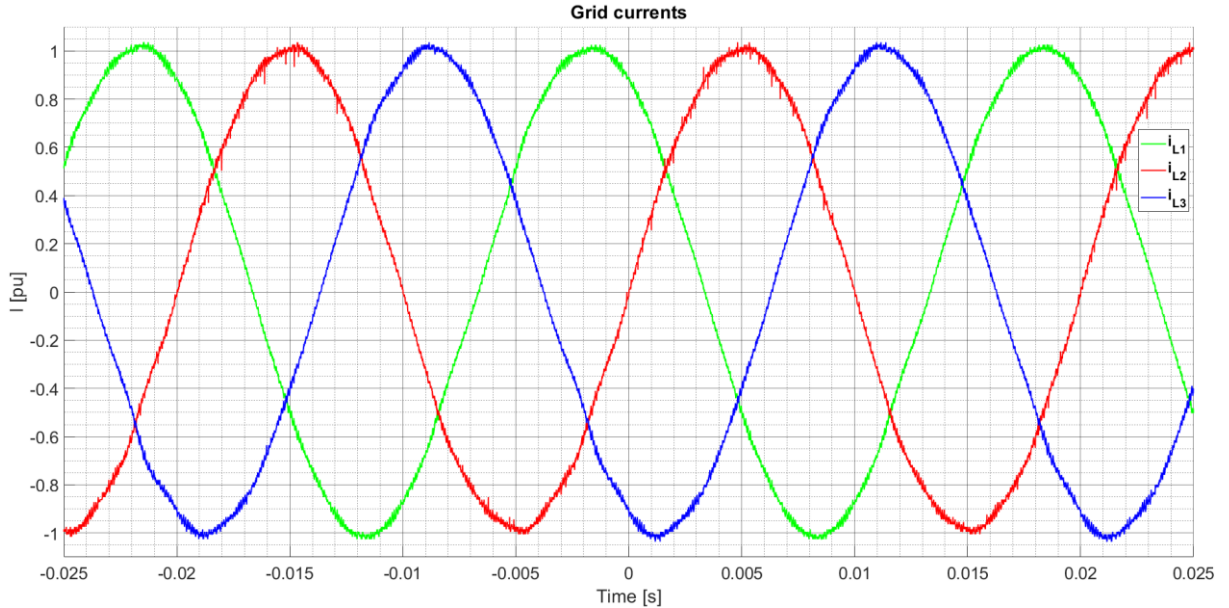


Figure 54: DSCC steady-state unbalanced one line-to-earth short-circuit grid currents during $I_{h1}^{++}=1\text{pu}$ inductive test

In Figure 54, it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD in one-minute average for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = 1.1\%$
- $THDi_{L2}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = 1.5\%$
- $THDi_{L3}(I_{h1}^{++} = 1 \text{ pu inductive and L1 in SC}) = 1.6\%$

Compared to simulation results, THD maximum increase is of 0.7%. This difference is negligible. This is mainly due to measurement noise and non-ideal components characteristics. It means one line-to-earth short-circuit is not degrading significantly the THD of the currents.



The fundamental RMS value of grid currents (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values in one-minute average are given:

- $\hat{I}_{L1_{h1}}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 1.022 \text{ pu}$
- $\hat{I}_{L2_{h1}}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 1.017 \text{ pu}$
- $\hat{I}_{L3_{h1}}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 1.004 \text{ pu}$

The same amplitudes as the to $Q_{STATCOM}^* = +1\text{pu}$ balanced voltage test are measured. Fundamental RMS value of grid currents are not affected by the one line-to-earth short-circuit.

The fundamental displacement angles are given below:

- $\varphi_{iL1 \rightarrow iL2}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = -120^\circ$
- $\varphi_{iL1 \rightarrow iL3}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = +120^\circ$

A relative deviation of 0% compared to 120° is measured which confirm currents are balanced.

Furthermore, power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^+(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 1.011 \text{ pu}$
- $\hat{I}_{h1}^-(I_{h1}^{+*} = 1 \text{ pu inductive and L1 in SC}) = 0.009 \text{ pu}$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.9 \%$ which is negligible. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit steady-state test.

The second goal is now to verify the DSCC exchanges fundamental positive sequence inductive reactive power with the grid. The power quality analyser measures the fundamental 3-phase reactive power (Q_{h1}^+) as well as the 3-phase fundamental active power (P_{h1}^+). During the one-minute test with the setpoint $I_{h1}^{+*}=1\text{pu}$ inductive, the average power values measured via the power quality analyser over this period in steady state are:

- $Q_{h1}^+(I_{h1}^{+*} = 1\text{pu inductive and L1 in SC}) = 1.002 \text{ pu}$
- $P_{h1}^+(I_{h1}^{+*} = 1\text{pu inductive and L1 in SC}) = 0.017 \text{ pu}$

The relative deviation between fundamental reactive power reference and measurement is equal to $\Delta_{Q_{h1}^+}(I_{h1}^{+*} = 1\text{pu inductive and L1 in SC}) = 0.2 \%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator. It can be noted, that compared to balanced voltage test results, as in simulation, the fundamental reactive power has slightly decreased due slight decrease of positive sequence voltage amplitude.

Fundamental active power stays equal to the one in the case of grid voltages balanced. It is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(I_{h1}^{+*} = 1\text{pu inductive and L1 in SC}) = 143 \%$. This is because, the simulation was not performed to precisely represent the prototype losses (cables, losses of components, components imperfection). It would have required an important additional work that was impossible to fulfil in the timeline of the project. However, the aim of the simulation was to design a STATCOM control strategy able to follow a reactive power reference as well as maintaining the internal behaviour stable.

The results confirm the correct operation of the converter to follow a reactive power setpoint with this control strategy.

Figure 55 and Figure 56 show each corresponding phase current and voltage for L2 and L3.

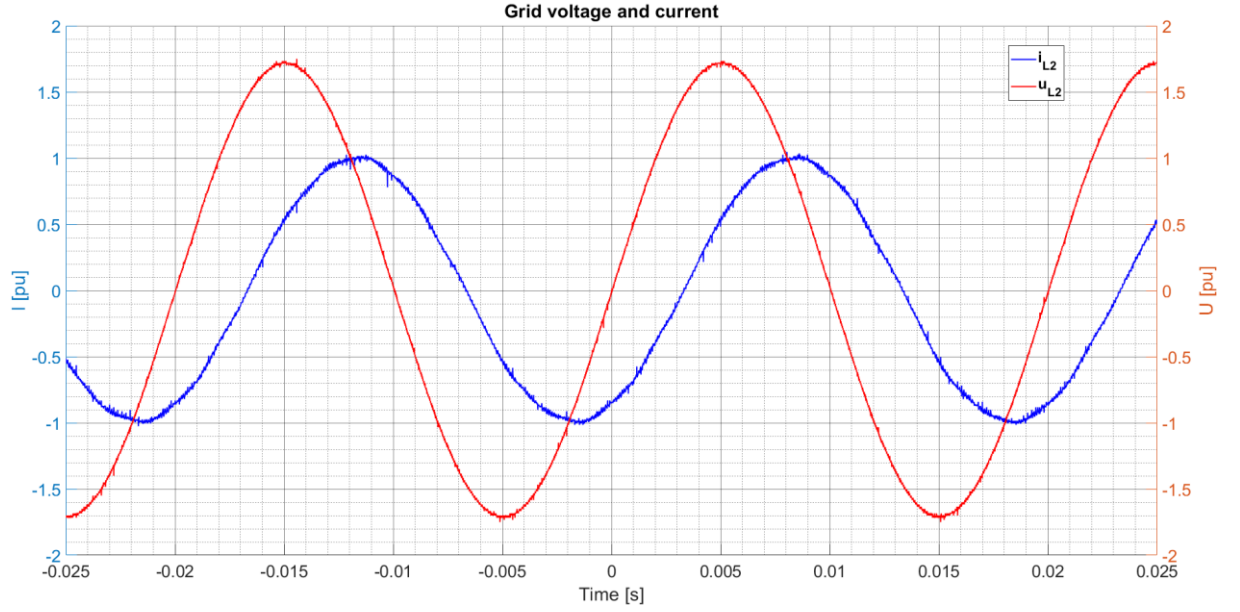


Figure 55: DSCC grid voltage and current of phase L2 when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit steady-state test

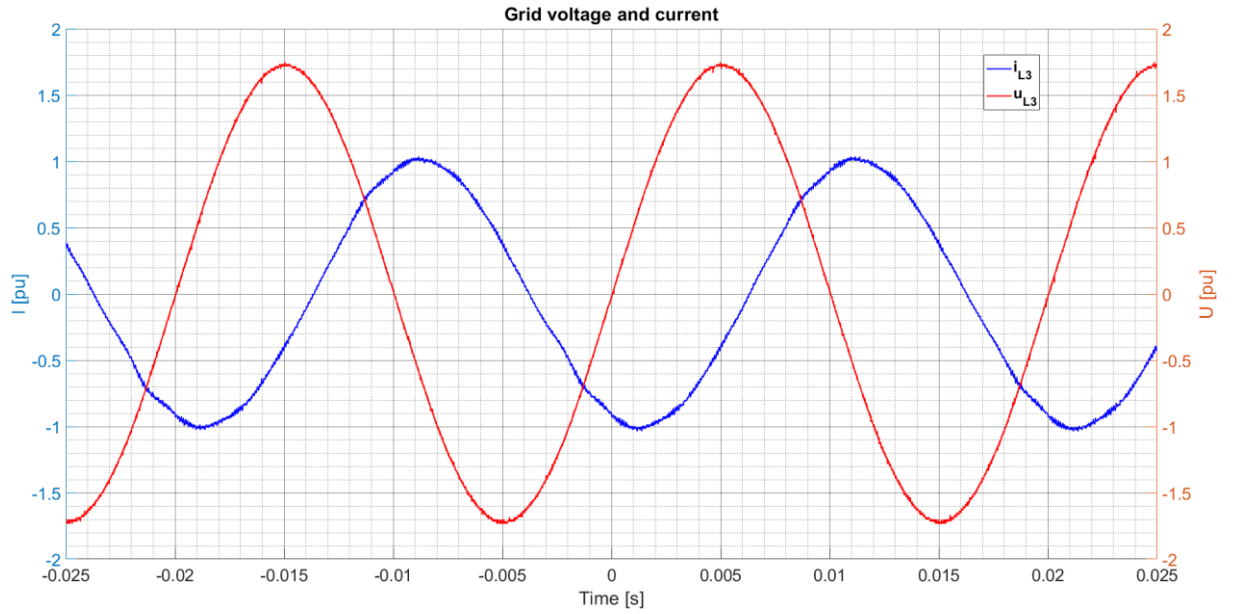


Figure 56: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit steady-state test

Firstly, the experimental waveforms in Figure 55 and Figure 56 are very similar to the simulation waveforms in Figure 34 and Figure 35. Secondly, the power quality analyser gives us the displacement angle between voltage and current for each phase:

- $\theta_{h1L2}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 59^\circ$
- $\theta_{h1L3}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 119^\circ$

Their relative deviation compared to simulation displacement angle are:

- $\Delta_{\theta_{h1L2}}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 0.7\%$
- $\Delta_{\theta_{h1L3}}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in } SC) = 0.7\%$



The displacement angles are very close to the one of the corresponding simulations (less than 1° of difference). It confirms again the correct STATCOM operation.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SMu,l}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SMu,l}^{\Sigma*}$) equal to 2.45 pu (as in simulation). The upper arm cluster voltage for each leg with $I_{h1}^{+*} = 1$ pu inductive and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 57.

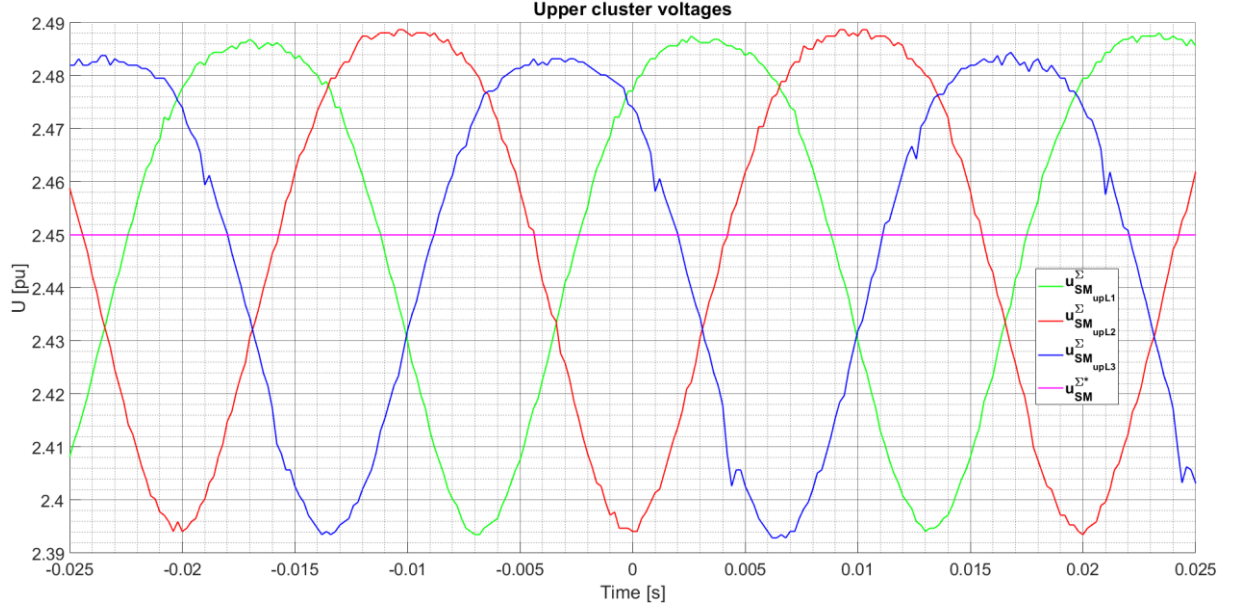


Figure 57: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1$ pu inductive during one line-to-earth short-circuit steady-state test

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.093 pu in average. The peak-to-peak amplitude of prototype is 1.18 times higher than in simulation. This difference is acceptable. It is mainly due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SMupL1}^\Sigma} (I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in SC}) = 2.450 \text{ pu}$
- $\overline{u_{SMupL2}^\Sigma} (I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in SC}) = 2.451 \text{ pu}$
- $\overline{u_{SMupL3}^\Sigma} (I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in SC}) = 2.447 \text{ pu}$

The highest relative deviation between reference value $u_{SMu,l}^{\Sigma*}$ and the three $\overline{u_{SMup}^\Sigma}$ is equal to: $\Delta_{\overline{u_{SMup}^\Sigma}}^{\overline{u_{SMu,l}^{\Sigma*}}} (I_{h1}^{+*} = 1 \text{ pu inductive and } L1 \text{ in SC}) = 0.1\%$. This highest relative deviation is very small, meaning

that the cluster voltages follow their reference. Small differences between phases are due to small inequalities of physical components between phases (principally SM capacitances, arm inductance and overall arm resistance) and hardware measurement accuracy.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*} = 1$ pu inductive recorded by the DSCC prototype and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 58.

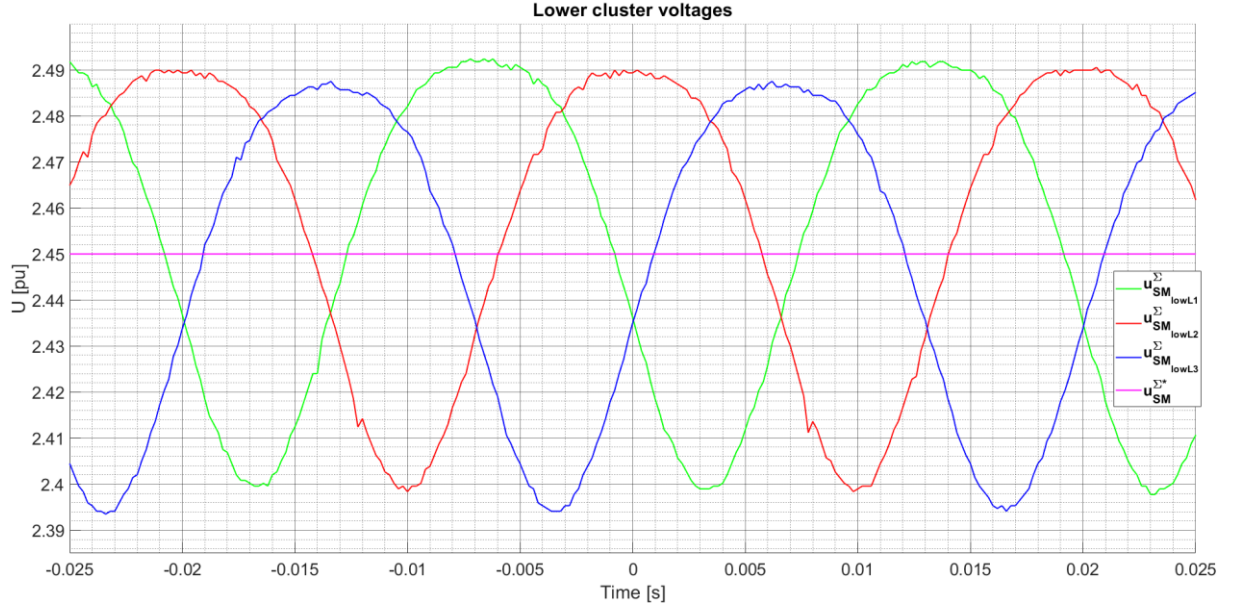


Figure 58: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*}=1pu$ inductive during one line-to-earth short-circuit steady-state test

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.092 pu in average. The peak-to-peak amplitude of prototype is 1.16 times higher than in simulation. This difference is acceptable. It is due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{lowL1}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 2.455 \text{ pu}$
- $\overline{u_{SM_{lowL2}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 2.453 \text{ pu}$
- $\overline{u_{SM_{lowL3}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 2.450 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{\Sigma*}$ and the three $\overline{u_{SM_{low}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{low}}^{\Sigma}}}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = 0.2 \%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference.

On both Figure 57 and Figure 58, some small spikes are sometimes visible. These spikes correspond to hardware measurement error that can occur for one sample. After many investigations, HEIG team did not succeed to correct these momentary errors. The error is always less than 0.008 pu which is negligible. This is why the results are still coherent. It is worth to be noted that this is not due to physical principle of the DSCC. Indeed, as it can be seen in simulation, these spikes are not present.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_{u,l}}^{\Sigma*}$ and so that internal stability is guaranteed with $I_{h1}^{+*} = 1pu \text{ inductive}$ during one line-to-earth short-circuit steady-state. Furthermore, the test results confirm the simulation correctness.

The verification of the correct current exchanged during transient operation for the case $I_{h1}^{+*} = 1pu \text{ inductive}$ is compared to simulation. Grid voltages during transient are shown in Figure 59.

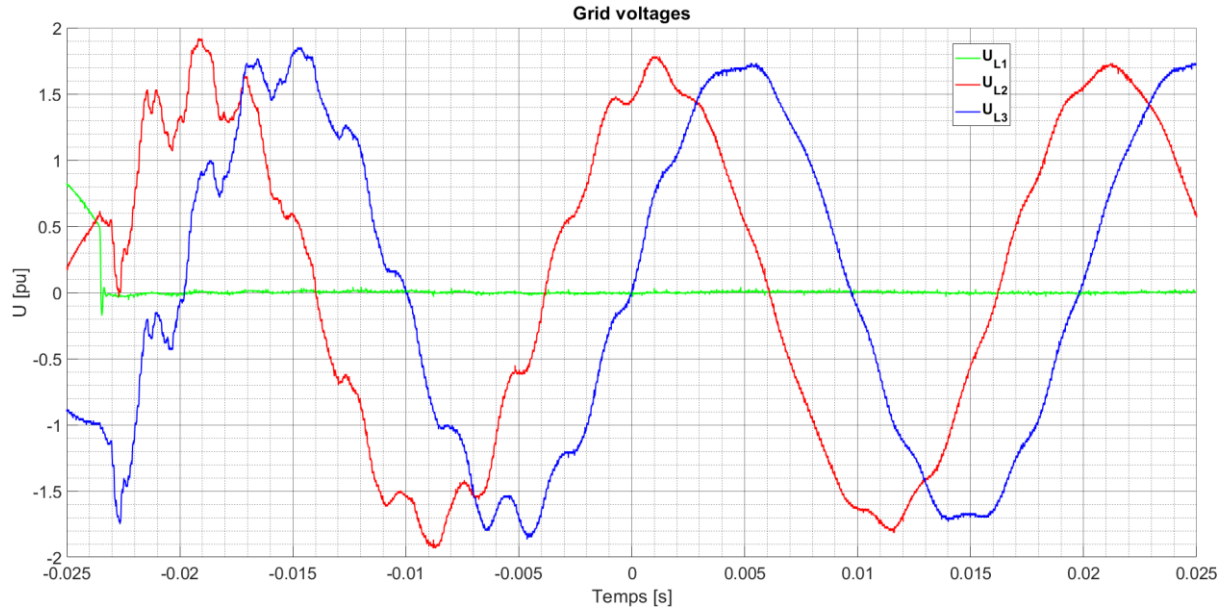


Figure 59: Grid voltages when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit transient in test

The measured voltage visible in Figure 59 is highly corresponding with the simulation transient voltage in Figure 11. The voltage during the transient is the same as the one in simulation. The grid currents exchanged between DSCC prototype and grid simulator during this transient are shown in Figure 60.

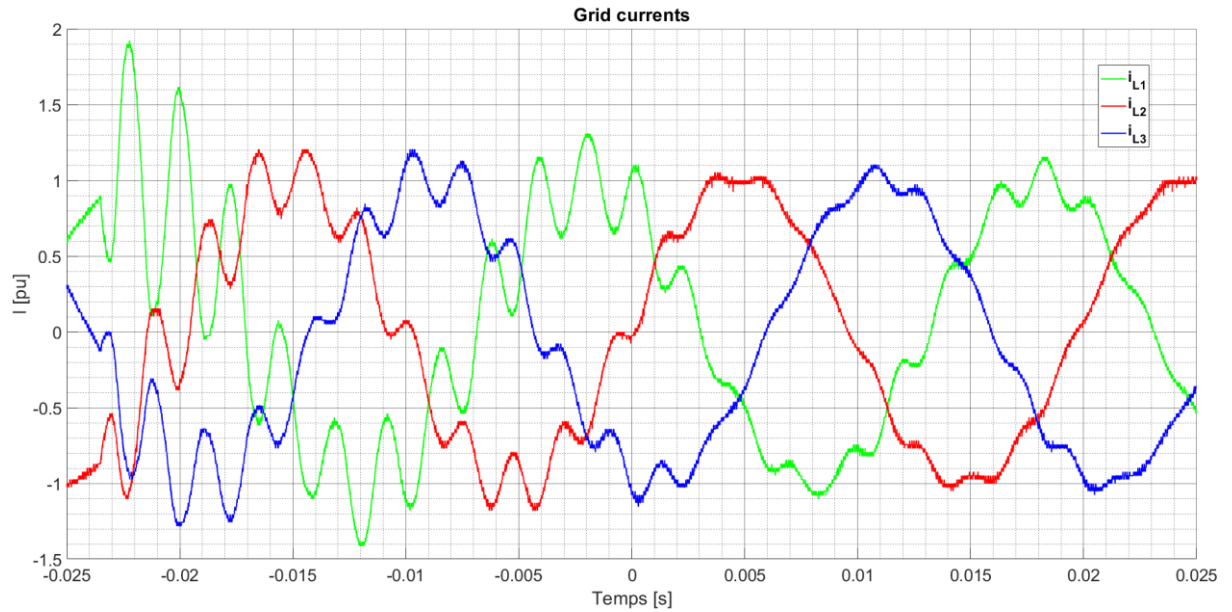


Figure 60: DSCC grid currents when $I_{h1}^{+*}=1\text{pu}$ inductive during one line-to-earth short-circuit transient in test

If we compare Figure 60 with simulation results in Figure 31, it can be seen that current waveform is highly similar. The maximum current reached is 1.923 pu which is 1.10 times more than in the simulation. Furthermore, grid currents continue to follow the $I_{h1}^{+*} = 1\text{ pu}$ inductive reference during the transient with the same oscillations as in simulation. It means DSCC prototype is dealing well with the transient.

A summary of DSCC test results when $I_{h1}^{+*} = 1\text{ pu}$ inductive during one line-to-earth short-circuit in steady state is given in Table 15. This table also contain simulation results as a comparison.



DSCC test and simulation results during one line-to-earth short-circuit in steady state when $I_{h1}^{+*} = 1$ pu inductive			
	Test results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.022	1.000	2.2
$\hat{I}_{h1}$ phase L2 [pu]	1.017	1.000	1.7
$\hat{I}_{h1}$ phase L3 [pu]	1.004	1.000	0.4
THDi phase L1 [%]	1.1	1.0	10 (not relevant for low values)
THDi phase L2 [%]	1.5	0.9	67 (not relevant for low values)
THDi phase L3 [%]	1.6	0.9	78 (not relevant for low values of THD)
Current Unbalance Factor [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	0.9	0.0	Impossible to calculate but low increase
P_{h1}^+ [pu]	0.017	0.007	142.9 (explained above)
Q_{h1}^+ [pu]	1.002	0.987	1.5
$u_{SM_{upL1}}^\Sigma$ pk-pk amplitude [pu]	0.092	0.079	16.5
$u_{SM_{upL2}}^\Sigma$ pk-pk amplitude [pu]	0.095	0.079	20.3
$u_{SM_{upL3}}^\Sigma$ pk-pk amplitude [pu]	0.089	0.079	12.7
$\overline{u_{SM_{upL1}}^\Sigma}$ average [pu]	2.450	2.450	0.0
$\overline{u_{SM_{upL2}}^\Sigma}$ average [pu]	2.451	2.450	0.0
$\overline{u_{SM_{upL3}}^\Sigma}$ average [pu]	2.447	2.450	0.1
$u_{SM_{lowL1}}^\Sigma$ pk-pk amplitude [pu]	0.093	0.079	17.7
$u_{SM_{lowL2}}^\Sigma$ pk-pk amplitude [pu]	0.091	0.079	15.2
$u_{SM_{lowL3}}^\Sigma$ pk-pk amplitude [pu]	0.093	0.079	17.7
$\overline{u_{SM_{lowL1}}^\Sigma}$ average [pu]	2.455	2.450	0.2
$\overline{u_{SM_{lowL2}}^\Sigma}$ average [pu]	2.453	2.450	0.1
$\overline{u_{SM_{lowL3}}^\Sigma}$ average [pu]	2.450	2.450	0.0

Table 15: DSCC test and simulation results during one line-to-earth short-circuit in steady state when $I_{h1}^{+*} = 1$ pu inductive



In case of one line-to-earth short-circuit steady-state and transient, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence inductive current with the grid simulator while maintaining the internal behaviour stable permanently. In addition, except for DSCC converter losses (see above in this section), test results precisely match the simulation results and THD of the currents are small enough not to disturb even more grid operation.

As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are presented and compared to simulation in Table 16. The detailed results are available in 16.8 appendix.



DSCC test and simulation results during one line-to-earth short-circuit in steady state when $I_{h1}^{+*} = 1$ pu capacitive			
	Test results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.022	1.001	2.1
$\hat{I}_{h1}$ phase L2 [pu]	1.018	1.001	1.7
$\hat{I}_{h1}$ phase L3 [pu]	1.003	1.001	0.2
THDi phase L1 [%]	1.4	1.0	40 (not relevant for low values)
THDi phase L2 [%]	1.8	1.0	80 (not relevant for low values)
THDi phase L3 [%]	2.0	1.0	100 (not relevant for low value)
Current Unbalance Factor [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	0.8	0.0	Impossible to calculate but low increase
P_{h1}^+ [pu]	0.022	0.007	214.3 (explained above)
Q_{h1}^+ [pu]	-1.006	-0.987	1.9
$u_{SM_{upL1}}^{\Sigma}$ pk-pk amplitude [pu]	0.095	0.079	20.3
$u_{SM_{upL2}}^{\Sigma}$ pk-pk amplitude [pu]	0.082	0.079	3.8
$u_{SM_{upL3}}^{\Sigma}$ pk-pk amplitude [pu]	0.093	0.079	17.7
$\overline{u_{SM_{upL1}}^{\Sigma}}$ average [pu]	2.447	2.450	0.1
$\overline{u_{SM_{upL2}}^{\Sigma}}$ average [pu]	2.452	2.450	0.1
$\overline{u_{SM_{upL3}}^{\Sigma}}$ average [pu]	2.453	2.450	0.1
$u_{SM_{lowL1}}^{\Sigma}$ pk-pk amplitude [pu]	0.088	0.079	11.4
$u_{SM_{lowL2}}^{\Sigma}$ pk-pk amplitude [pu]	0.100	0.079	26.6
$u_{SM_{lowL3}}^{\Sigma}$ pk-pk amplitude [pu]	0.086	0.079	8.9
$\overline{u_{SM_{lowL1}}^{\Sigma}}$ average [pu]	2.454	2.450	0.2
$\overline{u_{SM_{lowL2}}^{\Sigma}}$ average [pu]	2.447	2.450	0.1
$\overline{u_{SM_{lowL3}}^{\Sigma}}$ average [pu]	2.447	2.450	0.1

Table 16: DSCC test and simulation results during one line-to-earth short-circuit in steady state when $I_{h1}^{+*} = 1$ pu capacitive



In case of one line-to-earth short-circuit steady-state and transient, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence capacitive current with the grid simulator while maintaining the internal behaviour stable permanently. In addition, except for DSCC converter losses, test results precisely match the simulation results and THD of the currents are small enough not to disturb even more grid operation.

All experimental test results presented in section 4.3.10.2 confirm that DSCC prototype is able to exchange positive sequence inductive and capacitive current in the range of $\pm 1 \text{ pu}$ when one line-to-earth short-circuit occurs directly at STATCOM input (transient and steady state correct operation) while maintaining permanently stable internal behaviour. In addition, apart from active power, experimental results confirm with good accuracy the simulation results.



4.3.10.3. DSCC prototype measurements with two lines-to-earth short-circuit directly at STATCOM substation

DSCC prototype was tested in two lines-to-earth short-circuit voltages conditions. A grid simulator is used to provide two lines-to-earth short-circuit voltage at the input of the DSCC STATCOM prototype. The base voltage is still $200 V_{pk}$ and frequency is kept at 50 Hz. Coupling inductors with the same L_g and R_g values as in the simulation are added in series between STATCOM and grid simulator. Other STATCOM prototype parameters are the same as the simulation parameters presented in Table 8. The connections are presented in Figure 43.

For each STATCOM nominal power, the same test is performed 2 times, each one with a different measurement. They are necessary to confirm correct STATCOM operation.

The test protocols for $I_{h1}^{++}=1\text{pu}$ inductive are as follows:

- First test: DSCC prototype is connected as presented in Figure 43. In this configuration, the power quality analyser allows to measure the STATCOM positive sequence active and reactive power exchanged between STATCOM and grid simulator. Furthermore, it allows to measure voltages and currents quality in terms of RMS value, phases, harmonics, frequency and imbalance. The values are recorded with a sampling rate of 250ms for the complete test duration. In the same time, the three grid currents and L3 phase voltage waveforms are measured via the oscilloscope during transient and steady state operation. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) in order to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage for 2 minutes. This time duration allows the STATCOM prototype to preload and work at $I_{h1}^{++}=1\text{pu}$ inductive under balanced voltage conditions as during tests of section 4.3.10.1. Then the same two lines-to-earth short-circuit grid voltage as in simulation (including transient) is provided to the STATCOM prototype while positive sequence current setpoint is still $I_{h1}^{++}=1\text{pu}$ inductive. The operator saves oscilloscope waveform measurements in CSV format during the transient and in steady-state. The DSCC STATCOM stops automatically when one cluster voltage difference with respect to $u_{SMu,l}^{\Sigma*}$ setpoint reach 0.3 pu. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the first test at $I_{h1}^{++}=1\text{pu}$ inductive.
- Second test: DSCC prototype is connected as presented in Figure 45. In this configuration, the power quality analyser is used like in the first test. Now oscilloscope measures grid current i_1 as well as all grid phase voltages. Once the material is connected as presented in Figure 45, the test procedure is the same as the first and second test. STATCOM prototype is connected in debug mode to a computer via Code Composer studio software (version 11.1.0) in order to have access to internal STATCOM measurements during the test. The power quality analyser record is started. The grid simulator is parametrised to provide $200 V_{pk}$ and 50 Hz balanced grid voltage for 2 minutes. This time duration allows the STATCOM prototype to preload and work at $I_{h1}^{++}=1\text{pu}$ inductive under balanced voltage conditions as during tests of section 4.3.10.1. Then the same two lines-to-earth short-circuit grid voltage as in simulation (including transient) is provided to the STATCOM prototype while positive sequence current setpoint is still $I_{h1}^{++}=1\text{pu}$ inductive. The operator saves oscilloscope waveform measurements in CSV format during the transient and in steady-state. The DSCC STATCOM stops automatically when one cluster voltage difference with respect to $u_{SMu,l}^{\Sigma*}$ setpoint reach 0.3 pu. The operator stops power quality analyser record and saves it. Internal STATCOM measurements are saved in ".dat" format. And finally, the grid simulator is stopped as well. This marks the end of the third test at $I_{h1}^{++}=1\text{pu}$ inductive.

To completely test DSCC STATCOM prototype under two lines-to-earth short-circuit grid voltages, the same three test protocols are also performed above for $I_{h1}^{++}=1\text{pu}$ capacitive.

The results for $I_{h1}^{++}=1\text{pu}$ inductive operation under two lines-to-earth short-circuit grid voltages are presented below. The grid simulator voltage sequence was extracted from the simulation signal and imported directly in the grid simulator software "ACS Control" (version 2.3.0.13737). It means the sequence is the same as represented in Figure 17.

The grid simulator voltages during $I_{h1}^{++}=1\text{pu}$ inductive operation are visible in Figure 61.

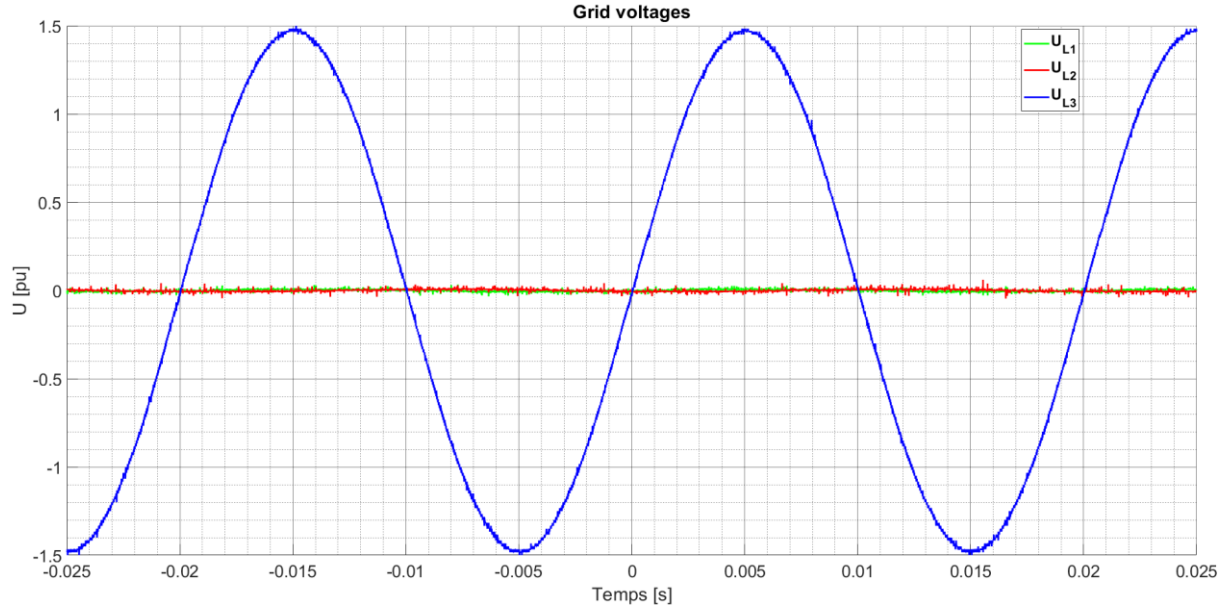


Figure 61: Steady-state unbalanced two lines-to-earth short-circuit grid voltages during $I_{h1}^{+*}=1pu$ inductive test

In Figure 61, it can be seen that the voltages are 50 Hz sinusoids unbalanced. The 50 Hz frequency is confirmed by power quality analyser measurements. The power quality analyser gives the voltage THD in steady-state for phase L3 (the one of interest) which is small:

$$- THDu_{L3}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.3 \%$$

The fundamental RMS value of grid voltages are given by the power quality analyser. The corresponding peak values are given in pu:

$$\begin{aligned} - \hat{U}_{L1h1}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) &= 0.006 \text{ pu} \\ - \hat{U}_{L2h1}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) &= 0.006 \text{ pu} \\ - \hat{U}_{L3h1}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) &= 1.485 \text{ pu} \end{aligned}$$

Relative deviation compared to simulation value is given for phase L3:

$$- \Delta_{\theta_{L3h1}}(I_{h1}^{+*} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 0.6\%$$

These relative deviations confirm the correct operation of the grid simulator to provide the correct amplitude for L3 while the others are close to 0 pu amplitude.

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 100.4%. The relative deviation with the value in Table 3 is equal to 0.4%, a very good result.

The correct operation of the grid simulator to provide the one line-to-earth short-circuit voltages with $I_{h1}^{+*} = 1pu$ inductive is confirmed.

Grid currents waveforms during $I_{h1}^{+*}=1pu$ inductive operation are visible in Figure 62.

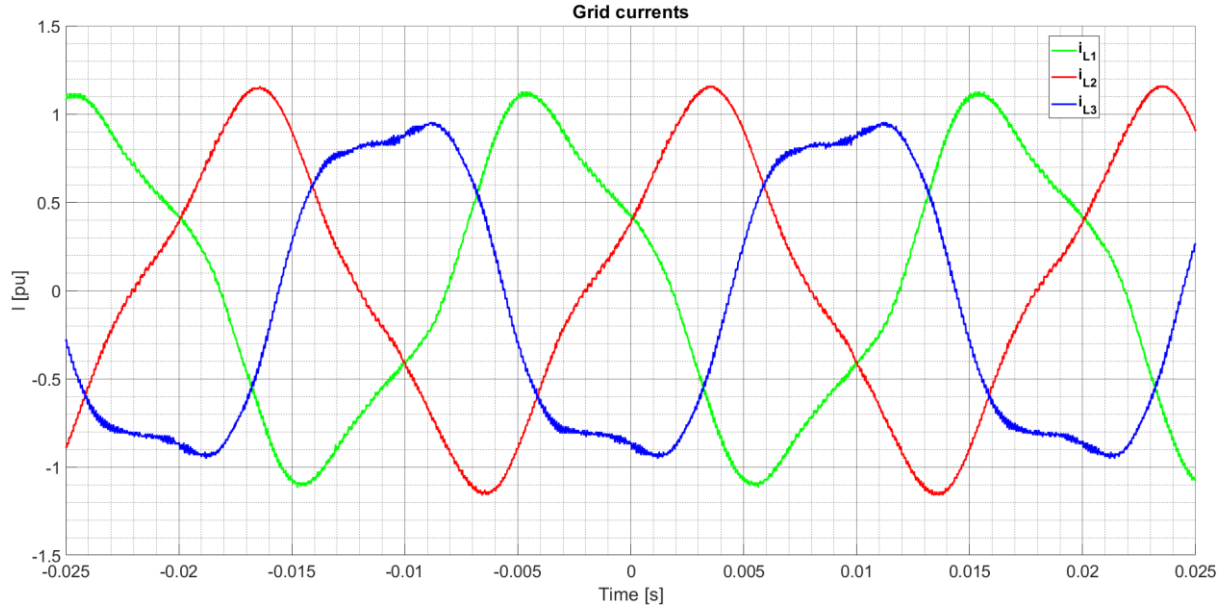


Figure 62: DSCC steady-state unbalanced two lines-to-earth short-circuit grid currents during $I_{h1}^{+}=1pu$ inductive test

In Figure 62, it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD for each phase:

- $THDi_{L1}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 16.3\%$
- $THDi_{L2}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 14.5\%$
- $THDi_{L3}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 17.1\%$

Compared to simulation results, THD maximum increase is of 1.8%. This difference is negligible. The same remark can be made as in simulation. THD is importantly increased during two lines-to-earth short-circuit. Currents exchanged are still 50Hz dominant but with important distortion.

The fundamental RMS value of grid currents (which are close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values are given:

- $\hat{I}_{L1h1}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 1.026 \text{ pu}$
- $\hat{I}_{L2h1}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 1.021 \text{ pu}$
- $\hat{I}_{L3h1}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 0.992 \text{ pu}$

A maximum relative deviation of 2.6% between test and simulation is measured. This difference is reasonable to consider correct amplitude of the fundamental currents exchanged

Power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^{+}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 1.013 \text{ pu}$
- $\hat{I}_{h1}^{-}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 0.012 \text{ pu}$

This implies fundamental Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 1.2 \%$ which is very low. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+}=1pu$ inductive during two lines-to-earth short-circuit steady-state test.

The second goal is now to verify the DSCC exchanges fundamental positive sequence inductive reactive power with the grid. The power quality analyser measures the fundamental 3-phase reactive power (Q_{h1}^{+}) as well as the 3-phase fundamental active power (P_{h1}^{+}). During the test with the setpoint $I_{h1}^{+}=1pu$ inductive, the average power values measured via the power quality analyser over this period in steady state are:

- $Q_{h1}^{+}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 0.502 \text{ pu}$
- $P_{h1}^{+}(I_{h1}^{+} = 1pu \text{ inductive and } L1 + L2 \text{ in } SC) = 0.018 \text{ pu}$



The relative deviation between simulation and measurement is equal to $\Delta_{Q_{h1}^+}(I_{h1}^{++} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 2.0 \%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator. It can be noted, that compared to balanced voltage test results, as in simulation, the fundamental reactive power has been decreased by a half compared to balanced conditions as expected.

Fundamental active power stays equal to the one in the case of grid voltages balanced. It is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(I_{h1}^{++} = 1 \text{ pu inductive and } L1 + L2 \text{ in } SC) = 157 \%$.

Test results during transient operation for the case $I_{h1}^{++} = 1 \text{ pu inductive}$ are compared to simulation. Grid voltages during transient are shown in Figure 63.

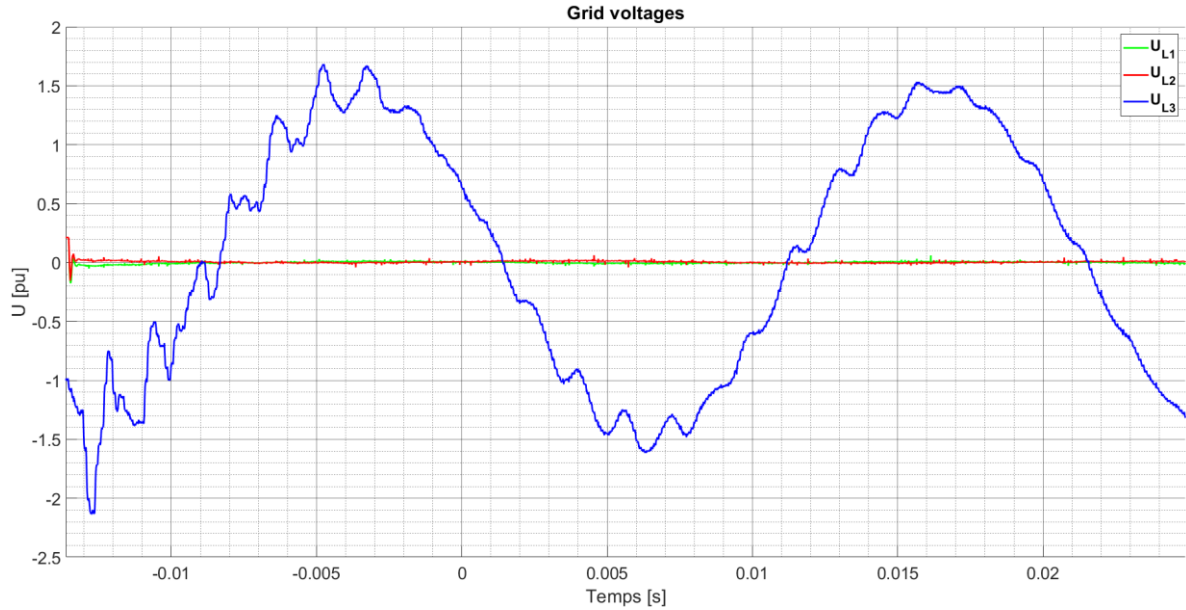


Figure 63: Grid voltages when $I_{h1}^{++} = 1 \text{ pu inductive}$ during two lines-to-earth short-circuit transient in test

The measured voltages visible in Figure 63 are highly corresponding with the simulation transient voltages in Figure 17. The voltage during the transient is the same as the one in simulation. The grid currents exchanged between DSCC prototype and grid simulator during this transient are shown in Figure 64.

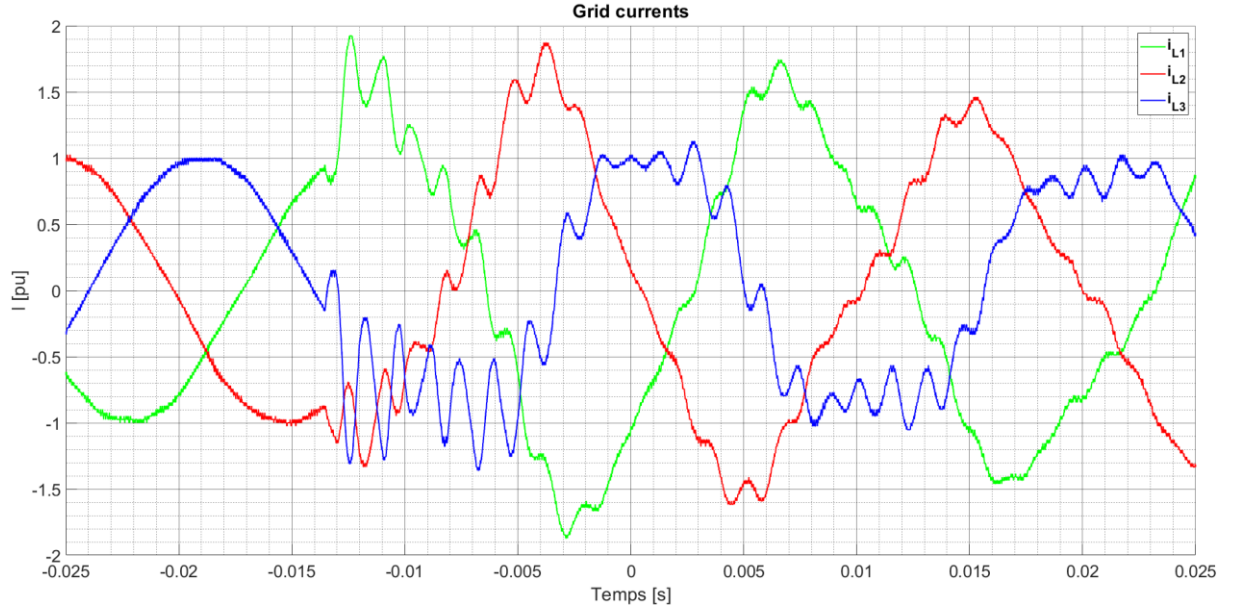


Figure 64: DSCC grid currents when $I_{h1}^{++} = 1$ pu inductive during two lines-to-earth short-circuit transient in test

If we compare Figure 64 with simulation results in Figure 37, it can be seen that current waveforms are highly similar. The maximum current reached is 1.923 pu which is 1.03 times more than in the simulation. Furthermore, grid currents continue to follow the $I_{h1}^{++} = 1$ pu inductive reference during the transient with the same oscillations as in simulation. It means DSCC prototype is dealing well with the transient.

We still need to verify internal behaviour of the DSCC. As in simulation, cluster voltages are slowly moving away from their reference ($u_{SM_{u,l}}^{\Sigma*} = 2.45$ pu). The duration time of the two lines-to-earth short-circuit was 2.5s before one cluster voltage difference with 2.45pu setpoint reached 0.3pu. STATCOM prototype reach the limit 2 times faster than the simulation. This is due to the internal unbalance of the physical components (non-ideal capacitances and inductances with values different between each component). They deteriorate faster the internal imbalance of the converter. These 2.5s are a correct result and could be increased by increasing the safety limit.

The upper arm cluster voltage for each leg with $I_{h1}^{++}=1$ pu inductive recorded by the DSCC prototype before one cluster voltage difference with 2.45pu setpoint equals 0.3pu are shown in Figure 65.

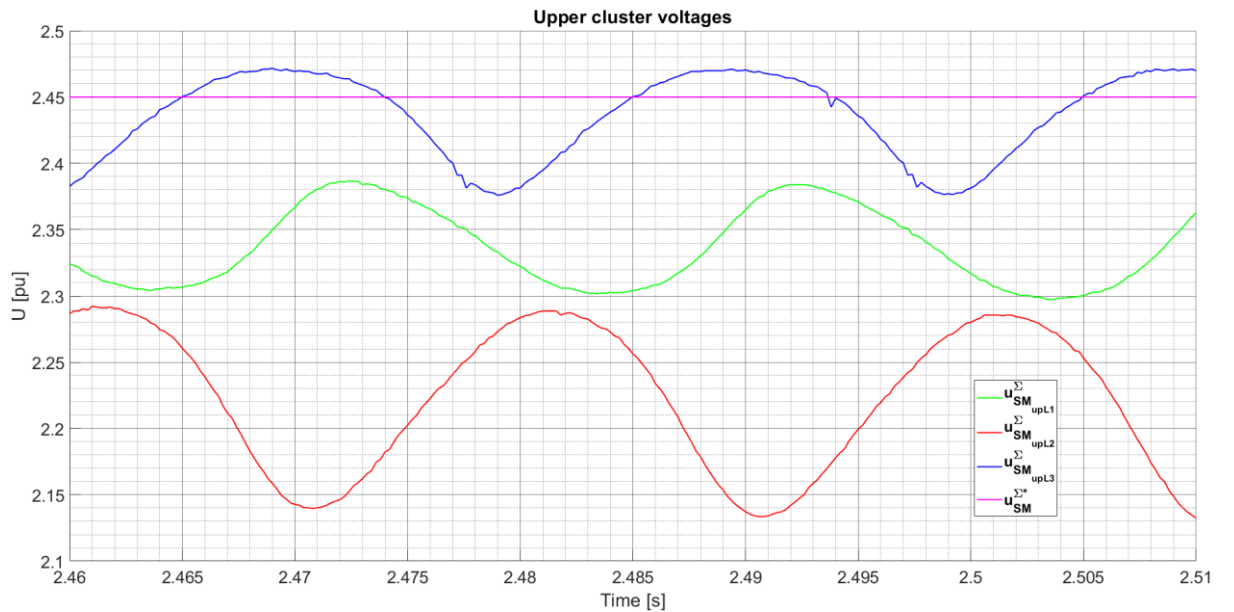


Figure 65: DSCC upper arm cluster voltage for each leg when $I_{h1}^{++}=1$ pu inductive at the end of two lines-to-earth short-circuit in test



As in simulation, upper cluster voltages are decreasing over the time. Indeed, all phases average in the last period are lower than the 2.45 pu setpoint. As in simulation, upper cluster voltage of phase L2 is the one decreasing the fastest. The minimum value is 2.134 pu reached by L2. It can also be noted that L3 phase is the closest to the setpoint value as in simulation.

As it can be seen, their peak-to-peak amplitudes are:

- $u_{SM_{upL1pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.082 \text{ pu}$
- $u_{SM_{upL2pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.151 \text{ pu}$
- $u_{SM_{upL3pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.095 \text{ pu}$

The same trend is visible as in simulation. The highest peak-to-peak amplitude belongs the phase L2. The relative deviations with simulation are given in Table 17 and stay reasonable.

The lower arm cluster voltage for each leg with $I_{h1}^{+*} = 1$ pu inductive recorded by the DSCC prototype before one cluster voltage difference with 2.45pu setpoint equals 0.3pu are shown in Figure 66.

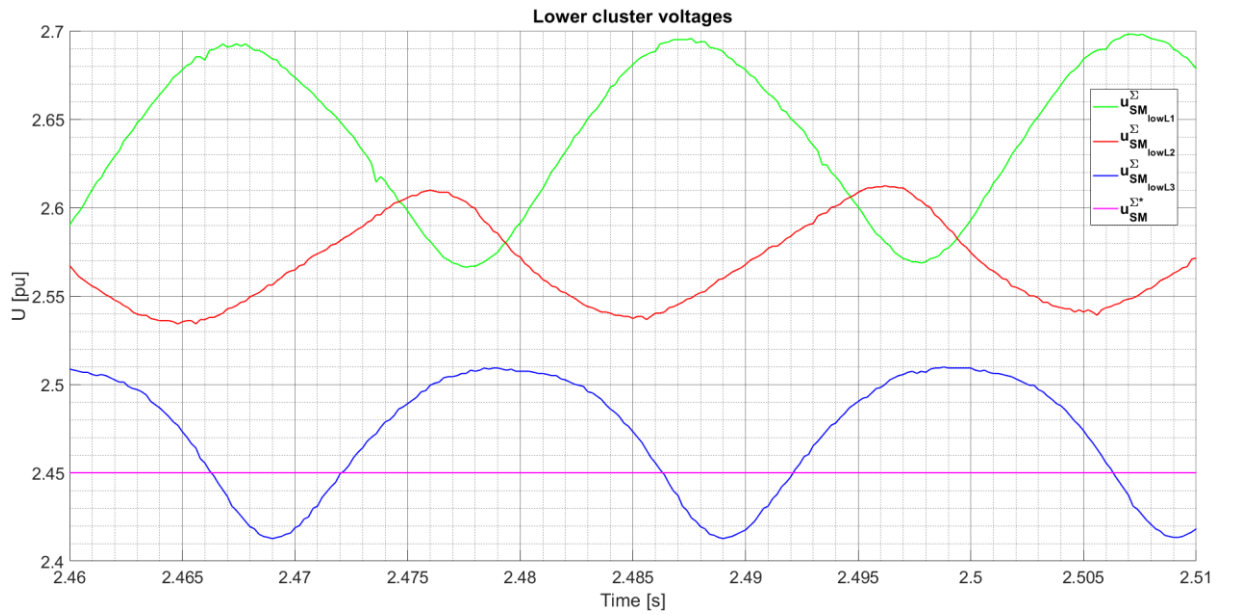


Figure 66: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*} = 1$ pu inductive at the end of two lines-to-earth short-circuit in test

As in simulation, lower cluster voltages are increasing over the time. Indeed, all phases average in the last period are higher than the 2.45 pu setpoint. As in simulation, lower cluster voltage of phase L1 is the one increasing the fastest. The maximum value is 2.695 pu reached by L1. It can also be noted that L3 phase is the closest to the setpoint value as in simulation.

As it can be seen, their peak-to-peak amplitudes are:

- $u_{SM_{lowL1pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.129 \text{ pu}$
- $u_{SM_{lowL2pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.074 \text{ pu}$
- $u_{SM_{lowL3pp}}^{\Sigma}(I_{h1}^{+*} = 1 \text{ pu inductive and L1 + L2 in SC}) = 0.096 \text{ pu}$

The same trend is visible as in simulation. The highest peak-to-peak amplitude belongs the phase L1. The relative deviations with simulation are given in Table 17 and stay reasonable.

As predicted by simulation, the arm energy balancing controller of each leg cannot be regulated to zero. But until one cluster voltage difference with 2.45pu setpoint equals 0.3pu, the cluster voltages of the converter behave like in simulation and allow the STATCOM to continue to exchange currents and stay connected to the grid for 2.5s. The 5 seconds of simulation are not reached but the 2.5s are a correct result and could be increased by increasing the safety limit.



A summary of DSCC test results when $I_{h1}^{+*} = 1$ pu inductive during two lines-to-earth short-circuit in steady state are given in Table 17. This table also contains simulation results as a comparison.

DSCC test and simulation results at the end of two lines-to-earth short-circuit when $I_{h1}^{+*} = 1$ pu inductive			
	Test results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.026	1.000	2.6
$\hat{I}_{h1}$ phase L2 [pu]	1.021	1.000	2.1
$\hat{I}_{h1}$ phase L3 [pu]	0.992	1.000	0.8
THDi phase L1 [%]	16.3	14.5	12
THDi phase L2 [%]	14.5	13.4	8
THDi phase L3 [%]	17.1	15.7	9
Current Unbalance Factor h1 [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	1.2	0.0	Impossible to calculate
P_{h1}^+ [pu]	0.018	0.007	157 (not relevant for low values)
Q_{h1}^+ [pu]	0.502	0.492	2.0
$u_{SM_u}^\Sigma$ maximum pk-pk amplitude [pu]	0.151 (phase L2)	0.200 (phase L2)	24.5
$u_{SM_u}^\Sigma$ minimum value [pu]	2.134 (phase L2)	2.133 (phase L2)	0.05
$u_{SM_l}^\Sigma$ maximum pk-pk amplitude [pu]	0.129 (phase L1)	0.165 (phase L1)	21.8
$u_{SM_l}^\Sigma$ maximum value [pu]	2.695 (phase L1)	2.712 (phase L1)	0.6

Table 17: DSCC test and simulation results at the end of two lines-to-earth short-circuit when $I_{h1}^{+*} = 1$ pu inductive

In case of two lines-to-earth short-circuit steady-state and transient, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence inductive current with the grid simulator during 2.5s with safety limit of 0.3 pu cluster voltage difference with 2.45 pu setpoint. In addition, except for DSCC converter losses (see above in this section) and time before reaching safety limit, test results precisely match the simulation results.

As already mentioned in section 4.3.6, only the summarized results for STATCOM capacitive operation are presented and compared to simulation in Table 18. The detailed results are available in 16.9 appendix.



DSCC test and simulation results during two lines-to-earth short-circuit when $I_{h1}^{+*} = 1$ pu capacitive			
	Test results	Simulation results	Relative deviation with simulation [%]
$\hat{I}_{h1}$ phase L1 [pu]	1.027	1.000	2.7
$\hat{I}_{h1}$ phase L2 [pu]	1.020	1.000	2.0
$\hat{I}_{h1}$ phase L3 [pu]	0.995	1.000	0.5
THDi phase L1 [%]	15.2	12.7	19.7
THDi phase L2 [%]	14.1	12.6	11.9
THDi phase L3 [%]	15.8	13.2	19.7
Current Unbalance Factor h1 [%]: $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+}$	1.0	0.0	Impossible to calculate
P_{h1}^+ [pu]	0.023	0.012	91.7 (not relevant for low values)
Q_{h1}^+ [pu]	-0.503	-0.492	2.2
$u_{SM_u}^{\Sigma}$ maximum pk-pk amplitude [pu]	0.155 (phase L1)	0.087 (phase L3)	78.2
$u_{SM_u}^{\Sigma}$ minimum value [pu]	2.162 (phase L1)	2.363 (phase L1)	8.5
$u_{SM_l}^{\Sigma}$ maximum pk-pk amplitude [pu]	0.125 (phase L2)	0.084 (phase L3)	48.8
$u_{SM_l}^{\Sigma}$ maximum value [pu]	2.708 (phase L2)	2.541 (phase L2)	6.6

Table 18: DSCC test and simulation results during two lines-to-earth short-circuit when $I_{h1}^{+*}=1$ pu capacitive

In case of two lines-to-earth short-circuit steady-state and transient, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence capacitive current with the grid simulator during 5s with safety limit of 0.3 pu cluster voltage difference with 2.45 pu setpoint. In addition, except for DSCC converter losses and time before reaching safety limit, test results precisely match the simulation results. It is important to mention that, as in simulation, the capacitive case is beneficial because DSCC prototype is able to work two times longer during two lines-to-earth short circuit (5 seconds against 2.5s for the inductive case).

All experimental test results presented in section 4.3.10.3 confirm that DSCC prototype is able to exchange positive sequence inductive and capacitive current in the range of ± 1 pu when two lines-to-earth short-circuit voltage is applied directly at STATCOM input (transient and steady state correct operation). However, as shown in simulation results, arm energy difference in each leg tends to increase indefinitely leading to instable internal behaviour. But as mentioned in simulation, the maximum duration time of a short-circuit is never more than 5 seconds. And even if experimental results lead to lower duration of time before security activation of the prototype than in simulation, the worst-case (inductive) is still 2.5s (5s for the capacitive case). These results show that with this control strategy and prototype security, DSCC prototype should be able to manage the majority of two lines-to-earth short-circuit without disconnecting from the grid.

4.3.10.4. Conclusion of DSCC experimental results for every possible grid voltages

The DSCC STATCOM operation was analysed in simulation and during experimental tests for nominal positive sequence inductive and capacitive reactive power with three different grid voltage states:

- Balanced voltages



- One line-to-earth short-circuit voltages directly at STATCOM input
- Two lines-to-earth short-circuit voltages directly at STATCOM input

During the balanced grid voltage state, simulation and experimental results of the DSCC with the control strategy proposed are highly similar. They demonstrate the ability of DSCC STATCOM to exchange nominal positive sequence inductive and capacitive reactive power with the grid indefinitely keeping internal behaviour stable permanently. In addition, low THDi of the currents exchanged indicates DSCC is not polluting the grid during its operation.

During one line-to-earth short-circuit directly at STATCOM substation, simulation and experimental results of the DSCC with the control strategy proposed are also highly similar. They demonstrate the ability of DSCC STATCOM to exchange nominal positive sequence inductive and capacitive reactive power with the grid indefinitely keeping internal behaviour stable permanently as in balanced case. This kind of short-circuit is easily managed by the DSCC with this control without any change in hardware or control compared to balanced case. In addition, the THDi of the currents exchanged with grid is still low for DSCC with this control strategy. So even during one line-to-earth short-circuit, DSCC is not polluting the grid during its operation.

During two lines-to-earth short-circuit directly at STATCOM substation, simulation and experimental results of the DSCC with the control strategy are mainly similar and confirm DSCC ability to exchange positive sequence inductive or capacitive reactive power with the grid during at least 2.5s for inductive case and at least 5s for capacitive case. During this time, the internal behaviour is still enough stable to guarantee low currents negative sequence, reasonable THDi and converter safety. To go further, [8] proposes different control strategies that could possibly maintain a permanent internal stability of the STATCOM DSCC topology. But the lack of time in the project did not allow us to explore a new control strategy. This point is still opened and would need more time to investigate.

As final conclusion, all the results (simulations and tests) validate the ability of DSCC to operate in all possible grid voltage states, with the control proposed, for power systems applications where two lines-to-earth short-circuit are cleared in few seconds.



5 WP2: Preliminary system (grid) analysis and test case definition

This section summarizes the WP2 activities and results. Section 5.1 summarizes how SIL defined their interested MV areas concerning RES massive integration and flexibility provision and then gave information to HEIA-FR team for treatment. Section 5.2 explains that a synthetic network was used as test to validate STATCOM control, correct operation of the STATCOM model in Power-Factory and method/script used for the computation of the performance indexes. Section 5.3 recapitulates how MV network was modeled in PowerFactory software. Section 5.4 gives estimation results of PV future expansion in SIL case study. Finally, section 5.5 presents the performance indexes used to evaluate STATCOM efficiency. Detailed explanations concerning this entire section 5 can be found in [5].

5.1 Definition of network areas to study

SIL are responsible for electricity distribution system in the city of Lausanne. They provided a lot of information on their MV network and their connection with HV network leading to the geographical representation shown in Figure 67.

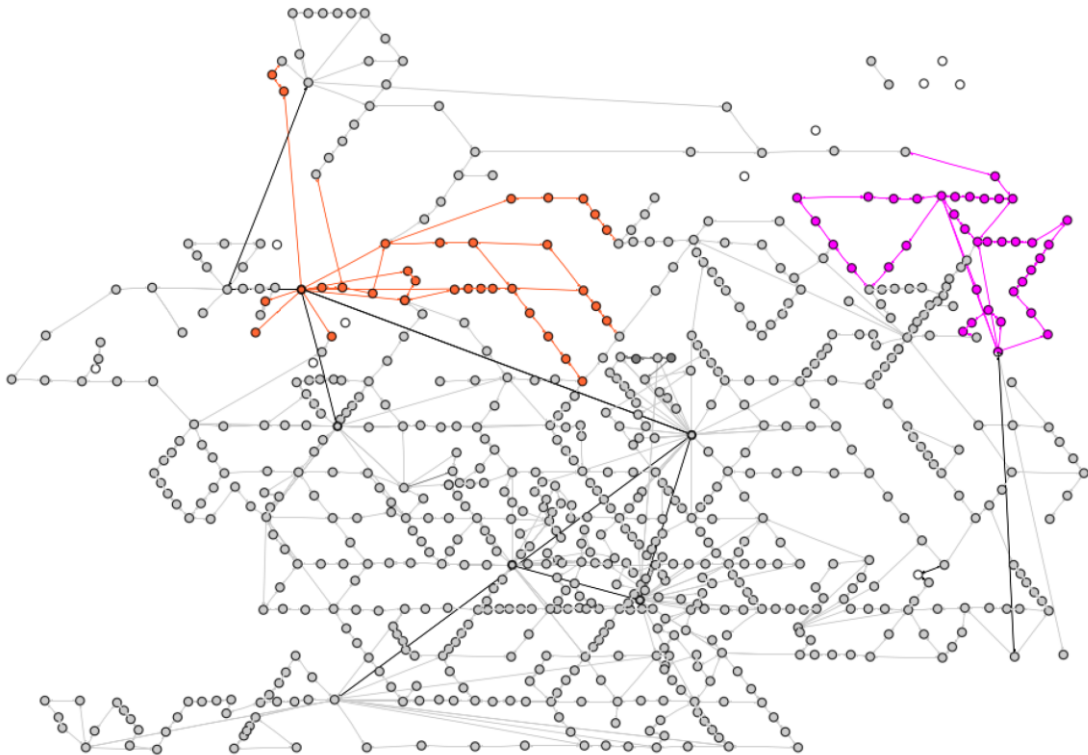


Figure 67: SIL MV network (with selected HV links in black), topological colouring (purple: B; orange: A), taken from [5]

Furthermore, “A” and “B” MV network area fed by a HV/MV transformer, respectively in orange and purple in Figure 67, are of interest for the needs of the project. Network area “A” is selected for its potential to export reactive power from MV grid to the transmission network. This case covers the provision of flexibility from MV grid to HV grid presented in section 1.1. In network area “B”, a high amount of RES are planned for installation and connection is relatively long to EHV/HV substations. This case deals with massive RES integration issues presented in section 1.1.



5.2 Preliminary tests on a synthetic network

Before SIL grids exploitation, a more general network was modelled via PowerFactory software in order to validate the scripts used to control the STATCOM, the correct operation of the STATCOM model (based on the built-in model in PowerFactory) and the method/script used for the computation of the performance indexes (described in section 5.5). The synthetic network is shown in Figure 68.

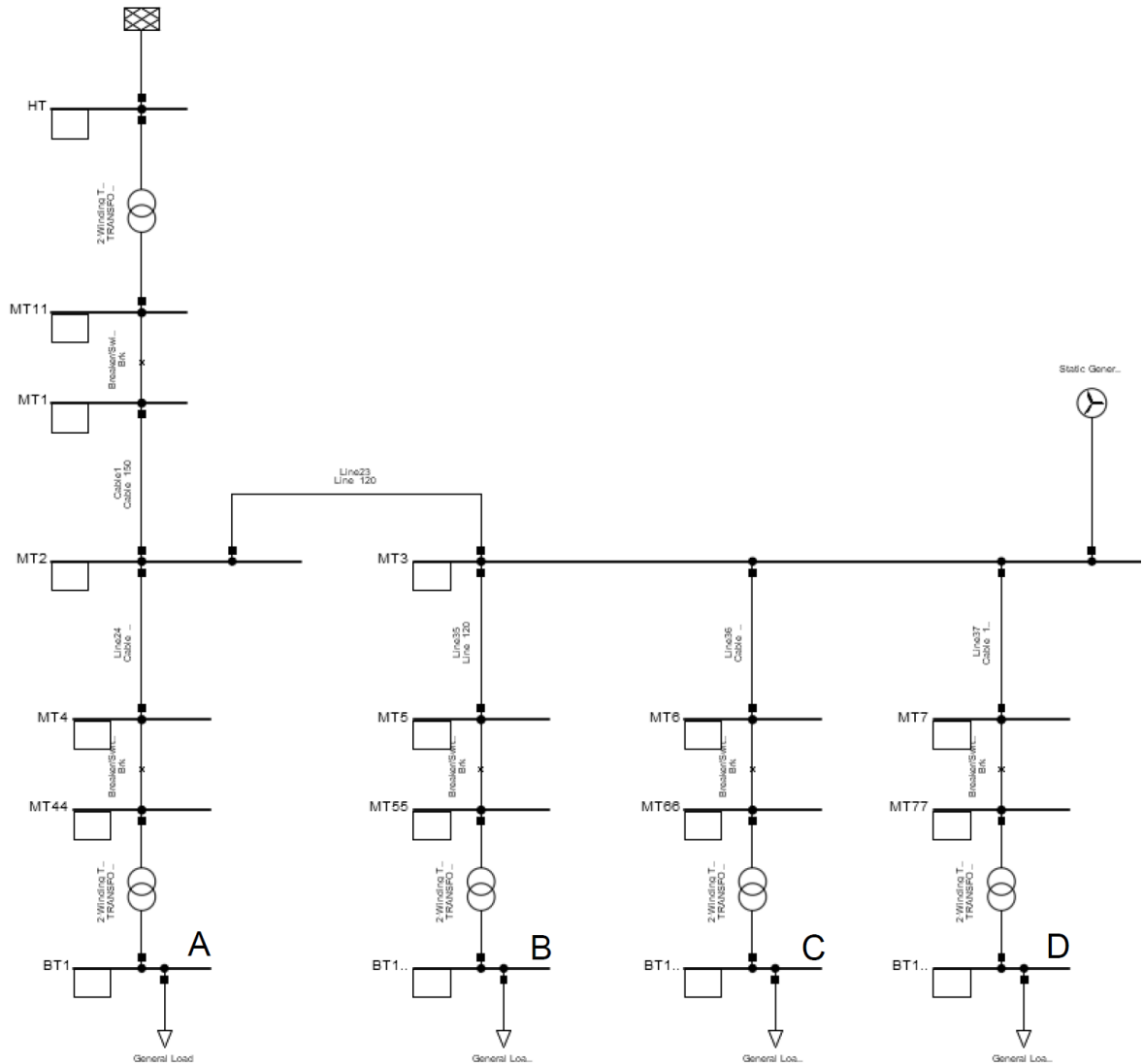


Figure 68: Synthetic network, taken from [5]

A STATCOM with a rating exceeding the maximum needed reactive power (in this sense "unlimited") was placed at four locations (A, B, C and D) within the network in four different simulation runs (snapshots). The control method of the STATCOM for this simulation was to control the voltage at the STATCOM connection point to 1 [pu]. A score comparing the STATCOM's effect on voltage variations, line loading, HV/MV transformer loading and network losses is assigned to each location and compared. The results validated the control, STATCOM model and computation of performance indexes. The detailed results are voluntarily not presented not to overload this annual report. However, they are available in [5].

5.3 Network data import and model creation

It was necessary to establish a model of the MV grid case studies in a comprehensive network simulation package (in this case, PowerFactory), as for the synthetic network in section 5.2. To do so, the network topology was extracted from the Lynx DMS of SIL. This included the topology of lines/cables, nodes,



switchgear and transformers in EHV, HV, MV and LV grids in Lausanne. Information regarding boundaries to other systems is included. Some adjustments were made based on plausibility checks in order to obtain a valid topology. The characteristics of network elements (such as impedances, etc.) have been selected mostly based on typical component data and where possible, based on available information from the DMS. Controller information and the characteristics of tap-changers for those transformers with OLTC was used as available in the information extracted from the DMS and guessed based on a discussion with SIL for all other transformers. Consumption data is based on current measurements in the bays of HV/MV substations. These measurements are available with an hourly interval for one year. The allocation to secondary substations was done using the estimated annual energy for each MV/LV transformer, recovered from aggregated billing data. Generation data is based on historic solar irradiance data from MeteoSwiss and the nominal power of PV systems extracted from the DMS. A future scenario with additional PV systems is also considered. The consumption and generation data permits to perform annual load flow simulations with hourly intervals. The annual data used corresponds to the year 2019.

The data discussed in this section permits to determine the loading of each component in the network, the voltage profile at each bus and the network losses (in the considered MV network) for a yearly simulation period. These are the values used in order to determine the scores of each variant of STATCOM insertion into the network.

5.4 Future generation scenarios

Figure 69 shows the evolution of the total installed PV power in Switzerland. An extrapolation of this data until 2050 is also included using two sets of data. Firstly, the blue curve is based on an extrapolation of the installed PV capacity based on SFOE statistics. Secondly the green curve is based on the 2050+ energy perspectives [9]. After discussion with SIL, it appears that it is unlikely that the installed PV in the city of Lausanne will be proportional to the national target, since obviously space availability is constrained. Therefore, the installed PV scenario in B MV network represented by the blue curve will be used. Figure 69 is also based on [10] and [11].

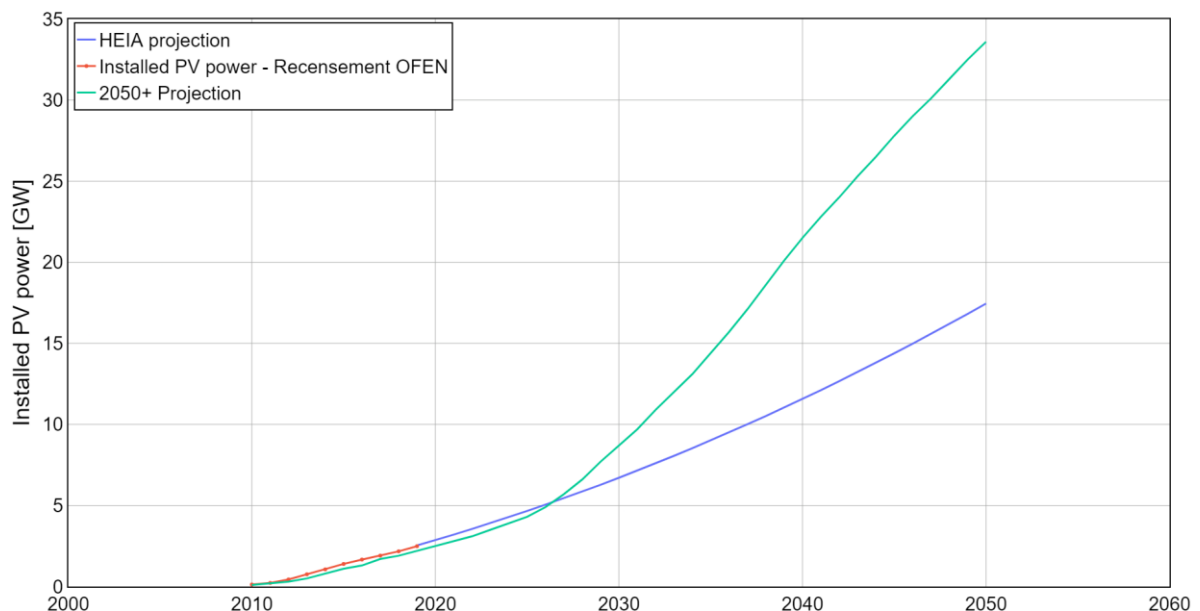


Figure 69: Evolution of installed PV power in SIL network including future projection, taken from [5]

In order to compute the increment for each MV/LV substation, a ratio between the current installed PV power in B (1.55MW, in 2019) and the rating power of each station transformer is made. Then, new PV generation are equally shared between substations as it should be made in the future. Furthermore, for the first projection of 2030, the current installed value is kept to maximise the unexploited PV potential.



5.5 Definition of performance indexes for STATCOM evaluation

The comparison of different STATCOM locations, control schemes and sizes requires a (relative) quantification of the STATCOM's effect on the considered network. Several effects need to be considered like component loading, voltage variations and network losses. An index, adapted from the development of a soft-open point demonstrator, was used in this study. The details of the index calculation are presented [5]. The index is a combined score of several criteria:

- The voltage index considers the maximum deviation of the voltage magnitude for each bus connected to a load among all scenarios;
- The current index introduces a penalty for lines that are loaded more than 50%;
- The transformer loading index indicates the peak load of the HV/MV transformer;
- The network losses index takes the mean value of total losses among all scenarios into account.

These indices are combined into a score, where lower scores are more desirable. Hence, the location with the lowest score would be the most interesting one with respect the criteria explained above. These scores will be used to rank the best STATCOM locations in the analysis part of this report.



6 WP3: Test cases simulations for benefits of a STATCOM located in SIL MV grid

This section summarizes the WP3 activities and results concerning the benefits of STATCOM against MV RES massive integration issues into network area “B”. Furthermore, an optimal location for STATCOM is also proposed. Finally, the benefits of adding a STATCOM to the distribution network in order to export reactive power towards the transmission system are studied. Section 6.1 summarizes the STATCOM control strategies implemented to improve MV grid behaviour. Section 6.2 summarizes the analyses made and the results leading to STATCOM optimal placement selection. Section 6.3 exposes the results of the comparison between alternative approaches and STATCOM to improve MV grid behaviour. Section 6.4 proposes a suggestion of Relne laboratory topology to represent MV grid during LV tests. These results are considered as a base for the Relne Laboratory setup explained in WP5. Section 6.5 discusses the benefits of adding a STATCOM to the distribution network in order to export reactive power towards the transmission system in the specific case-study. Finally, section 6.6 outlines possible future improvements for data usage. Detailed explanations concerning the entire section 6 can be found in [5].

6.1 Definition and implementation of control strategies

The effect of the STATCOM on the network performance indicators will largely depend on the specific control to be applied. For the purpose of comparing the variants, the following control strategies have been added to the models:

- Control the busbar at which the STATCOM is installed to 1 [p.u.]: in the specific case of the SIL network, the 50/11.5 kV transformers are not continuously regulated using OLTC. Instead, the 50 kV voltage is controlled. The result is that the 11.5 kV network voltage will vary slightly more in this case. This will be exacerbated in case of an increase in installed PV. In general, this kind of control would rather help to reduce the number of control actions on OLTC (which is a real concern due to maintenance involved with these systems) and to reduce the amount of reactive power exchanged with the higher network levels;
- Control the MV busbar with the highest voltage deviation with respect to B to the same level as the B MV busbar: with this control objective, the variation of voltages during the day due to load and generation will decrease as the voltage difference between the extreme values in the MV network will be reduced by the STATCOM.
- Control the reactive power exchange with the HV network to zero: this will reduce the adverse influence of the loaded MV cable network on the HV network.
- PowerFactory OPF with the objective to minimise the MV network losses: this control mode is a comparison basis with the other defined modes. Since the OPF requires the values of all state variables in the network, this solution can hardly be implemented in practice since only few measurements will be available to the STATCOM control system. The comparison will however be a good indication of the performance of the above simplified control modes.

6.2 Optimal STATCOM placement

To select the best location to place the STATCOM in the B MV network, several simulations with different initializations were made. In summary, the following important simulation series were carried out:

- QDS over one year, 1h data resolution, unlimited STATCOM power, all substations tested as candidates for locating the STATCOM;
- QDS over one year, 1h data resolution, limited STATCOM power, all substations tested as candidates for locating the STATCOM. Two ratings have been considered: 1 Mvar and 3 Mvar (i.e. rating exceeding the maximum Mvar demand) for a more realistic point of view.

Table 19 shows the results of the annual simulations with unlimited STATCOM power. For each of the four control modes introduced in previous section, the achieved performance index and the maximum required reactive power from the STATCOM are given. A so-called “final index” is obtained by multiplying the two values. A lower index score indicates better network performance and a lower STATCOM rating



implies a lower technical and financial effort to achieve this performance improvement. A low final score thus indicates a combination of low effort and high impact. For example, the first three columns of Table 19 contain the scores for simulations where the STATCOM is used to control its connection point voltage to 1 pu. If placed at the Xavier or Morandquar stations, the STATCOM leads to the best improvement of the network performance.

Substation name	Local busbar @ 1pu			Busbar with max deviation as B			Q flow @ B fixed at 0VAr			OPF: minimisation of losses in B			Overall
	In-dex	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	
(A) XAVIER	0.137	5.50	0.753	0.198	6.87	1.36	0.167	2.63	0.546	0.114	4.96	0.564	3.12
(B) MORANDQUAR	0.144	5.46	0.786	0.209	6.82	1.42	0.169	2.63	0.551	0.120	4.93	0.591	3.25
(C) PRAMUSY	0.201	5.12	1.03	0.262	6.39	1.67	0.185	2.64	0.602	0.169	4.62	0.781	3.97
(D) BOISDAVAUX	0.210	5.65	1.19	0.242	6.74	1.63	0.0915	2.63	0.298	0.206	5.30	1.09	4.15
(E) TANNINS	0.239	5.36	1.28	0.253	6.22	1.57	0.0785	2.64	0.255	0.240	5.05	1.21	4.22
(F) OIES	0.224	5.00	1.12	0.280	6.22	1.74	0.192	2.63	0.624	0.189	4.52	0.854	4.27
(G) MARIN	0.245	5.12	1.25	0.315	6.23	1.96	0.191	2.64	0.622	0.202	4.69	0.946	4.67
(H) OZAIRE	0.291	4.55	1.32	0.346	5.59	1.93	0.218	2.64	0.709	0.245	4.11	1.01	4.84
(I) PERRONNE	0.309	4.41	1.36	0.363	5.41	1.96	0.227	2.64	0.738	0.263	3.99	1.05	4.97
(J) GOLF	0.297	4.83	1.43	0.361	5.85	2.12	0.206	2.64	0.670	0.254	4.45	1.13	5.22
REFERENCE CASE		0.506			0.504			0.513			0.507		

Table 19: Performance index and required STATCOM rating for different control modes and locations. The locations shown are the 10 locations with the best (i.e. lowest) score, taken from [5]

Figure 70 shows the 10 best locations for the STATCOM according to Table 19. It appears that the locations where the STATCOM is most useful are grouped in three clusters. Within these clusters, the line lengths are relatively short. The clusters correspond to nodes with several connections, i.e. well-inter-connected nodes. The required STATCOM size appears to be a combination of the distance to the “B” primary substation and the degree of meshing of the node chosen for the STATCOM connection.

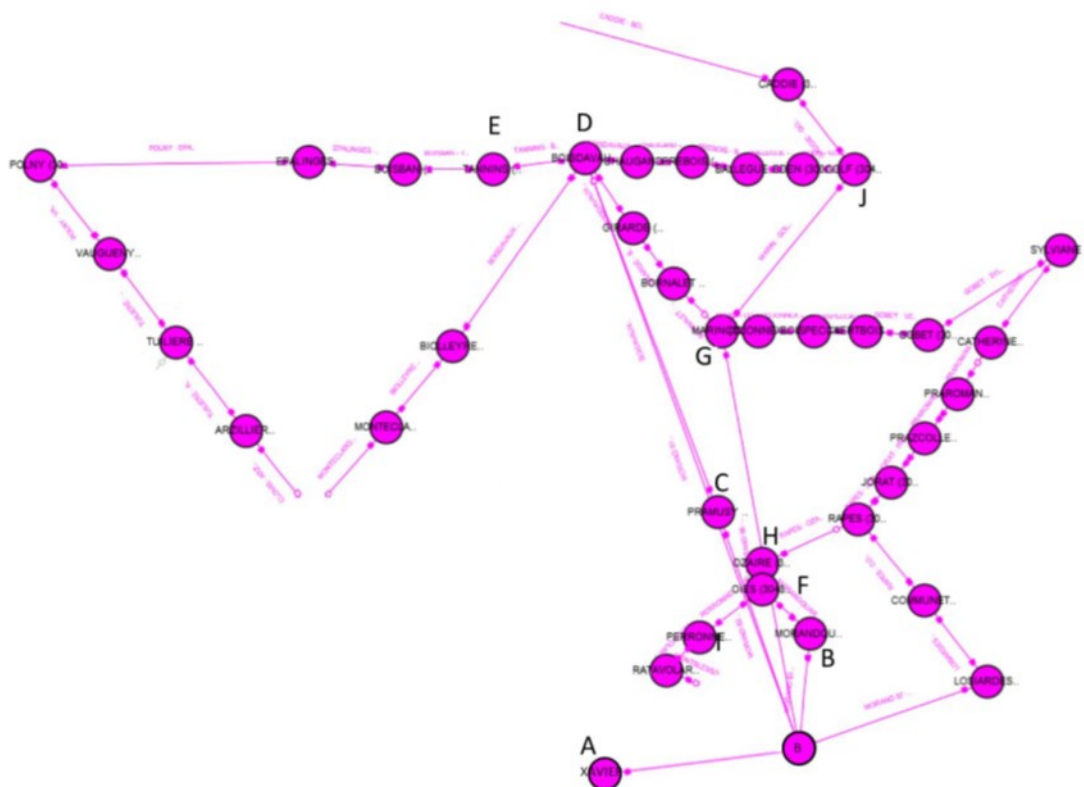


Figure 70: Overall best locations. Line lengths: (E-D)=1.9km / (F-I)=1.1km / (F-H)=0.5km / (F-B)=0.7km / (G-J)=0.6km / (D-C)=1.8km, taken from [5]

The placement and control mode comparison were also carried out for STATCOMs with reduced ratings for more realistic results. It is worth to mention that the limited rating influences the trade-off between the positive influence of the voltage support and the negative influence of the increased line loading.



Results for 1 Mvar limited power are shown in Table 20 and Figure 71. It appears the locations with a higher level of interconnection remain attractive, but locations closer to the HV/MV transformer loose in attractiveness. Hence it can be qualitatively seen that the best suited locations are slightly more distant from the HV/MV substation. The results for limited STATCOM ratings can be better for control modes other than OPF, which is due to the formulation of the problem, i.e. minimisation of losses. It is worth mentioning that the area around Boisdavaux consists of relatively short cable and line sections, hence the concentration of several of the best locations around this particular substation.

Substation name	Local busbar @ 1pu			Busbar with max deviation as B			Q flow @ B fixed at 0VAr			OPF: minimisation of losses in B			Overall
	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	
(A) VAUGUENY	0.0761	1.00	0.0762	0.0528	1.00	0.0529	0.0546	1.00	0.0546	0.327	1.00	0.327	0.511
(B) POLNY	0.0829	1.00	0.0830	0.0589	1.00	0.0589	0.0600	1.00	0.0601	0.324	1.00	0.324	0.526
(C) ARZILLIER	0.0695	1.00	0.0696	0.0454	1.00	0.0454	0.0477	1.00	0.0477	0.366	1.00	0.366	0.529
(D) TUILIERE	0.0713	1.00	0.0714	0.0480	1.00	0.0481	0.0500	1.00	0.0500	0.361	1.00	0.362	0.531
(E) EPALINGES	0.0994	1.00	0.0994	0.0718	1.00	0.0719	0.0724	1.00	0.0725	0.316	1.00	0.316	0.560
(F) BOISBAN	0.122	1.00	0.122	0.0911	1.00	0.0912	0.0852	1.00	0.0853	0.302	1.00	0.302	0.601
(G) TANNINS	0.158	1.00	0.159	0.124	1.00	0.124	0.0966	1.00	0.0967	0.290	1.00	0.290	0.669
(H) BOISDAVAUX	0.216	1.00	0.216	0.168	1.00	0.169	0.144	1.00	0.144	0.185	1.00	0.185	0.714
(I) CHAUGAN	0.220	1.00	0.220	0.180	1.00	0.180	0.156	1.00	0.156	0.242	1.00	0.242	0.798
(J) BIOLLEYRE	0.222	1.00	0.223	0.180	1.00	0.180	0.155	1.00	0.155	0.271	1.00	0.271	0.829
REFERENCE CASE		0.725			0.749			0.691			0.504		

Table 20: Performance index and required STATCOM rating for different control modes and locations. The STATCOM power was limited as indicated, taken from [5]

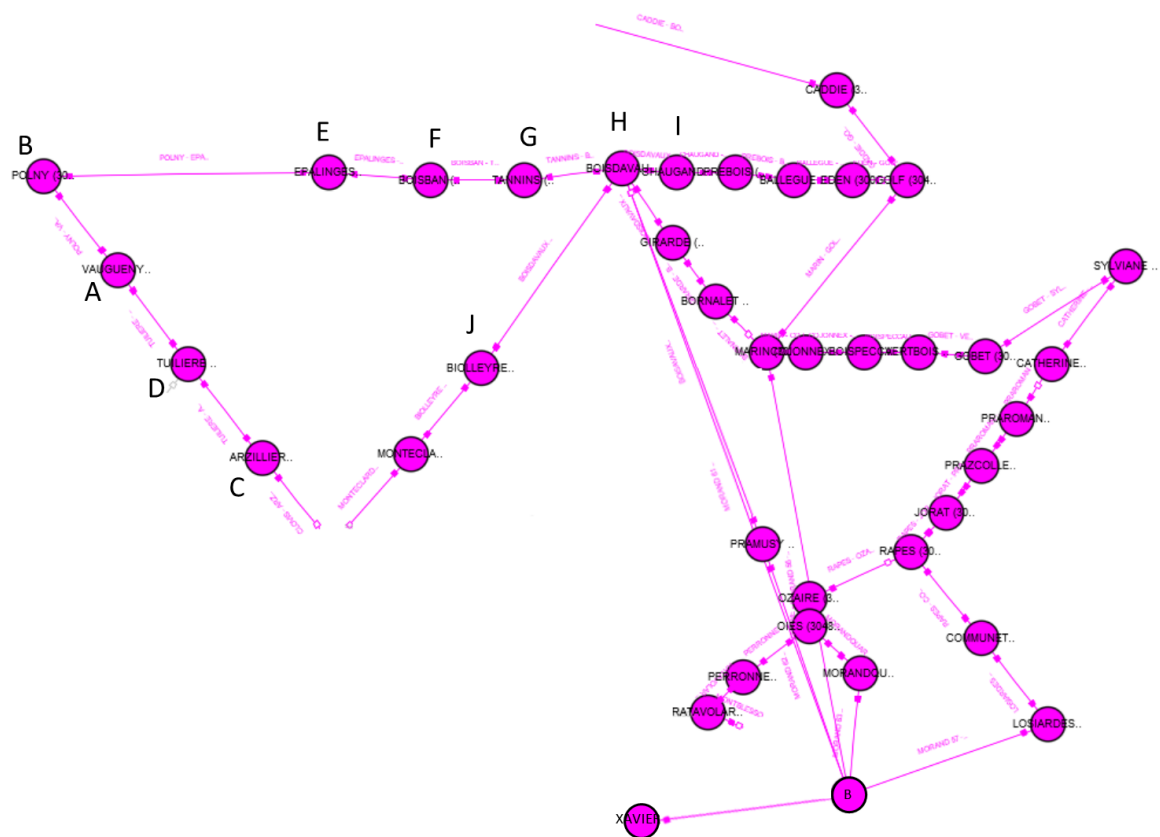


Figure 71: Overall best locations for a limited power of 1MVA, taken from [5]

A third realistic rating of 3 Mvar for the STATCOM has been selected as in intermediate case between the two previously discussed ones. Table 21 and Figure 72 show the simulation results for the placement of the 3 MVar STATCOM. These results show a continuity in the distribution of the best-suited locations: the locations at meshed nodes remain attractive, and in addition, the locations closer to the HV/MV substation gain in attractiveness compared to the smallest STATCOM rating of 1 Mvar.



Substation name	Local busbar @ 1pu			Busbar with max deviation as B			Q flow @ B fixed at 0Var			OPF: minimisation of losses in B			Overall
	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	Index	max STATCOM Q	Final Index	
(A) BOISDAVAUX	0.233	3.00	0.698	0.107	3.00	0.322	0.109	2.62	0.285	0.185	3.00	0.556	1.86
(B) TANNINS	0.239	3.00	0.716	0.151	3.00	0.453	0.081	2.62	0.213	0.290	3.00	0.870	2.25
(C) MORANDQUAR	0.275	3.00	0.826	0.206	2.78	0.573	0.215	2.62	0.564	0.119	3.00	0.357	2.32
(D) BIOLLEYRE	0.276	3.00	0.827	0.163	3.00	0.488	0.134	2.62	0.351	0.271	3.00	0.814	2.48
(E) XAVIER	0.271	3.00	0.814	0.203	2.80	0.567	0.214	2.62	0.560	0.113	3.00	0.339	2.28
(F) CHAUGAND	0.289	3.00	0.866	0.180	3.00	0.542	0.145	2.62	0.380	0.242	3.00	0.726	2.51
(G) BOISBAN	0.264	3.00	0.791	0.194	3.00	0.582	0.094	2.62	0.247	0.302	3.00	0.907	2.53
(H) EPALINGES	0.269	3.00	0.806	0.220	3.00	0.659	0.089	2.62	0.234	0.316	3.00	0.947	2.65
(I) PRAMUSY	0.308	3.00	0.923	0.240	2.62	0.628	0.230	2.63	0.605	0.168	3.00	0.504	2.66
(J) POLNY	0.272	3.00	0.816	0.244	3.00	0.733	0.082	2.63	0.215	0.324	3.00	0.971	2.74
REFERENCE CASE		0.506			0.515			0.528			0.504		

Table 21: Performance index and required STATCOM rating for different control modes and locations. The STATCOM power was limited as indicated, taken from [5]

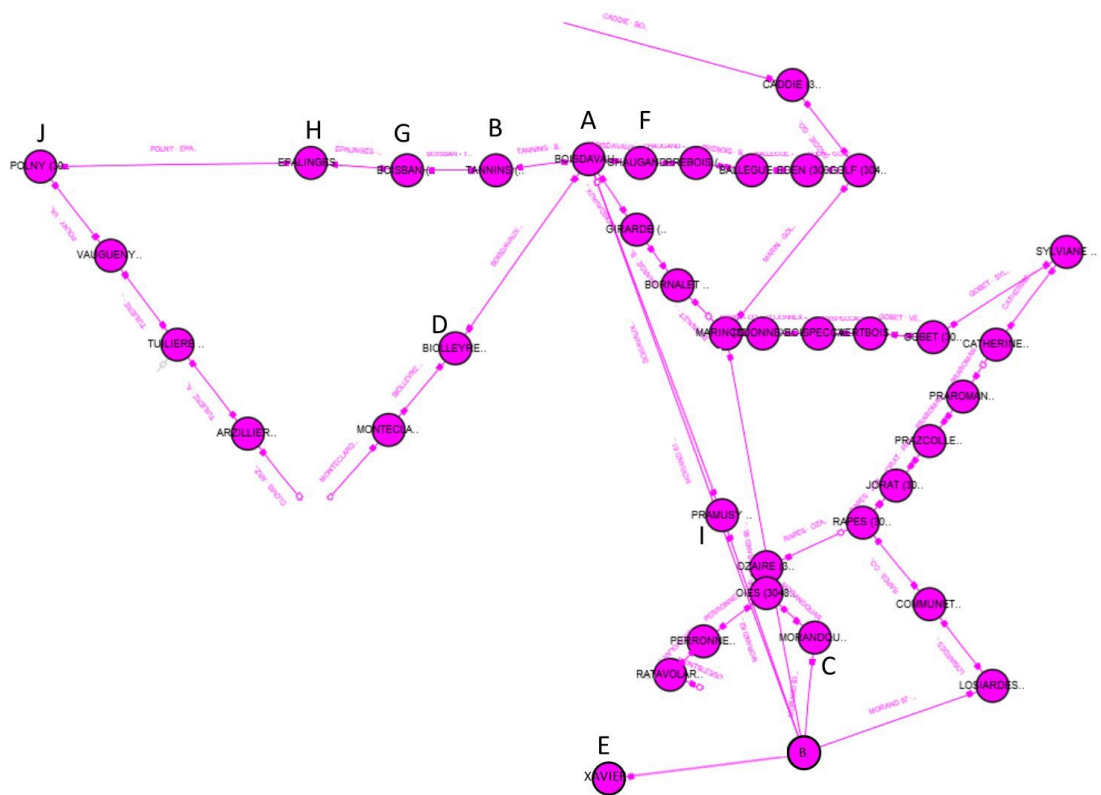


Figure 72: Overall best locations for a limited power of 3MVA, taken from [5]

As a global result based on the 3 simulations proposed above, the substation of Boisdavaux appears to be a robust candidate location, since it ranks high regardless of the size limitation. The Tannins substation is also present in all lists of best-suited stations, which is due to its vicinity to the Boisdavaux station. If a unique candidate for the placement of a STATCOM should be identified, this would be Boisdavaux. This station was used in further investigations realized on best topologies as presented in [2] and [4]. Figure 73 shows the best location areas to install STATCOM for each STATCOM nominal power.

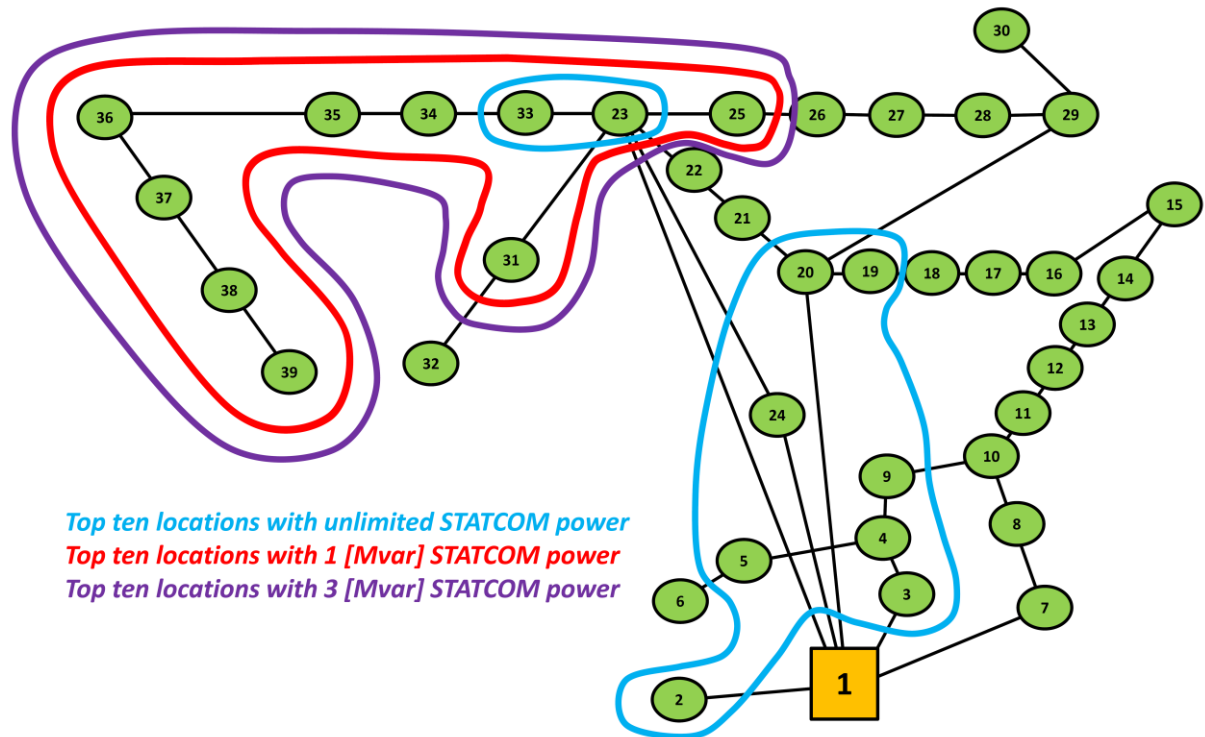


Figure 73 : Topological representation of the network with best location areas to install STATCOM circled

6.3 Comparison with alternative approaches

Although the topic of this project is the use of STATCOMs, the effectiveness of placing a STATCOM into a distribution network will be briefly compared to other reinforcement measures that might achieve similar effect. The following types of measures have been included in the comparison: adding parallel lines/cables to existing ones, replacing existing cables by cables with increased cross-section, increasing the rating of selected MV/LV transformers and increasing the rating of the HV/MV transformer. This investigation was carried out using the example of a 1 Mvar STATCOM placed at the Arzillier station, using the voltage control mode (Q flow at B fixed at 0). Arzillier is the station that provided the best possible STATCOM location for this control. The alternative network reinforcement measures considered in this case were the following (each of these being considered separately):

- Addition of parallel lines: for the three 3 lines (or cable) with highest load over the year, a parallel line is added: B-BOISDAVAUX (74.8%, 2.3km), B-MARIN (48.7%, 1.14km), TANNINS-BOISDAVAUX (43.4%, 1.19km);
- Each of the following alternatives is considered: Situation A: Addition of a parallel line to line B-BOISDAVAUX, Situation B: Addition of a parallel line to lines B-BOISDAVAUX and B-MARIN, Situation C: Addition of a parallel line to lines B-BOISDAVAUX, B-MARIN and TANNINS-BOISDAVAUX;
- Increase lines section: for the three 3 lines (or cable) with highest load over the year, the cross-section is changed from 150 mm² Alu to 300 mm² Cu. Each of the following alternatives is considered: Situation A: Improved characteristics on line B-BOISDAVAUX, Situation B: Improved characteristics on lines B-BOISDAVAUX and B-MARIN, Situation C: Improved characteristics on lines B-BOISDAVAUX, B-MARIN and TANNINS-BOISDAVAUX;
- Increase B HV/MV transformer power: the rating of the B HV/MV transformer is increased from 15 to 25 MVA.
- Increase MV/LV transformer ratings: the 3 transformers with highest load over the year are replaced by transformer with a rating equal to twice the currently installed power of each one of those 3 transformers: Arzillier (0.4MVA → 0.8MVA), Prazcollet (0.4MVA → 0.8MVA), Marin (0.63MVA → 1.26MVA).



Table 22 taken from [5] shows the results of the comparison between the classical reinforcement approaches and the STATCOM. All measures are assessed using the same scoring system that can be compared to the initial situation (without STATCOM and without reinforcement), i.e. the "reference case". The best control mode for the STATCOM (i.e. minimisation of the reactive power exchange with the HV network) is given in the second column. The results show that the STATCOM is the most competitive option for improving the voltage profile whereas the improvement to component loadings is less attractive. In practice, the type of issue to be resolved will therefore decide on the attractiveness of using a STATCOM.

	REFERENCECASE	STATCOM	PARALLEL LINES			INCREASE LINE SECTION			INCREASE TRANSFO POWER
		ARZILLIER (Q flow at B fixed at 0)	A	B	C	A	B	C	Transfo HV/MV B 15MVA→25MVA
U index	0.641	0.186	0.429	0.423	0.383	0.462	0.461	0.421	0.462
I index	0.8825	0.857	0.349	0.346	0.346	0.737	0.734	0.733	0.737
L index	0.013	0.014	0.013	0.012	0.012	0.012	0.012	0.012	0.012
T index %	177.89	173.41	176.59	176.57	176.21	176.9	176.9	176.6	176.47
Index	0.894	0.488	0.456	0.307	0.264	0.529	0.527	0.488	0.728

Table 22: Comparison with alternative approaches, taken from [5]

6.4 Relne Laboratory topology proposal

In analogy with the results obtained for the SIL distribution network, the following rules are suggested for the deployment of a STATCOM to the Relne laboratory:

- Select a location with several branches, midway between the primary substation and the edge of the network;
- Select a rating in the range of 10...20% of the primary substation's transformer;

Figure 74 shows the suggested topology for the tests to be run in the Relne laboratory, based on the criteria mentioned above. The objective is to have two branches, with the STATCOM located at the junction of these branches. In order to best exploit the available elements of the laboratory, the addition of two disconnectors is recommended.

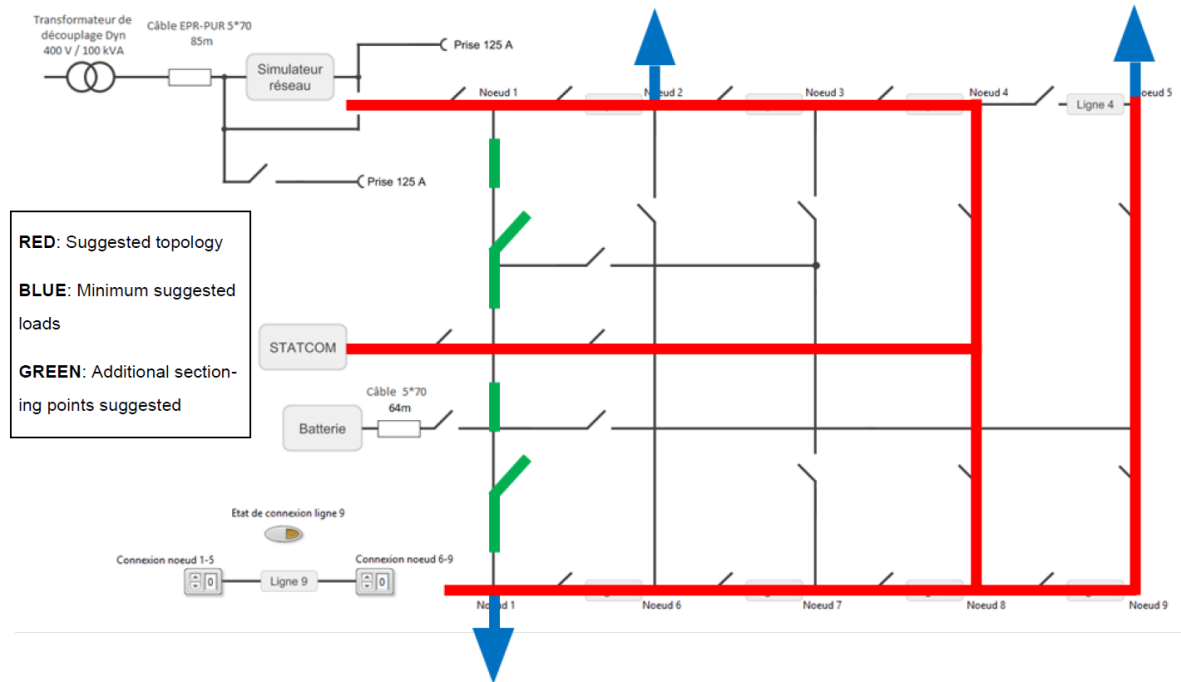


Figure 74: Suggested topology for the tests to be run in the Relne laboratory, taken from [5]

6.5 Benefits of STATOM to the HV network: export of reactive power

This section summarizes the WP3 activities and results of the benefits of adding a STATCOM to the distribution network in order to export reactive power towards the transmission system. Detailed explanations can be found in [5]. Two cases are investigated in A network area, presented in orange in Figure 67:

- (A) case: Exporting from an MV network relatively far from the interconnection point with the 220/380 kV transmission system;
- (B) case: Exporting from within an MV network adjacent to the EHV system.

For this analysis, a reactive power of 10MVar is injected at 5 different locations. The four different injection points in A network area have the following characteristics, and can be seen in Figure 75:

- Hauteville (A): Many substations to A, total cable length of 4.5 km;
- Pavement (B): Many substations to A, total cable length of 5.2 km;
- Romandquart (C): Direct connection with A, cable length of 0.12 km;
- Borello (D): Direct connection with A, cable length of 2.4 km.

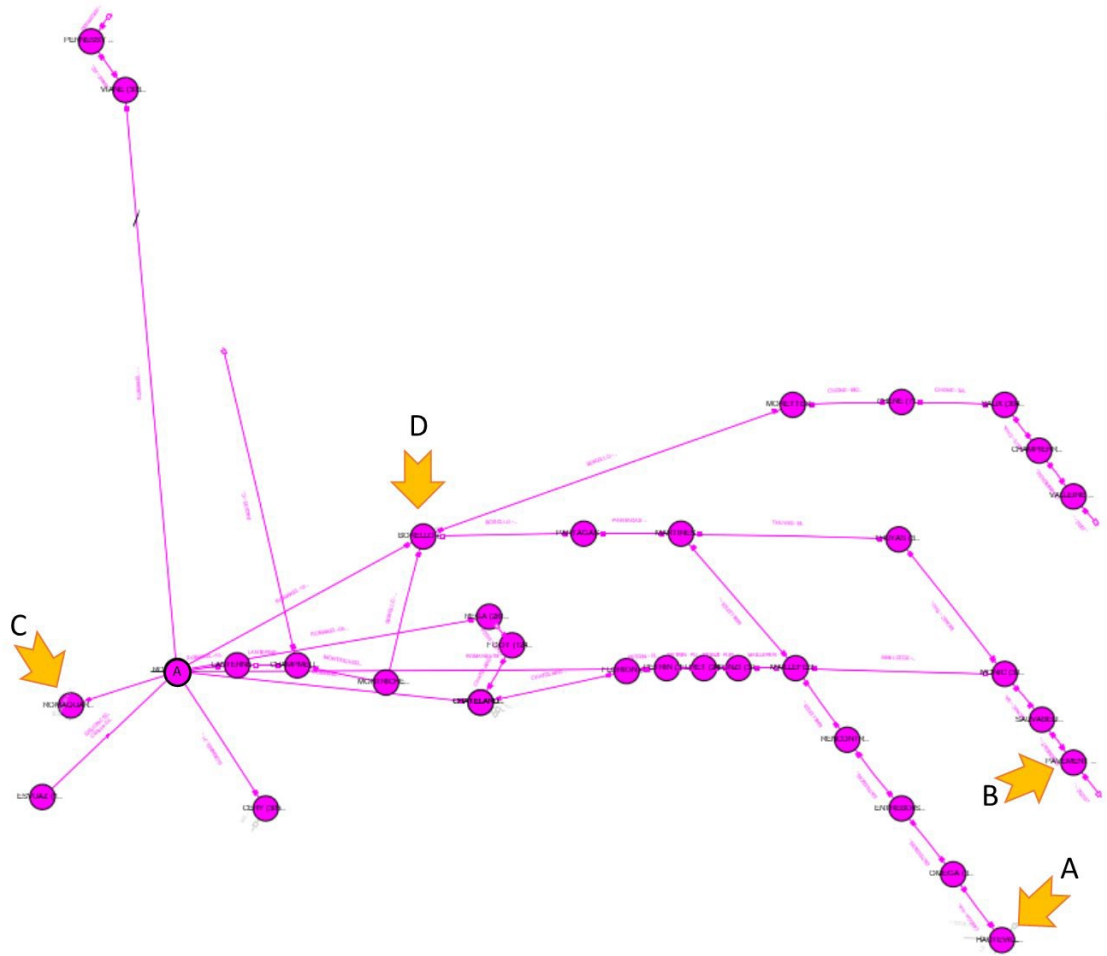


Figure 75: Injections points in A grid, taken from [5]

The objective of these simulations was to assess whether the export of reactive power from the MV system to the HV system was a realistic scenario. Table 23 and Table 24 contain the summary of the effect of the reactive power injection on one of the exchange points (with two transformers) with the 220/380 [kV] system in A grid. The difference between Table 23 and Table 24 is the load situation. In Table 23, the load at B corresponds to a measured load whereas the remainder of the distribution system has no load (no data was available for this and the effort related to integrating the load of B into the model is not negligible). Table 24 shows the situation with no load in the distribution network. The reference corresponds to the situation with no STATCOM installed.



				P ¹ [MW]	Q [MVar]	S [MVA]	Losses [MW]		
REFERENCE				0.44	24.00	24.00	0.0806	Increase of losses [%]	Percentage of Q [%]
Injecting 10MVar into MV	B	-10MVar at B		0.32	27.75	27.75	0.0813	-0.89	37.5
			Δ from ref	0.112	-3.750	-3.748	-0.00072		
	A	-10MVar at HAUTEVILLE (A)		0.08	28.45	28.45	0.0815	-1.07	44.5
			Δ from ref	0.359	-4.45	-4.45	-0.00087		
		-10MVar at ROMAQUARD (C)		0.30	28.61	28.62	0.0815	-1.12	46.2
			Δ from ref	0.1393	-4.62	-4.61	-0.00090		
		-10MVar at BORELLO (D)		0.17	28.53	28.53	0.0815	-1.09	45.3
			Δ from ref	0.263	-4.53	-4.52	-0.00088		
		-10MVar at PAVEMENT (B)		0.04	28.43	28.43	0.0815	-1.07	44.3
			Δ from ref	0.394	4.43	-4.42	-0.00086		
Drawing 10MVar from MV	B	10MVar at B		0.52	19.40	19.40	0.0799	0.93	46.0
			Δ from ref	-0.0799	4.6037	4.6008	0.00075		
	A	10MVar at HAUTEVILLE (A)		0.29	18.06	18.06	0.0797	1.17	59.4
			Δ from ref	0.1505	5.9438	5.9455	0.00094		
		10MVar at ROMAQUARD (C)		0.54	18.27	18.28	0.0797	1.13	57.3
			Δ from ref	-0.1011	5.7300	5.7260	0.00091		
		10MVar at BORELLO (D)		0.40	18.16	18.17	0.0797	1.15	58.4
			Δ from ref	0.0326	5.8376	5.8371	0.00093		
		10MVar at PAVEMENT (B)		0.24	18.02	18.02	0.0797	1.18	59.8
			Δ from ref	0.1985	5.9839	5.9863	0.00095		

Table 23: Different injections points and their influence on HV/MV transformer in A station in 01.10.18 at 10h00, taken from [5].

¹ Positive values correspond to transfers from the HV to the LV side. In the present case, no active load is simulated in the distribution grid outside B. Therefore, and because of other interconnections of the distribution grid with the 125 kV and 220 kV systems, the transformer at A station might see a negative power.



				P [MW]	Q [MVar]	S [MVA]	Losses [MW]		
REFERENCE				1.22	24.25	24.28	0.0807	Increase of losses [%]	Percentage of Q [%]
Injecting 10MVar into MV	B	-10MVar at B	1.11	28.00	28.02	0.0814	1.11	-0.90	37.5
			0.113	-3.745	-3.736	-0.00072	0.113		
	A	-10MVar at HAUTEVILLE	0.86	28.70	28.71	0.0815	0.86	-1.08	44.5
			0.359	-4.45	-4.43	-0.00087	0.359		
		-10MVar at ROMAQUARD	1.08	28.86	28.88	0.0816	1.08	-1.12	46.1
			0.1402	-4.61	-4.60	-0.00091	0.1402		
		-10MVar at BORELLO	0.96	28.77	28.79	0.0815	0.96	-1.10	45.2
			0.264	-4.52	-4.51	-0.00089	0.264		
		-10MVar at PAVEMENT	0.83	28.67	28.69	0.0815	0.83	-1.07	44.2
			0.395	4.42	-4.40	-0.00086	0.395		
Drawing 10MVar from MV	B	10MVar at B	1.30	19.65	19.69	0.0799	1.30	0.94	46.0
			-0.0818	4.5983	4.5859	0.00076	-0.0818		
	A	10MVar at HAUTEVILLE	1.09	19.07	19.10	0.0798	1.09	1.05	51.8
			0.1285	5.1809	5.1804	0.00084	0.1285		
		10MVar at ROMAQUARD	1.34	19.28	19.33	0.0798	1.34	1.01	49.7
			-0.1230	4.9672	4.9511	0.00081	-0.1230		
		10MVar at BORELLO	1.21	19.18	19.21	0.0798	1.21	1.03	50.7
			0.0107	5.0748	5.0674	0.00083	0.0107		
		10MVar at PAVEMENT	1.04	19.03	19.06	0.0798	1.04	1.06	52.2
			0.1765	5.2210	5.2231	0.00085	0.1765		

Table 24: Different injections points and their influence on HV/MV transformer in A station – No loads in B Feeder, taken from [5]

The results show that the particular situation of the 125 [kV] network running in parallel with the 220/380 [kV] system of western Switzerland largely affects the effectiveness of the export from the distribution system towards the transmission system. Almost regardless of the distance between the connection point of the STATCOM and the interconnection point with the transmission system, the effectiveness of the transfer of reactive power is around 50%, which is a low share of the reactive power. The comparison of Table 23 and Table 24 shows that the loading of the distribution system only slightly affects the situation. With even higher loads, the effect of the well-known P-U relation which has the consequence that a network will react with more sensitivity to variations of the injected reactive power if its loading is higher would be expected. In practice, the value of injecting reactive power into the MV network with the objective of adjusting the exchange with the transmission network will depend on the costs and/or remuneration, but the low effectiveness would rather be in favour of connecting a reactive power compensation system to the transmission system directly.

6.6 Future improvements

As previously mentioned, STATCOMs are anticipated to deliver further benefits with respect to the network's dynamic behaviour. With an adequate control, STATCOMs could contribute to reducing flickers and improve post-fault recovery of the voltage. Such simulations however require EMT models of the grid and the power electronic converter. Initial investigations have been carried out with the available data and these have shown that further work is required in order to adequately understand higher frequency phenomena that become relevant in the MV system for such analyses which are beyond the scope of the work presented in this report.



7 WP4: STATCOM prototypes modifications

The existing HEIG-VD modular converter prototypes were set up to fulfil the requirements of the project as STATCOM. The requirements are based on the results of WP1 simulations, WP2 and WP3. More precisely, the prototypes were set up to be the LV representative reduced scale of a full scale MV system, especially concerning topologies, control and hardware.

Being highly technical and consuming a lot of space in the report, only a summary of the technical information is presented in the section. For detailed explanations of the set up, please refer to [6].

In [6], the hardware is firstly presented for both prototypes. It includes a photo of SSBC and DSCC prototypes (also shown in Figure 1), the hardware topology for submodules control using one master card controlling slave control cards (one by submodule). Cabling explanations of both prototypes cabinet are also included in the hardware section of [6].

Second part of [6], is the firmware design realised. The firmware concept is the same for both SSBC and DSCC prototype. The master control card realises the measurements and controls each slave card associated with one submodule. The master is also responsible of the synchronisation of all the slaves. The coding structures used in the firmware as well as the state machine of each control card are also described the second part of [6].

As a remark, this set up was of course realised before realising the DSCC prototype tests presented in section 4 (WP1) and also before Relne laboratory tests presented in section 9 (WP6).



8 WP5: Relne Laboratory setup to represent SIL MV network

Work packages 2 and 3 results (section 5 of this report) show that the complex interlinks between the transmission and sub-transmission systems of western Switzerland are a limit to the effectiveness of exporting reactive power from the distribution to the transmission system. Hence, according to this, the STATCOM is considered only for its local benefits in the MV grid for the reduced scale tests. Based on these considerations, the Relne setup is realised to match with the “B” MV network case study only. “A” MV network is not treated for WP5 and WP6.

The purpose of this section is to explain how to set up the Relne Laboratory to effectively represent the “B” MV network case-study of WP2 and WP3 in a reduced scale in order to test one of the reduced scale STATCOM prototypes in an existing urban network.

8.1 Description of the original MV network

The SIL MV case-study is named “B” as in WP2 and WP3. A topological representation of the “B” MV network is shown in Figure 76. As mentioned in the conclusions of WP3, STATCOM is located in the most interconnected MV/LV substation of “B” network. This one is substation number 23 (in blue in Figure 76).

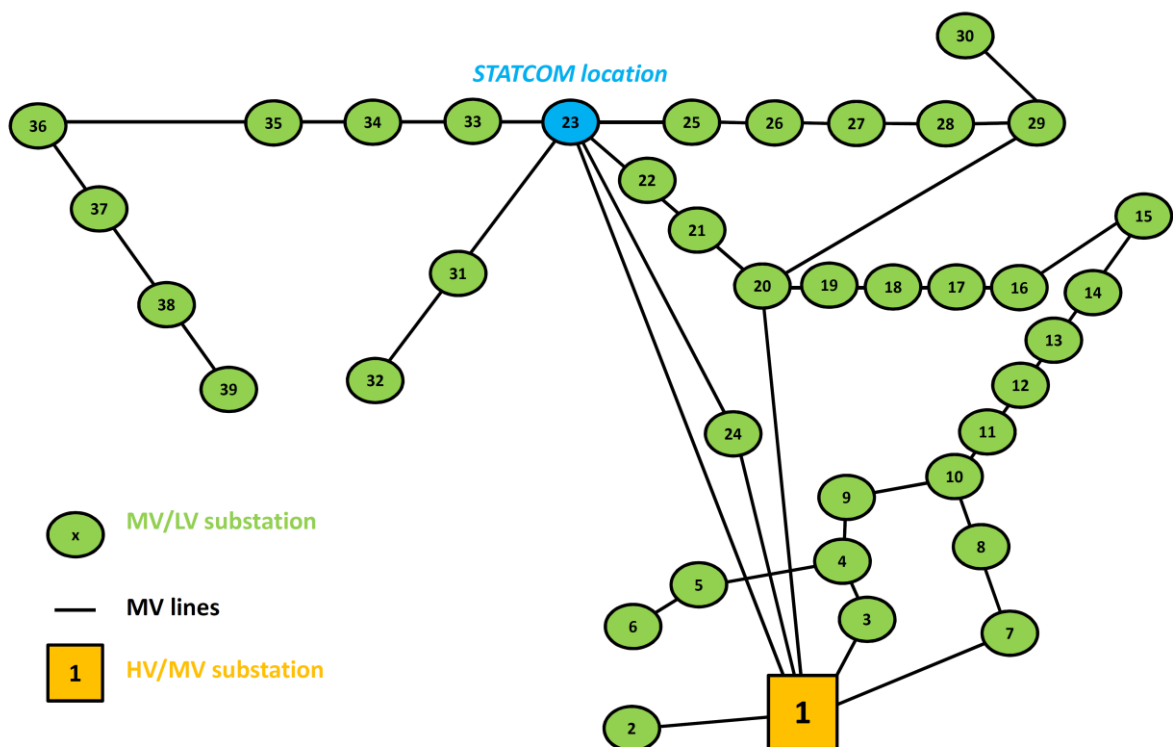


Figure 76: Topological representation of the “B” MV network case-study of SIL

The MV network studied is fed by a HV/MV transformer located in HV/MV substation number 1 (in orange) in Figure 76. The main characteristics of the transformer are given in Table 25.



HV/MV transformer main characteristics	
Rated power	15 MVA
Ratio	53/11.5 kV
Vector group	YN-D

Table 25: HV/MV transformer main characteristics

The rated power of each MV/LV substation (in green in Figure 76) is known but for confidential reason are not provided in the report.

R_1 , C_1 , X_1 (positive sequence components of the line) et R_0 , C_0 , X_0 (homopolar components of the lines) parameters of each MV lines of the “B” network are known but for confidential reason are not provided in the report.

8.2 Base quantities used for “B” MV network and Relne laboratory

The key point to transpose a MV network into another equivalent network with different powers and voltages is to define the per unit bases of each network. These bases are shown in Table 26.

	“B” MV network bases	Relne network bases
$S_{base_{3phases}}$	15 MVA	75 kVA
$U_{base_{LL}}$	11.5 kV	400 V
I_{base}	753 A	108 A
Z_{base}	8.82 Ω	2.13 Ω

Table 26: Base quantities for initial “B” MV Network and for Relne laboratory

The base power and voltage values for “B” MV network is chosen equal to nominal values of the HV/MV transformer. This is a common choice in power systems calculations.

The base power value for Relne network is chosen to 75 kVA. This value is close to the maximum power of the grid simulator (source of the Relne laboratory network) and is a result of the line aggregation technic presented in the following sections. The line-to-line voltage is chosen to 400V because most of the devices (loads and generators) of Relne laboratory work at low voltage. STATCOM prototypes were designed by HEIG-VD teams to work at low voltage.

I_{base} and Z_{base} are then calculated thanks to power and voltage base values.

8.3 Relne technical capabilities

The Relne laboratory is a modular network. Its representation is visible in Figure 77.

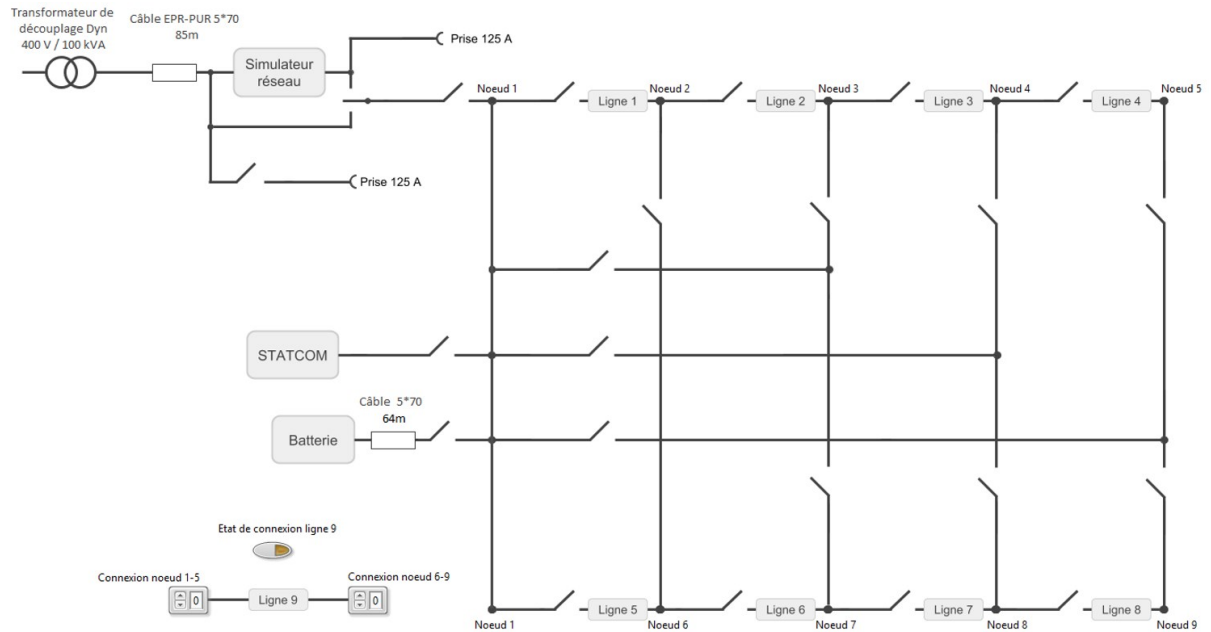


Figure 77: Relne synoptic view of lines and nodes

The network part of the laboratory is made of 8 lines positioned in a matrix and a 9th line that can be connected freely between the node desired. Each line is emulated with discrete impedances. The line equipment available is listed in Table 27.

Type of equipment	Number available
Inductance 100 μH	3
Inductance 200 μH	27
Inductance 400 μH	3
Resistance with variable steps (22, 44, 66, 88, 110, 132, 154, 176, 198 or 220 m Ω)	27

Table 27: Line equipment available in Relne

The configuration of the network to the chosen topology is made via SCADA and is realized in a remote controlled wiring board. This board also enable the users to connect all the different devices to the node chosen, every node being available for a device.

For the tests performed, the source of Relne network is the grid simulator (Programmable Bidirectional AC Power Source). The reference of the device is: "TC.ACS.50.528.4WR.S.LC" from Regatron company.

Table 28 shows the devices available that can be used as load or generator in Relne network. These devices can be placed at every node in the Relne network for 400V applications.



Device reference	P operating range [kW]	Q operating range [kvar]	S max power [kVA]
Electronic Load: « Cinergia EL-AC-20 »	+/-18	+/-18	20
Battery: “Leclanché TiRack”	+/-100	According to P	100
Soft Open Point converter (SOP) designed by HEIG-VD team	+/-10	+/-10	10
Battery: “Eaton”	+/-20 (by 1 kW step)	No reactive power	20

Table 28: List of available devices as load or generators in Relne Laboratory

8.4 Relne set up according to “B” MV network

As it can be seen from previous sections, the “B” MV network is composed of more than 9 lines and nodes. Then a method of aggregation of loads and lines is necessary to effectively set up the Relne laboratory as the “B” MV network. This section explains the method used.

Given that “B” is a distribution network with short transmission lines, the R-L line model is considered. Furthermore, the Relne laboratory tests focus only on balanced network. Then only the positive sequence components R_1 and X_1 of the network are used. The per-phase representation of the lines is given in Figure 78.

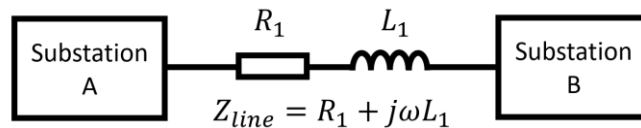
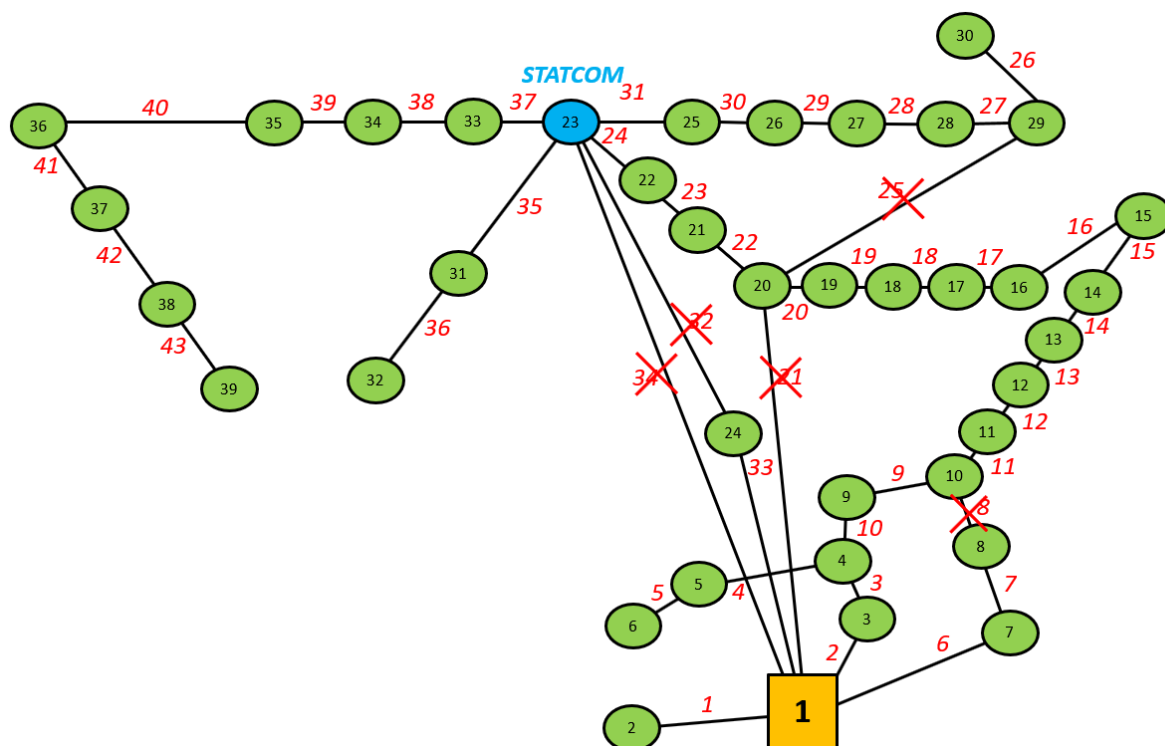
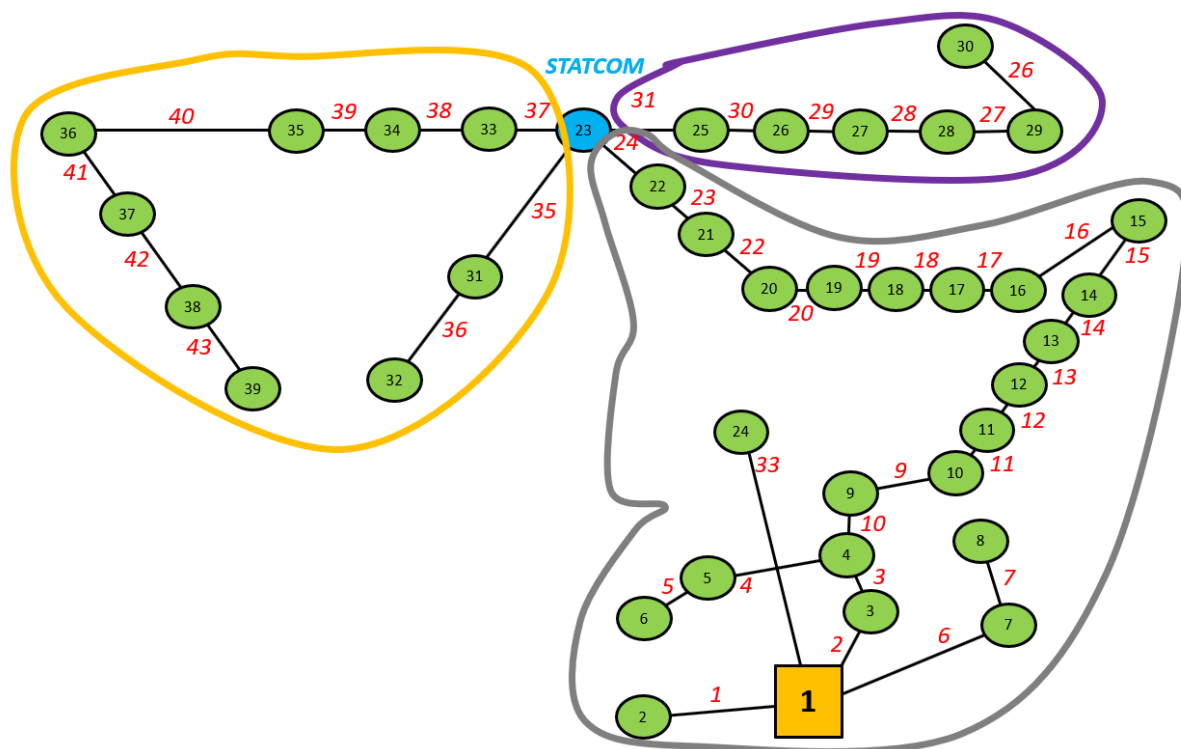


Figure 78: Per-phase representation of the lines

One other point is that the “B” distribution network is exploited in a radial configuration. As a consequence, several lines (8, 21, 25, 32 and 34) are opened in normal operation as it can be seen in Figure 79.



The radial network is then separated into groups of nodes and lines that will be aggregated into equivalent lines and nodes. The groups are circled with different colours in Figure 80. The groups are chosen based on the STATCOM location and the possible nodes/lines configuration of Relne laboratory.



The first aggregation phase consists in aggregation of isolated lines. In grey group lines 1, 6, 7 and 33 and nodes 2, 7, 8 and 24 are aggregated in node 1. The principle of aggregation for these isolated



lines/nodes is the following. The powers (P and Q) of lines and nodes are summed and added as a load on node 1. Mathematically, the new equivalent load of node 1 with these aggregations is given in (7).

$$\begin{aligned}\underline{S}_{1eq} &= P_{1eq} + jQ_{1eq} \\ &= (P_2 + P_{l1} + P_{l6} + P_7 + P_{l7} + P_8 + P_{24} + P_{l33}) \\ &\quad + j(Q_2 + Q_{l1} + Q_{l6} + Q_7 + Q_{l7} + Q_8 + Q_{24} + Q_{l33})\end{aligned}\quad (7)$$

Where:

- P_{1eq} is equivalent active power at node 1
- Q_{1eq} is equivalent reactive power at node 1
- P_x is active power at node x
- Q_x is reactive power at node x
- P_{lx} is active power at line x
- Q_{lx} is reactive power at line x

Then a new representation of the beginning of network from node 1 to node 10 is given in Figure 81.

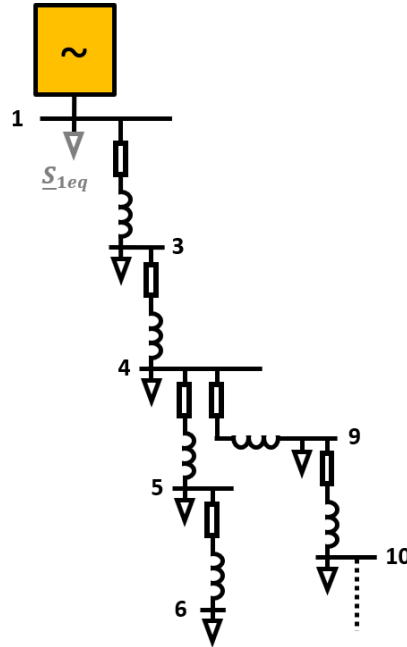


Figure 81: «B» network diagram from node 1 to node 10 with node 1 aggregation

Then the same aggregation principle is realized for isolated lines 4 and 5 as well as nodes 5 and 6. They are aggregated to node 4. Then diagram in Figure 81 becomes the one in Figure 82.

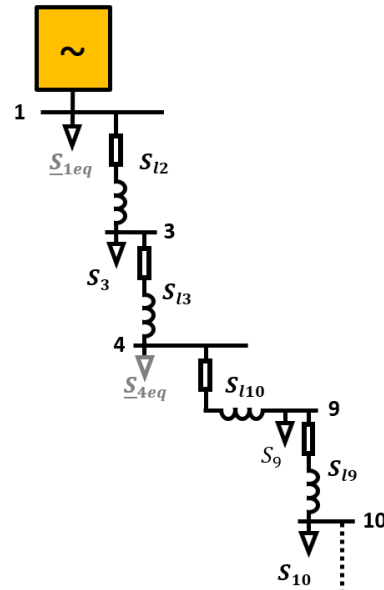


Figure 82 : «B» network diagram from node 1 to node 10 with node 4 aggregation

In orange group, lines 35 and 36 and nodes 31 and 32 are aggregated in node 23 with the same principle as before. The topological representation of the “B” network with isolated lines and nodes aggregated is shown in Figure 83.

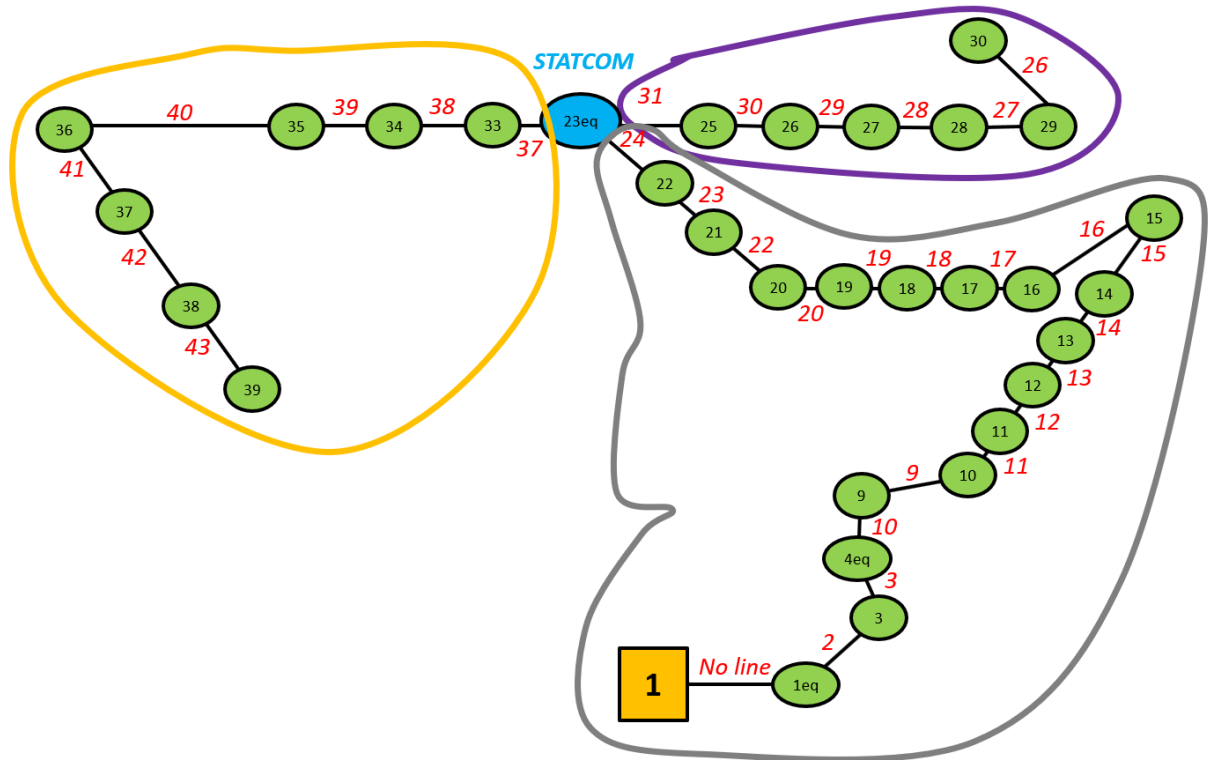


Figure 83: “B” network with isolated lines and nodes aggregated

Now in each group, only the loads of nodes are aggregated together with the same principle as before. Active powers and reactive powers added in the complex domain. For example, the aggregated load of the purple group is given in (8).



$$\begin{aligned}\underline{S}_{purple} &= P_{purple} + jQ_{purple} \\ &= (P_{25} + P_{26} + P_{27} + P_{28} + P_{29} + P_{30}) + j(Q_{25} + Q_{26} + Q_{27} + Q_{28} + Q_{29} + Q_{30})\end{aligned}\quad (8)$$

However at this time, the active and reactive powers of the lines 26 to 31 are not included. Indeed, the lines 26 to 31 information are aggregated with another principle. Resistances R_1 and reactances X_1 of each line are added together to form the aggregated line of the group. For purple group, the aggregated line impedance is given by (9).

$$\begin{aligned}\underline{Z}_{l_{purple}} &= R_{l_{purple}} + jX_{l_{purple}} \\ &= (R_{l_{26}} + R_{l_{27}} + R_{l_{28}} + R_{l_{29}} + R_{l_{30}} + R_{l_{31}}) + j(X_{l_{26}} + X_{l_{27}} + X_{l_{28}} + X_{l_{29}} + X_{l_{30}} + X_{l_{31}})\end{aligned}\quad (9)$$

Where:

- R_{l_x} is resistance of line x
- $X_{l_x} = 2\pi f L_x$ is reactance of line x
- L_x is the inductance of line x
- f is the frequency of the network (50Hz in our case)

Then the “B” network becomes as in Figure 84.

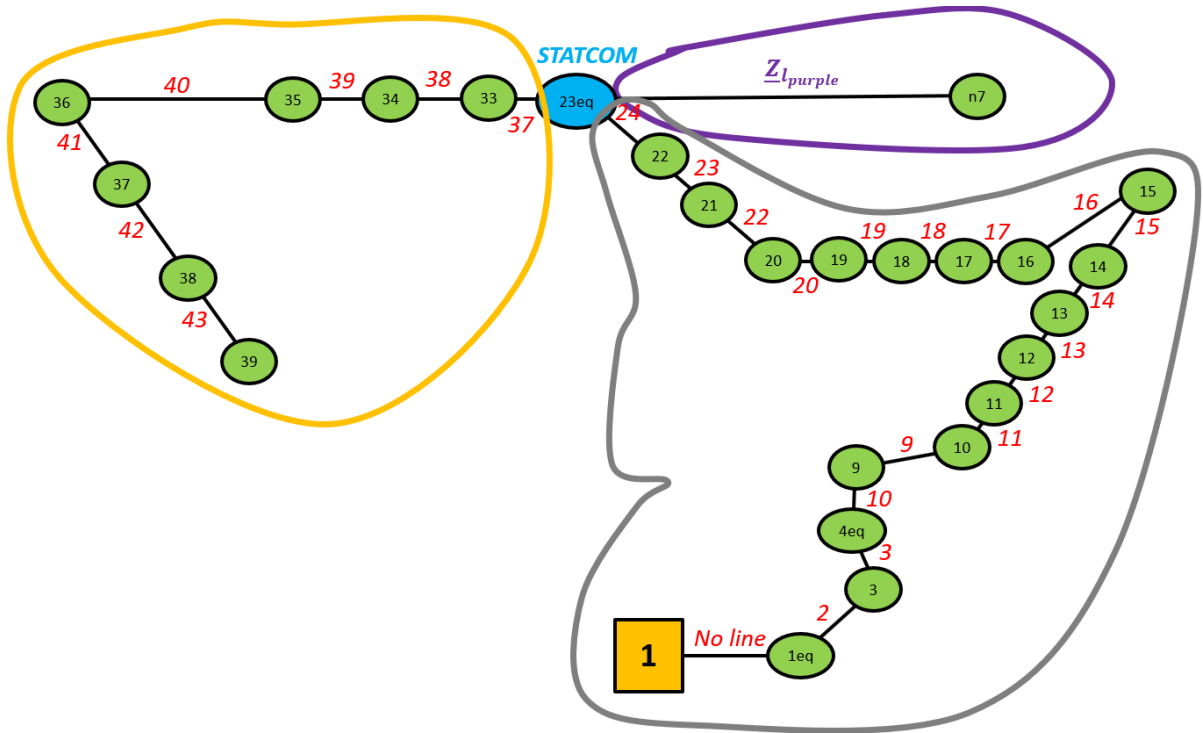


Figure 84: “B” network with purple group aggregated

We repeat the process for nodes and lines of orange group. For the grey group, the same principle is used but to avoid a huge load in one node, the load of nodes is split in two. One aggregation goes to node 1 and the other one goes to node 23. Finally, once all that aggregations are realised, the final “B” aggregated diagram obtained is shown in Figure 85.

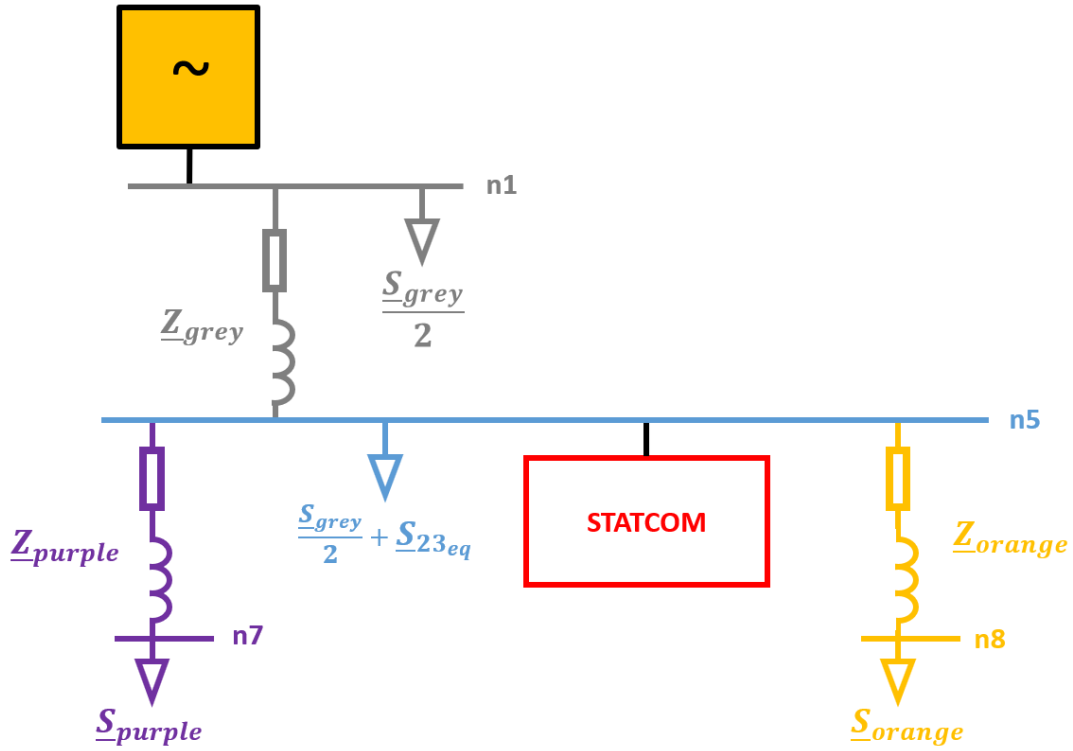


Figure 85: Final “B” aggregated diagram

The final aggregation of “B” network is composed of the aggregated lines and load in the “B” MV network base power. To set up the Relne laboratory, a change of the base power is mandatory.

To do this, lines aggregated impedances are divided by Z_{base} to obtain their value in per unit. It means these values are a percentage of the base value of the network. The per-phase line impedances of the “B” aggregated network in per unit are given in Table 29.

Line name	R_1 [pu]	X_1 [pu]	$\frac{R_1}{X_1}$ [pu]
Grey	0.2357	0.1767	1.33
Purple	0.0633	0.0508	1.25
Orange	0.0560	0.0501	1.12

Table 29: Per-phase line impedances of the “B” aggregated network in per unit

The same principle is used for the aggregated loads. Active (P) and reactive (Q) powers are divided by S_{base} leading to their per unit value. The load powers (P and Q) depend on the test scenario. The values are given in the corresponding section 9 for each test.

We now have “B” aggregated network in per unit which is the model the Relne laboratory has to reach. The goal is then to set up the lines of Relne laboratory to match with the “B” reference network in per unit. To do so, we need to choose the right base power for the Relne laboratory to ensure that the per unit model of Relne laboratory is the same as the one of “B” aggregated MV network.

The choice of Relne base power is realised considering the maximum source of power of Relne and the available the lines equipment available (see Table 27) in Relne.

The base power cannot be much higher than the grid simulator power which is the source of Relne network in our case. Indeed, the source of a network has to be able to provide the amount of power asked by the network even in case the network load is high. In our case study, the total load measurements of the “B” MV studied in WP2 and WP3 shown that the maximum load reached by the



HV/MV transformer is 0.45 pu. It means the base power for Relne laboratory cannot be more than 1.5 times the grid simulator nominal power to keep a margin.

The base power calculation in our case is mainly influenced by lines equipment available in Relne. Indeed, as it can be seen in Table 27, only one line (a set of 3 inductances = one by phase) can be set to 100 μH and one line can be set to 400 μH . The others are mandatorily 200 μH . As a consequence, there is quite low flexibility in the choice of X_1 . For the best matching of X_1 values, the Relne base power has to be maximum. In our case, the higher is 75 kVA. Once this power is defined, we can easily calculate line parameters of “B” aggregated lines in the Relne base. They are shown in Table 30.

Line name	R_1 [mOhms]	L_1 [μH]	$\frac{R_1}{X_1}$ [pu]
Grey	503	1200	1.33
Purple	135	345	1.25
Orange	119	340	1.12

Table 30: Per-phase line parameters of the “B” aggregated network in Relne base

Knowing the R_1 and L_1 values of the per-phase aggregated branches, the idea is to select which combination of Relne lines will fit the most. The best distribution of lines is given via the final Relne setup diagram shown in Figure 86.

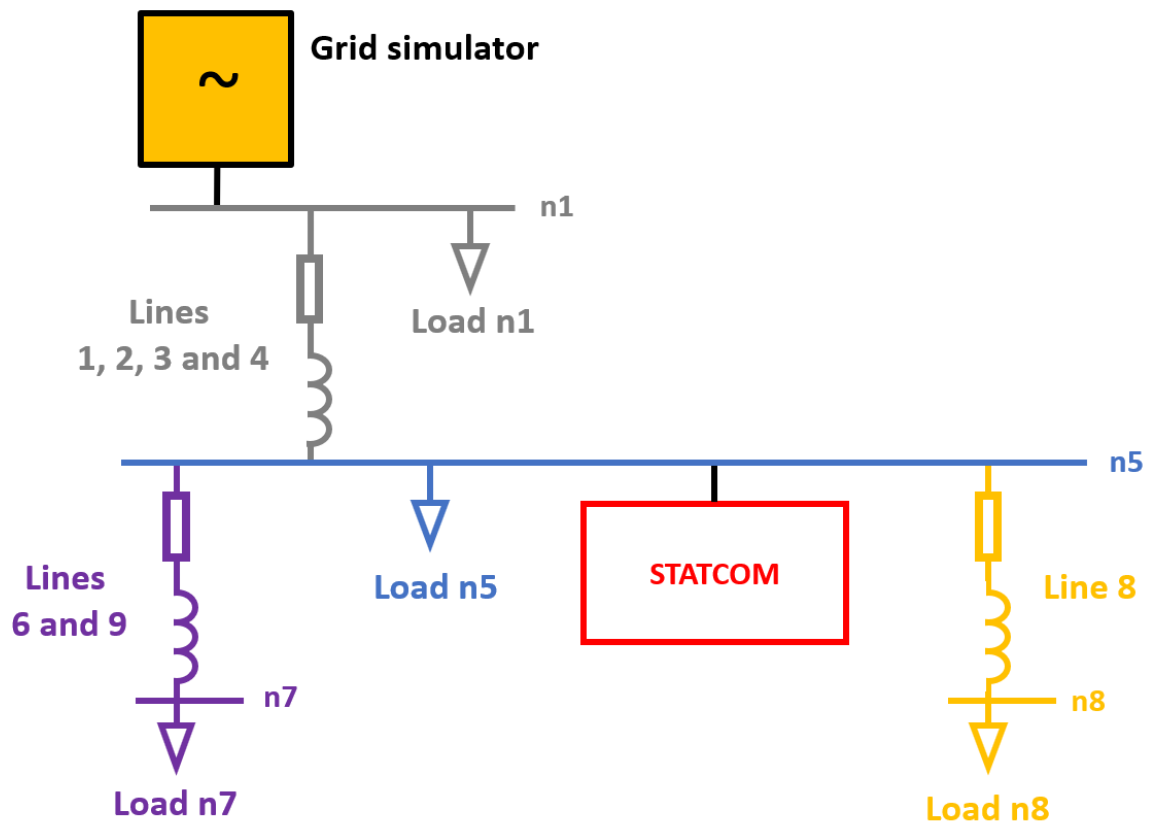


Figure 86: Final Relne setup diagram

It can be seen that grey aggregated line corresponds to 4 lines in series (line 1, 2, 3 and 4 of Relne). Purple aggregated line corresponds to lines 6 and 9 of Relne in series. Finally, orange aggregated line corresponds to line 8 in Relne. The per-phase line parameters of the Relne network setup are given in Table 31.



Line name	R_1 [mOhms]	L_1 [μH]	$\frac{R_1}{X_1}$ [pu]
Line 1	88	200	1.40
Line 2	88	200	1.40
Line 3	154	400	1.23
Line 4	88	200	1.40
Line 6	88	200	1.40
Line 8	66	200	1.05
Line 9	66	200	1.05

Table 31: Per-phase line parameters of the Relne network setup

To validate the proposed Relne setup, it is compared to “B” MV network. Table 32 gives the final Relne setup parameters in pu.

Line name	R_1 [pu]	X_1 [pu]	Maximum relative deviation of R_1 and X_1 with Table 29 [%]	$\frac{R_1}{X_1}$ [pu]
Grey	0.1959	0.1473	16.9	1.33
Purple	0.0722	0.0589	15.9	1.23
Orange	0.0309	0.0295	44.5	1.05

Table 32: Per-phase aggregated line impedances of Relne network setup in per-unit

It can be seen that the relative deviations for R_1 , X_1 and $\frac{R_1}{X_1}$ are globally small enough to validate the setup.

As a conclusion, the Relne setup proposed in Figure 86 with values of lines given in Table 31 represent the “B” MV network with a good accuracy. This setup is the one used for the tests performed in WP6 (see section 9).



9 WP6: Relne laboratory tests with STATCOM in SIL MV grid configuration

The goal of this work package 6 is to show experimental results of the benefits of a STATCOM integrated in an existing network setup.

The DSCC prototype is tested into Relne set up proposed in section 8 (WP5). As a remainder, this set up corresponds to an existing portion of the SIL MV network. So, the STATCOM prototype is tested with an existing network configuration.

The effect of the STATCOM on the network performance mainly depends on the specific control to be applied. WP2 and WP3 proposed 3 control strategies implementable in a real prototype. The control chosen is the one which controls the busbar at which the STATCOM is installed to 1 pu. This control is chosen because it is the easiest one to implement on the field by DSOs. Indeed, this control do not need any additional hardware and software other than the STATCOM itself. For other control strategies proposed, measurements are realised far from STATCOM location and need additional devices to communicate this information. Furthermore, an additional processing unit is necessary to calculate the setpoint of the STATCOM based on the measurements.

To summarise, the DSCC prototype is tested in the Relne set up proposed in Figure 86 with values of lines given in Table 31. The STATCOM control strategy regulates the busbar at which the STATCOM is installed to 1 pu. The benefits of the STATCOM are tested under 3 different scenarios based on the MV network simulations realised in WP2 and WP3. These scenarios and the corresponding results are presented in section 9.1, 9.2 and 9.3.

In these tests, STATCOM nominal reactive power that can be exchanged with the network is of 0.066pu.

9.1 Scenario 1: Underloaded MV network (summer scenario)

9.1.1 Load allocation without STATCOM

Firstly, we need to define the load allocation inside the network. In this first scenario, the total load value of the network is based on the 2019 measurements of the HV/MV transformer feeding the “B” MV network. This scenario 1 is more specifically based on the lowest possible daily load measured. The lowest daily active power load value equals 0.083 pu on average for 24h. It corresponds to a day in summer.

Unfortunately, the load at each MV/LV substation is not recorded directly in DSO database. Then in the original “B” MV network, we decided to allocate the loads via the following process. We know the MV/LV substation nominal apparent power. We decided to evenly share the HV/MV transformer load based on the nominal power of MV/LV substations. Furthermore, the typical power factor of MV/LV substation is generally of 0.9. Then based on these considerations, it is possible to list the active and reactive power of each MV/LV substation for scenario 1. To lighten the report, this list is provided in Table 39 in appendix 16.10.

The aggregation of the loads is made according to section 8.4 principle. We get the load allocation without STATCOM for the “B” network aggregated. For the practical test, there are some limitations due to devices used to emulate the loads in Relne. List of devices and their operating range are given in Table 28. Notably, Eaton battery cannot exchange reactive power and its active power changes by steps of 1 kW. It means that the power factor of node 5 is not the same as the “B” network aggregated calculation. However, the value of power at this node is very low compared to other nodes meaning there is no important change compared to initial calculations. Considering all these points, the practical load allocation for each node used for the scenario 1 test is given in Table 33. In this table, a positive active power means active power is absorbed at the node (load operation). For reactive power, a positive reactive power means the load is absorbing reactive power (inductive operation).



Node name according to Figure 86	Active power (P) [pu]	Reactive power (Q) [pu]	Apparent power (S)
n1: Leclanché battery	0.050	0.029	0.058
n5: Eaton battery	0.014	0 (Eaton battery cannot exchange reactive power)	0.014
n7: SOP	0.009	0.002	0.009
n8: Cinergia electronic load	0.018	0.009	0.020
Overall loads in the network	0.091	0.040	0.100

Table 33: Three-phase load allocation without STATCOM in Relne laboratory for scenario 1

9.1.2 Test protocol

The test is divided in two steps. The first step is to maintain for nearly 2 minutes the three-phase load allocation without STATCOM presented in Table 33. After 2 minutes, the STATCOM starts to exchange reactive power with the goal to regulate the node 5 voltage to 1 per unit. In this test, STATCOM delivers its maximum capacitive reactive power according to the control strategy calculation. After some minutes, all loads are disconnected from the grid and the grid simulator is stopped. This marks the end of the test for scenario 1. During all the test long, the currents, voltages and powers (P and Q) are measured for each node and line with a sampling time of 0.2 seconds. All measurements are saved at the end of the test in ".txt" format. Matlab is finally used to exploit the data.

9.1.3 Analyse of STATCOM benefits in case of underloaded network

As for WP2 and WP3 simulations, three performance indices are defined to quantify the benefits of the STATCOM in the network during the test. The three performance indices used in the WP6 to analyse the Relne test results are the following:

- Voltage deviation index: Maximum voltage difference compared to nominal voltage in the network. The less the index is, the better the network behaves.
- Transformer loading index: Apparent power of the grid simulator. It is the apparent power the HV/MV transformer would have in the "B" MV network. The less the index is, the better the network behaves.
- Line loading index: The average of currents in all lines. The less the index is, the better the network behaves.

These performance indices calculated with and without STATCOM are shown in Table 34. For the same index, the comparison is made with and without STATCOM to analyse the benefits of the STATCOM for the network in scenario 1. In this test, STATCOM is exchanging its nominal capacitive reactive power: - 0.066pu.

Performance index	Without STATCOM [pu]	With STATCOM [pu]	Deviation from initial case [pu]
Voltage deviation	$ 0.983-1 = 0.017$	$ 0.996-1 = 0.004$	-0.013
Transformer loading	0.102	0.098	-0.004
Line loading	0.030	0.046	+0.016

Table 34: Performance indices with and without STATCOM for scenario 1

From Table 34, it can be seen that the maximum voltage deviation from 1 pu is decreased with STATCOM exchanging reactive power. Figure 87 shows even more. It can be seen that voltage of each node is increased closer to 1 pu. This is an important consideration because these nodes represent



MV/LV substation in reality. If the MV side is far from 1 pu, the BT side is also far from 1pu and could lead to inappropriate voltage for the consumers. Another remark is that, the grid simulator (n1 on the figure) is less affected than downstream nodes because its internal control aims to keep the generated voltage close to 1pu. It does not absorb reactive power as a transformer which would probably be more affected by voltage variation.

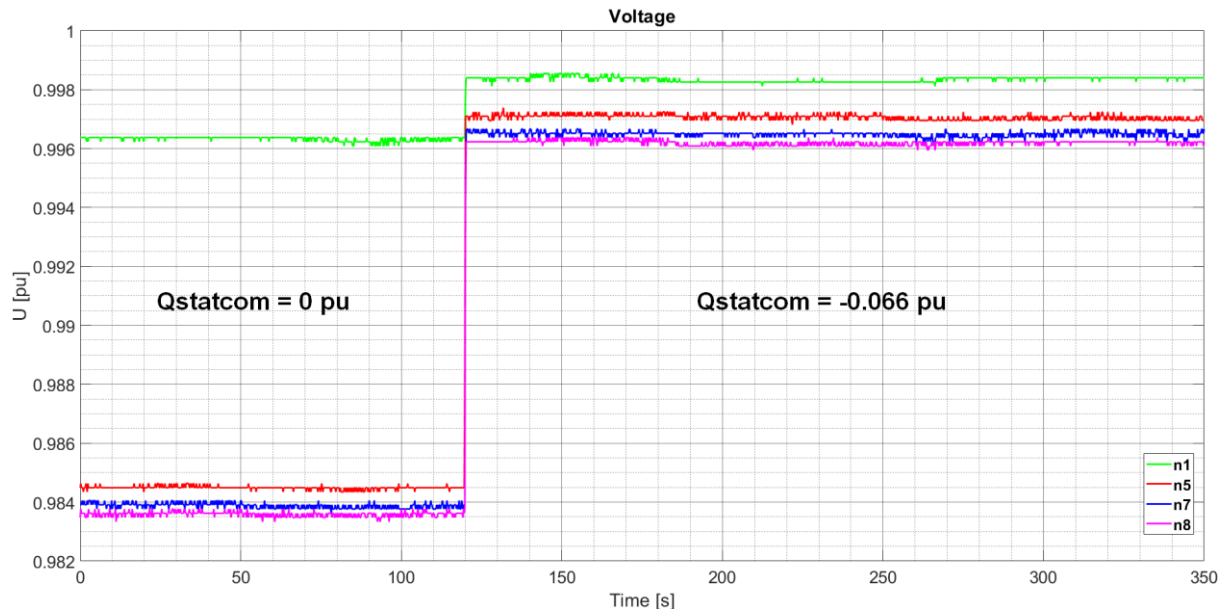


Figure 87: Voltages of all the nodes without and with STATCOM for scenario 1

Another remark is that 1 pu nominal voltage at node 5 (n5 in the figure) is not reached because STATCOM nominal power is not high enough. To reach 1 pu in this case, STATCOM nominal power has to be increased.

From Table 34, it can be seen that apparent power of the grid simulator is decreasing which is beneficial. Indeed, the HV/MV substation is less loaded meaning less stress on the equipment and so a longer lifetime of the equipment.

However, the line loading in average is higher in the network with STATCOM. This is one drawback of the control strategy used for the STATCOM. Even if line currents downstream of the STATCOM (lines 6, 8 and 9) see their current decreasing, lines upstream (1, 2, 3 and 4) see their current increasing higher than the one downstream. This overall current increase leads to more overall losses in the network which is not desired. So, DSO has to consider this when designing the control strategy of the STATCOM.

Figure 88 shows the active and reactive power exchanged from the upstream network. In our case, this is the powers delivered by the grid simulator. In scenario 1, upstream network (grid simulator) is injecting active power into the Relne network for both case with and without STATCOM. As mentioned before, due to more line losses and STATCOM losses, active power is increased when the STATCOM operates. However, the inductive reactive power without STATCOM becomes capacitive with STATCOM. With STATCOM operation, the reactive power amplitude is also highly decreased compared to active power increase. This is the reason why overall apparent power of the network is decreased with STATCOM operation, which is beneficial.

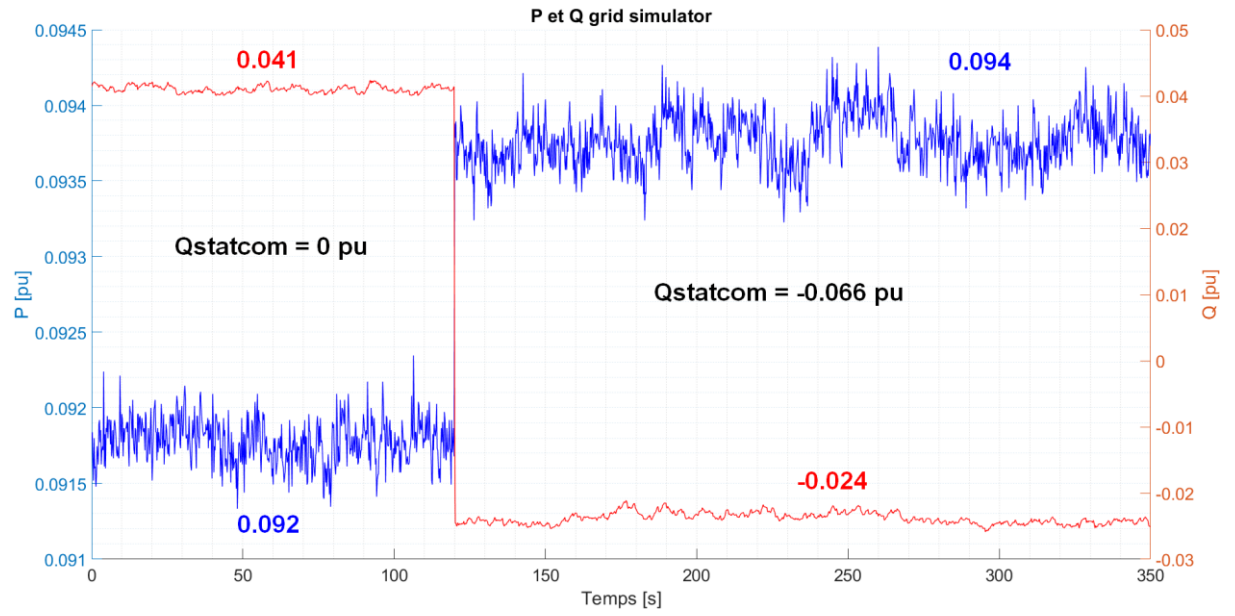


Figure 88: Active and reactive power exchanged from the upstream network for scenario 1



9.2 Scenario 2: high loading of the MV network (winter scenario)

9.2.1 Load allocation without STATCOM

Firstly, we need to define the load allocation inside the network. In this second scenario, the total load value of the network is based on the 2019 measurements of the HV/MV transformer feeding the “B” MV network. This scenario 2 is more specifically based on the highest possible daily load measured. The highest daily active power load value equals 0.367 pu on average for 24h. It corresponds to a day in summer.

Unfortunately, the load at each MV/LV substation is not recorded directly in DSO database. Then in the original “B” MV network, we decided to allocate the loads via the following process. We know the MV/LV substation nominal apparent power. We decided to evenly share the HV/MV transformer load based on the nominal power of MV/LV substations. Furthermore, the typical power factor of MV/LV substation is generally of 0.9. Then based on these considerations, it is possible to list the active and reactive power of each MV/LV substation for scenario 2. This list is not given in Table 40 in appendix 16.11.

The aggregation of the loads is made according to section 8.4 principle. We get the load allocation without STATCOM for the “B” network aggregated. For the practical test, there are some limitations due to devices used to emulate the loads in Relne. List of available devices and their operating range are given in Table 28. Notably, Eaton battery cannot exchange reactive power and its active power changes by steps of 1 kW. It means that the power factor of node 5 is not the same as the “B” network aggregated calculation. However, the value of power at this node is low compared to other nodes meaning there is no important change compared to initial calculations. Considering all these points, the practical load allocation for each node used for the scenario 2 test is given in Table 35. In this table, a positive active power means active power is absorbed at the node (load operation). For reactive power, a positive reactive power means the load is absorbing reactive power (inductive operation).

Node name according to Figure 86	Active power (P) [pu]	Reactive power (Q) [pu]	Apparent power (S)
n1: Leclanché battery	0.217	0.1	0.239
n5: Eaton battery	0.040	0 (Eaton battery cannot exchange reactive power)	0.040
n7: SOP	0.037	0.017	0.041
n8: Cinergia electronic load	0.072	0.037	0.081
Overall loads in the network	0.366	0.154	0.397

Table 35: Three-phase load allocation without STATCOM in Relne laboratory for scenario 2

9.2.2 Test protocol

The test is divided in two steps. The first step is to maintain for nearly 2 minutes the three-phase load allocation without STATCOM presented in Table 35. After 2 minutes, the STATCOM starts to exchange reactive power with the goal to regulate the node 5 voltage to 1 per unit. In this test, STATCOM delivers its maximum capacitive reactive power according to the control strategy calculation. After some minutes, all loads are disconnected from the grid and the grid simulator is stopped. This marks the end of the test for scenario 2. During all the test long, the currents, voltages and powers (P and Q) are measured for each node and line with a sampling time of 0.2 seconds. All measurements are saved at the end of the test in “.txt” format. Matlab is finally used to exploit the data.

9.2.3 Analyse of STATCOM benefits in case of high loading of network

The same three performance indices used for scenario 1 calculated with and without STATCOM are shown in Table 36. For the same index, the comparison is made with and without STATCOM to analyse



the benefits of the STATCOM for the network in scenario 2. In this test, STATCOM is exchanging its nominal capacitive reactive power: - 0.066pu.

Performance index	Without STATCOM [pu]	With STATCOM [pu]	Deviation from initial case [pu]
Voltage deviation	$ 0.936-1 = 0.064$	$ 0.950-1 = 0.050$	-0.014
Transformer loading	0.405	0.384	-0.021
Line loading	0.120	0.114	-0.006

Table 36: Performance indices with and without STATCOM for scenario 2

From Table 36, it can be seen that the maximum voltage deviation from 1 pu is decreased with STATCOM exchanging reactive power. Figure 89 shows even more. It can be seen that voltage of each node is increased closer to 1 pu. This is an important consideration because these nodes represent MV/LV substation in reality. If the MV side is far from 1 pu, the BT side is also far from 1pu and could lead to inappropriate voltage for the consumers. Another remark is that, the grid simulator (n1 on the figure) is less affected than downstream nodes because its internal control aims to keep the generated voltage close to 1pu. It does not absorb reactive power as a transformer which would probably be more affected by voltage variation. As a remark, it can be seen that the maximum voltage deviation in 2019 is 0.064 which is still in the 10% deviation limit given by the grid codes.

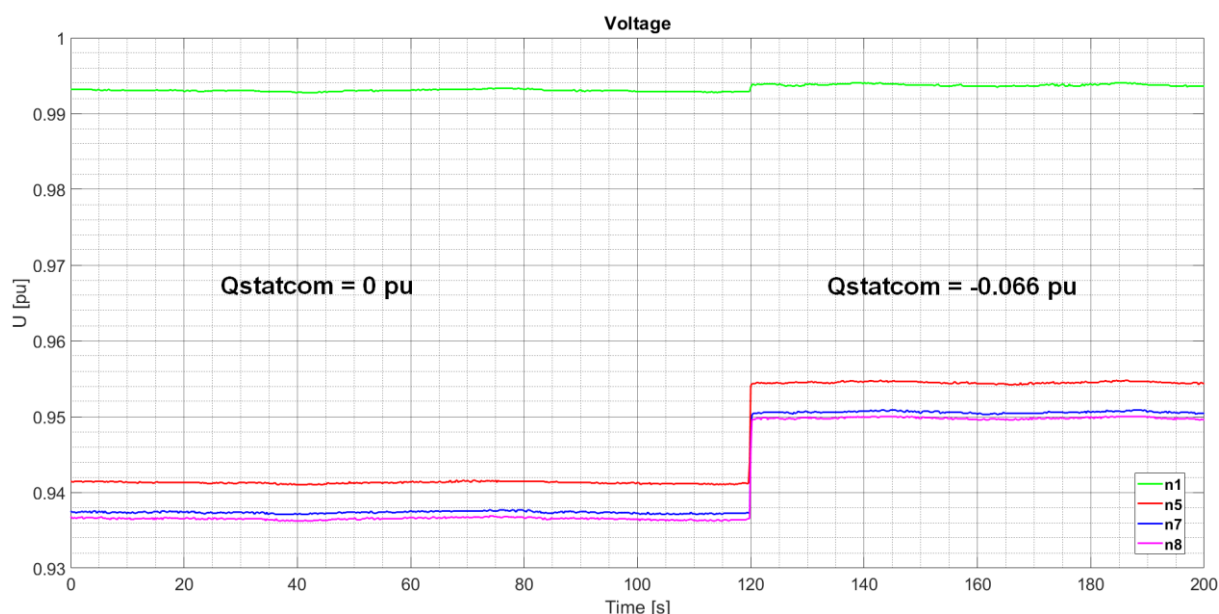


Figure 89: Voltages of all the nodes without and with STATCOM for scenario 2

Another remark is that 1 pu nominal voltage at node 5 (n5 in the figure) is not reached because STATCOM nominal power is not high enough. To reach 1 pu in this case, STATCOM nominal power has to be greatly increased.

From Table 36, it can be seen that apparent power of the grid simulator is decreasing which is beneficial. Indeed, the HV/MV substation is less loaded meaning less stress on the equipment and so a longer lifetime of the equipment. It is interesting to see that the overall apparent power reduction is almost 6 times higher than in scenario 1 (underloaded network).

Furthermore, the line loading in average is lower in the network with STATCOM. All the line currents are decreased when STATCOM operates. STATCOM decreases the line loading allowing to pass more active power through the lines.

Figure 90 shows the active and reactive power exchanged from the upstream network. In our case, this is the powers delivered by the grid simulator. In scenario 2, upstream network (grid simulator) is injecting the same active power into the Relne network for both case with and without STATCOM. STATCOM



decreases the inductive reactive power amplitude of the network via capacitive power injection but do not compensate it totally in this case. These are the reason why overall apparent power of the network is significantly decreased with STATCOM operation, which is beneficial.

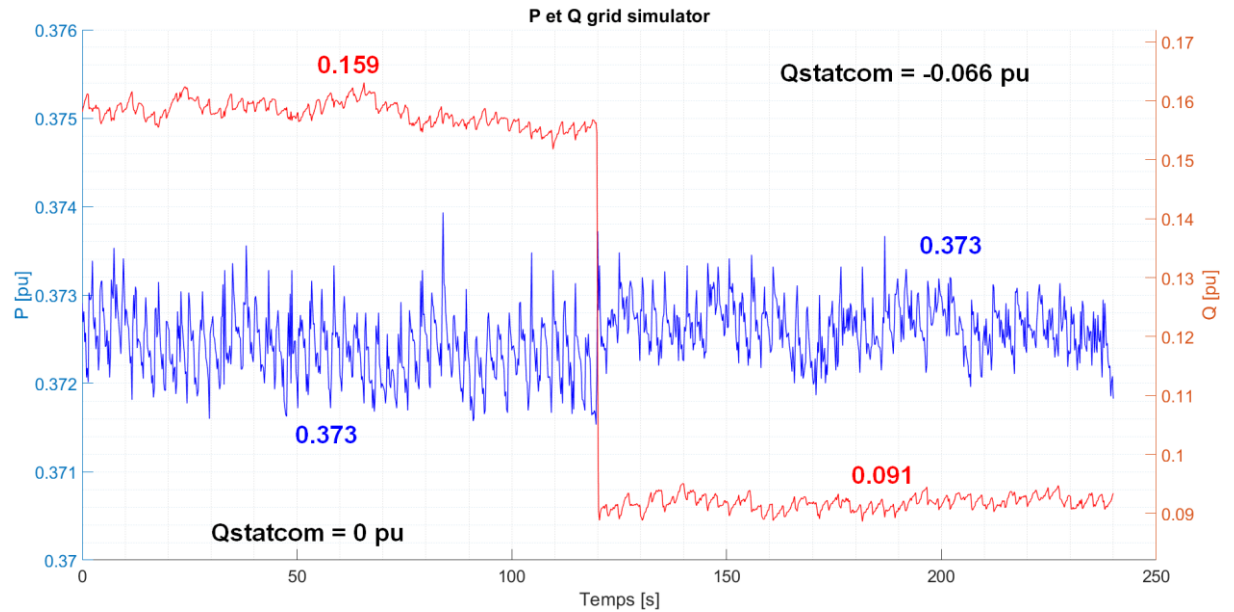


Figure 90: Active and reactive power exchanged from the upstream network for scenario 2



9.3 Scenario 3: high PV production in MV (2040 forecast summer scenario)

9.3.1 Load allocation without STATCOM

The idea of scenario 3 is to show the benefits of the STATCOM when the PV production becomes higher than the network overall load.

Firstly, we need to define the load allocation inside the network. This third scenario correspond to a forecast scenario in summer 2040. It is assumed that the overall load of the network is the same as the underloaded scenario 1 (measurements of 2019) given that no detailed load forecasting was realised in the project. The load allocation in “B” network is the same as scenario 1. So the list is given in Table 39 appendix 16.10.

In WP2 [5], “B” network PV production forecast until 2050 was realised based on the swiss energy perspectives 2050+. This forecast scenario expects 0.313 pu of PV power installed in the “B” network for 2040. Considering this, we can assume that the maximum power injected from PV to the MV network is around 80% of the PV power installed. Then the maximum PV production in 2040 in “B” network is 0.250 pu. We decided to allocate all PV production in node 8 of Relne. We also consider the PV inverter injects pure active power in the grid.

The aggregation of the loads is made according to section 8.4 principle. We get the same load allocation as in scenario 1. However, we also add the 0.250 pu PV production to node 8. Considering all these points, the practical load allocation for each node used for the scenario 3 test without STATCOM is given in Table 37. In this table, a positive active power means active power is absorbed at the node (load operation). For reactive power, a positive reactive power means the load is absorbing reactive power (inductive operation).

Node name according to Figure 86	Active power (P) [pu]	Reactive power (Q) [pu]	Apparent power (S)
n1: Leclanché battery	0.050	0.029	0.058
n5: Eaton battery	0.014	0 (Eaton battery cannot exchange reactive power)	0.014
n7: SOP	0.009	0.002	0.009
n8: Cinergia electronic load	0.018-0.250 = -0.232	0.009	0.232
Overall loads in the network	-0.159	0.040	0.164

Table 37: Three-phase load/production allocation without STATCOM in Relne laboratory for scenario 3

9.3.2 Test protocol

The test is divided in two steps. The first step is to maintain for nearly 2 minutes the three-phase load allocation without STATCOM presented in Table 37. After 2 minutes, the STATCOM starts to exchange reactive power with the goal to regulate the node 5 voltage to 1 per unit. In this test, STATCOM delivers its maximum inductive reactive power according to the control strategy calculation. After some minutes, all loads are disconnected from the grid and the grid simulator is stopped. This marks the end of the test for scenario 3. During all the test long, the currents, voltages and powers (P and Q) are measured for each node and line with a sampling time of 0.2 seconds. All measurements are saved at the end of the test in “.txt” format. Matlab is finally used to exploit the data.

9.3.3 Analyse of STATCOM benefits in case of high PV production in the network

The same three performance indices used for scenario 1 and 2 calculated with and without STATCOM are shown in Table 38. For the same index, the comparison is made with and without STATCOM to



analyse the benefits of the STATCOM for the network in scenario 3. In this test, STATCOM is exchanging its nominal inductive reactive power: +0.066pu.

Performance index	Without STATCOM [pu]	With STATCOM [pu]	Deviation from initial case [pu]
Voltage deviation	$ 1.066-1 = 0.066$	$ 1.052-1 = 0.052$	-0.014
Transformer loading	0.158	0.185	-0.027
Line loading	0.149	0.157	+0.008

Table 38: Performance indices with and without STATCOM for scenario 3

From Table 38, it can be seen that the maximum voltage deviation from 1 pu is decreased with STATCOM exchanging reactive power. Figure 91 shows even more. It can be seen that voltage of each node is decreased closer to 1 pu. This is an important consideration because these nodes represent MV/LV substation in reality. If the MV side is far from 1 pu, the BT side is also far from 1pu and could lead to inappropriate voltage for the consumers. Another remark is that, the grid simulator (n1 on the figure) is less affected than downstream nodes because its internal control aims to keep the generated voltage close to 1pu. It does not absorb reactive power as a transformer which would probably be more affected by voltage variation. As a remark, it can be seen that the maximum voltage deviation in case of important PV production at the end of the network keep voltage inside the 10% deviation limit given by the grid codes even without STATCOM.

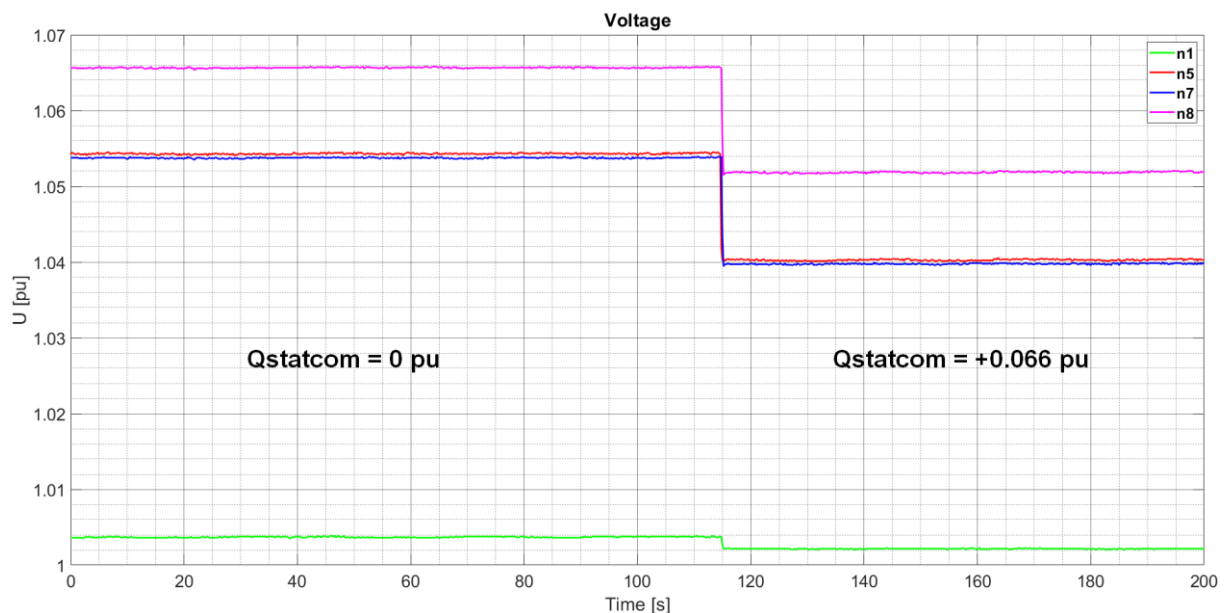


Figure 91: Voltages of all the nodes without and with STATCOM for scenario 3

Another remark is that 1 pu nominal voltage at node 5 (n5 in the figure) is not reached because STATCOM nominal power is not high enough. To reach 1 pu in this case, STATCOM nominal power has to be greatly increased.

From Table 38, it can be seen that apparent power of the grid simulator is increasing. It means the HV/MV substation is more loaded with the STATCOM operation. In case of PV production, STATCOM has to inject inductive reactive power with the grid to lower the voltage. But it increases the already reactive power of the network leading to apparent power increase.

Line loading in average is also higher in the network with STATCOM. All the line currents are increased when STATCOM operates. As a consequence, losses of the network are increased and lines are more loaded.

Figure 92 shows the active and reactive power exchanged to the upstream network. In our case, this is the powers absorbed by the grid simulator. In scenario 3, upstream network (grid simulator) is absorbing



less active power when STATCOM operates due to losses decrease in the network (which is beneficial). But STATCOM highly increases also the inductive reactive power amplitude of the network via inductive power injection. This is why overall apparent power of the network is significantly increased with STATCOM operation which is unwanted in general.

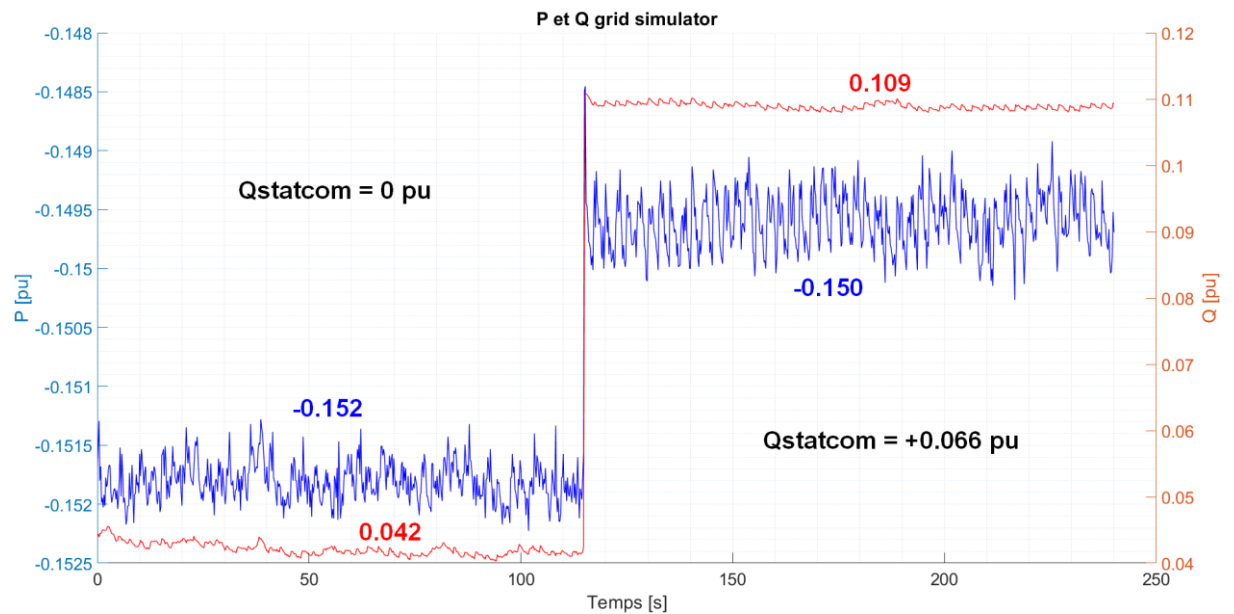


Figure 92: Active and reactive power exchanged to the upstream network for scenario 3



9.4 Overall conclusion of the Relne laboratory tests

The first conclusion of these tests is the correct ability of the STATCOM prototype to bring the voltage amplitude of its node closer to 1 pu using inductive or capacitive reactive power.

These 3 tests have demonstrated that the most the network is loaded, the more the STATCOM improve network performances. Indeed, for scenario 2, STATCOM is improving voltage deviation and at the same time is unloading the lines and the HV/MV transformer.

Scenario 3 has demonstrated that in the extreme case when MV network is injecting active power inside the upstream network, the only benefit of the STATCOM is its ability to improve voltage deviation and slightly decreases the losses. Apart from that, it loads even more the lines and HV/MV transformer which degrades the MV network performances. In this situation, the STATCOM has to operate only when high voltage deviation in the MV network becomes an issue.

It is important to mention that in case the goal of DSO is to keep the STATCOM node to exactly 1 pu, a nominal power 0.066 pu is not sufficient even in the low loading scenario. But as a remark, it is not always necessary to have exactly 1 pu to the most interconnected node.



10 WP8: Generalisation of the STATCOM applications: Workshop and discussions with Swissgrid and DSOs

Aim of the final part of the project was to share and discuss the main results of the COSTAM project with swiss DSOs and Swissgrid.

This goal was realised in two steps. The first step was to carry out a survey about reactive power management in distribution network. The results of this survey, aimed to prepare the workshop organisation and content. The second step was the workshop itself. This allowed to share the COSTAM project main results, the results of the survey and to discuss about different thematics linked with reactive power issues.

This section presents the survey content and results, workshop organisation and content, interesting discussions during the workshop and the feedback of the participants.

10.1 Survey content and results

The survey main objective was to understand what DSOs know about reactive power compensation and what are their current plan concerning this problematic. It was also used as invitation to the workshop. The survey was divided in 5 sections presented hereafter. The survey was sent to 36 DSOs and Swissgrid that both could be interested in this problematic. We received 15 answers.

10.1.1 Renewable energies and network reinforcement

This section asked the DSO if it has a plan to facilitate the new renewable energies integration into its network until 2035. Only 29% of the DSOs have such a plan. They have a planning for PV, gaz or biogaz, hydroelectric and hydrogen. PV is the best planned of these energies new integration.

Each DSO is aware their network will need to be reinforced at the horizon of 2035. The most cited types of reinforcement are transformer reinforcement or adding new ones. Then smart metering was the second most cited element, in order to better understand the needs of their network. No DSO has proposed to integrate a reactive power compensator as grid reinforcement tool.

10.1.2 Interaction with transmission grid

We asked DSOs if the new concept of voltage support of the Swiss transmission grid (which came into force on 1st January 2020) required them to implement some measures. 29% of DSOs was concerned by this new concept. The measures proposed to deal with this was:

- Installation of 50 Mvar inductors with tap changer (in progress for one DSO)
- A Virtual Power Plant is currently used by a DSO to manage automatically all the production units available and, when it is possible, the reactive power compensation is realised.
- One DSO is managing the reactive power by changing the voltage level of their HV autotransformers or by using rotating machines.

Some DSOs are still analysing their network in order to solve this problematic.

No DSOs have proposed the use of STATCOM technologies for this problematic.

10.1.3 Reactive power compensator equipment

We asked if DSOs are already using reactive power compensator. No DSOs are using reactive power compensator equipment for the time being. Only one is currently installing a 50 Mvar inductors with tap changer.

Swissgrid uses the power plants of its network to manage the reactive power but are currently designing a potential SVC for their extra-high-voltage level network. TSOs of other countries are already using this equipment.



If DSOs would use compensators, they mainly proposed shunt technology.

10.1.4 Understand what DSOs want to know about STATCOM

The idea was to ask if the DSO want to know more about STATCOM and choose what they want to learn between the following subjects :

- Cost of STATCOMs available on the market
- Type of technologies available on the market
- Comparison of advantages/disadvantages between market topologies
- Advantages/disadvantages between classical and modular topologies
- Detailed study of modular topologies on the real case of the SIL network (simulations / small scale LV tests)

79% of DSOs wanted to know more about STATCOM. This brought us to integrate the STATCOM market study of COSTAM project into the workshop.

10.1.5 Disturbances a STATCOM must be able to support

We asked questions about unbalance in the voltages and currents of DSO MV network. It allowed us to note that DSO network is rarely unbalanced and that the most common default is the phase-to-earth short-circuit. This information confirmed us that it is important to study the behaviour of the STATCOM in case of short-circuit.

10.2 Workshop organisation and content

Thanks to the survey it was possible to organise a workshop for half a day in the HEIG-VD premises. 7 DSOs and Swissgrid for an overall of 10 persons participated to this workshop. It was realised the 2nd of December 2022 from 8 am to 1pm.

10.2.1 Workshop planning

- Presentation of attending people
- Presentation of reactive power issue and STATCOM benefits
- Share of the survey results (part 1)
- Share of the survey results (part 2)
- STATCOM market study presentation
- Visit of Relne laboratory
- Explanation of Relne setup and Relne results with STATCOM

10.2.2 Presentation of reactive power issue and STATCOM benefits

In this presentation, the COSTAM project goals was presented. Then the reactive power problematic was recalled as well as the principle of compensation with an example. Then the family of existing compensators and STATCOM family were presented with advantages and drawbacks of each one, especially modular STATCOM advantages and structures selected during the project (SDBC, SSBC and DSCC topologies). Finally, STATCOM benefits and best location selection technique in the case study of SIL network was presented.

10.2.3 Share of the survey results

The results of the survey were shared with the same principle as presented in section 10.1.

10.2.4 STATCOM market study presentation

A summary of the most important information of the STATCOM market study realised in the COSTAM project [3] was presented to DSOs.



10.2.1 Relne laboratory visit and live demonstration

A visit of the laboratory was first realised. Then the Relne laboratory set up to represent the SIL “B” MV network was explained. Some results of STATCOM integrated into Relne laboratory for power system tests (WP6) and power electronics tests (WP1) were presented.

10.3 Discussions during the workshop

It was interesting to note that electrical vehicle integration was an important subject which came back several time.

A DSO mentioned that PV converter could also be used to control the reactive power of the grid. In the case where the DSO is able to control enough converters, it could be an equivalent solution to a STATCOM. However, for the moment no DSO is able to do this. The hardware resources as well as the budget allocated are not sufficient at this time. One STATCOM is still an easier solution nowadays but the high cost of this technology is the principal drawback for DSOs to integrate it in their network.

It was mentioned that STATCOM does not replace the fact that cables and transformers need to be repaired or changed at the end of their lifetime. Then at this time, they will be upgraded. In this case, STATCOM has a lower interest.

10.4 Feedback on the workshop

A great majority thanks us for the quality of the workshop and the logistics which was really appreciated.

We asked for what the workshop brought to the attendance: They generally learned a lot on the STATCOM technologies. They appreciated to share the point of view of other DSOs and also Swissgrid on these themes. They also noticed that STATCOM technologies are expensive.

We asked what other points/topics would you like to discuss in the future: charging station integration in the network was asked. Development and use of intelligent networks. A complete technico-economic study of STATCOM leading to integration would be interesting for some of them.

Two DSOs asked if HEIG-VD team would be able to realise a pilot project to integrate à MV or HV STATCOM in their network. We answered that we do not have the equipment to realise such high voltage and powers in our installations. But it means that some of them are interested by the concept of STATCOM.

Some contacts were made for potential other pilot projects.

11 Conclusions

The major part of the project objectives has been successfully achieved.

The modular STATCOM structures were deeply investigated. The WP1 results shown that modular topologies are highly effective for STATCOM applications. SDBC, SSBC and DSCC modular STATCOM topologies seems to be the most promising topologies when considering network imbalances and defaults. However, SDBC is not working when grid voltages are highly unbalanced while SSBC topology is not working when grid currents are highly unbalanced. DSCC is able to manage all the network imbalances with a suitable control strategy. The detailed simulation results realised in this project demonstrated the ability of SSBC and DSCC topologies to operate in every possible grid voltage imbalance. The DSCC simulation results were confirmed by experimental tests on the DSCC prototype designed by HEIG-VD.

STATCOM market study analysis based on 11 manufacturers shown that modular converters (SDBC and SSBC) are increasingly used, especially for high-power applications. A list of STATCOMs that could potentially be implemented in the SIL network studied in the project was proposed.

An existing part of the SIL MV network was successfully simulated and then implemented in the reconfigurable Relne laboratory. A PV production forecast was proposed for the network studied based on the swiss energy perspectives 2050+.



Simulations of STATCOM network integration in the MV network show that the STATCOM power required for optimal operation can be relatively high, up to 5Mvar. In this case, STATCOMs are best located close to the HV/MV feeder substation, or at well-interconnected nodes. If the power available to the STATCOM is limited (due to space or financial constraints), the best location is a well-interconnected node, in the "middle" of a MV feeder. The efficiency of exporting reactive power from the distribution system to the transmission system has been analysed, for two relatively simple cases. The results show that the complex interconnections between the two distribution and transmission systems in Western Switzerland limit the potential of such a concept for a MV STATCOM. Better results would be obtained by placing the STATCOM on high voltage or extra-high voltage side.

Thanks to the reconfigurable Relne laboratory, it was possible to successfully test DSCC prototype (developed by HEIG-VD) operating as a STATCOM under real conditions in different scenarios on a per unit base. The results shown that STATCOM is most profitable when the network is heavily loaded. On the other hand, it is less profitable when production is high.

The final part of the project involved sharing and discussing the main findings of the COSTAM project with the Swiss DSOs and Swissgrid through a workshop. Seven DSOs and Swissgrid took part in the workshop, which enabled them to gain a better understanding of the current technologies available for reactive power compensation and of each other's points of view on the subject.

12 Outlook and next steps

The following elements could be interesting to deal with in another project:

- DSCC control strategy could possibly be improved to permanently operate during two lines-to-earth short-circuit. This point is still opened and would need more time to investigate.
- SSBC prototype was not tested mainly due to lack of time. It would be interesting to see if the simulation results are also validated by tests in the Relne laboratory.
- Selection of an industrial STATCOM to integrate in one DSO network and assessment of its benefits to the network in a real application.

13 National and international cooperation

The main cooperation was with SIL DSOs which provided information on its MV network and help HEIA-FR team to design the simulation model. We thank them for this fruitful cooperation.

Some STATCOM suppliers were contacted during the market study to improve its content. COMSYS, Nidec and Siemens provided some information on their product. We also thank them.

Seven Swiss DSOs and Swissgrid took part in the workshop. We exposed them the project results presented in this report and discussed about reactive power issues and also briefly on some other themes. They generally learned a lot on the STATCOM technologies and they appreciated to share the point of view of other DSOs and also Swissgrid on these themes.

14 Publications

The following publication is directly resulted from developments in the COSTAM project:

- G. Courteau, E. Aurberson, P. Favre-Perrod, O. De Marignac, M. Bozorg and M. Carpita, "STATCOM optimal placement method applied to a Swiss urban distribution network considering future photovoltaic integration scenarios," *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, 2022, pp. 124-129, doi: 10.1109/SPEEDAM53979.2022.9842206.

The following paper is under review for publication in IEEE Transaction on Industry Applications:



- G. Courteau, E. Aurberson, P. Favre-Perrod, O. De Marignac, M. Bozorg and M. Carpita, "STATCOM optimal placement method applied to a Swiss urban distribution network and reduced scale prototype tests under unbalanced conditions", under review in IEEE Transaction on Industry Applications.

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16 Appendices

16.1 SSBC capacitive operation simulation with balanced voltages (detailed results)

In this simulation, grid voltages (u_{gs}) are balanced 50 Hz sinusoidal waveforms with peak value of 1 pu. They are visible in Figure 7. When reactive power reference is set to $Q_{STATCOM}^* = -1$ pu (capacitive case), grid currents are well balanced with Current Unbalance Factor (CUF) = $\frac{I_-}{I_+} =$ of 0.0%. Their fundamental peak value are all of 1.000 pu. These three balanced currents exchanged between SSBC converter and grid are visible in Figure 93. THD of the currents of all phases are around 1.9% in the simulation for balanced grid voltages.

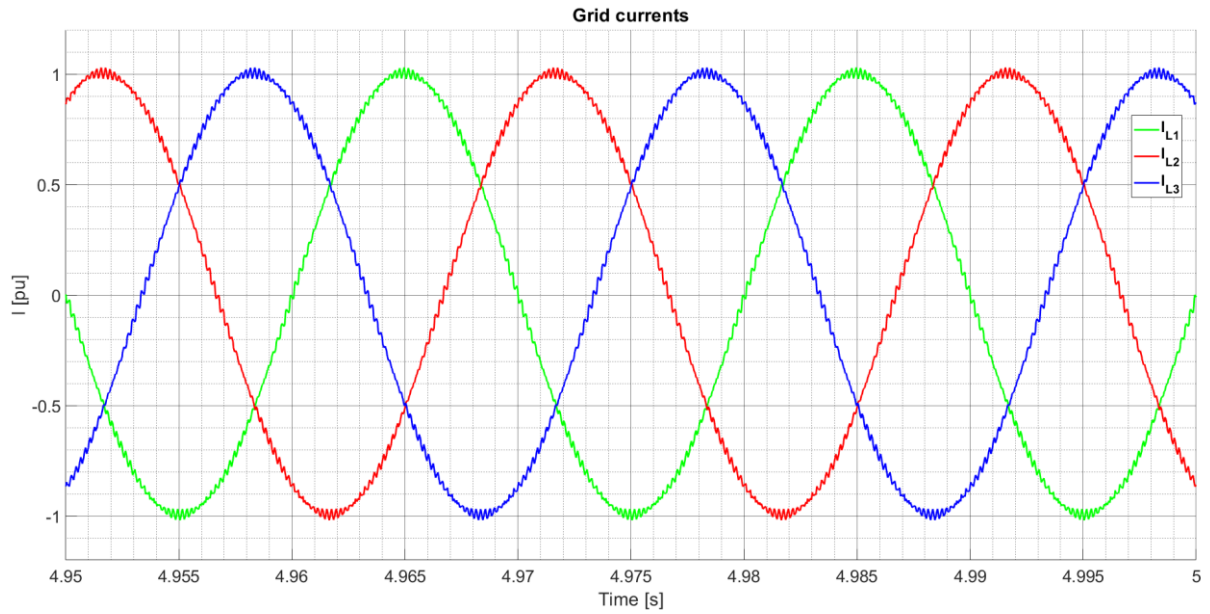


Figure 93: SSBC grid currents when $Q_{STATCOM}^* = -1$ pu and grid voltages are balanced in simulation

Due to their very low THD, currents and voltages are considered purely 50 Hz signals (without harmonics), active and reactive powers are calculated via equations (1) and (2):

- $P_{h1}(Q^* = -1 \text{ pu simulation balanced voltages}) = 0.007 \text{ pu}$
- $Q_{h1}(Q^* = -1 \text{ pu simulation balanced voltages}) = -1.000 \text{ pu}.$

(Powers are calculated with voltage and current accuracy taken at mA and mV.)

The relative deviation between reference value and measurement value is:

- $\Delta_Q(Q^* = -1 \text{ pu simulation balanced voltages}) = 0.0 \text{ \%}.$

Figure 94 allows to confirm that the STATCOM is used as a reactive power device. Indeed, fundamental grid voltage L3 is lagging its fundamental grid current by 89.6° . A pure reactive power device would have 90° phase shift between current and voltage but the converter includes also losses which correspond to active power P_{h1} . With the current convention chosen, a positive reactive power means the converter works as a capacitor.

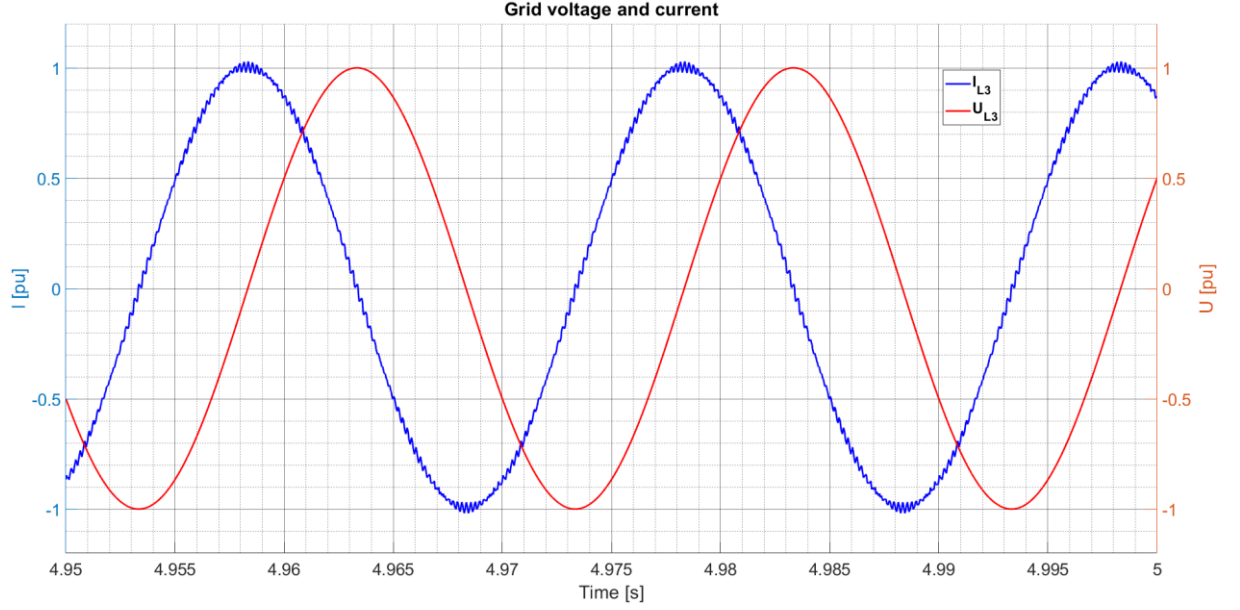


Figure 94: SSBC grid voltage and current of phase L3 when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation

Given that the 3 currents are 120° phase shifted as well as the voltages, only Figure 94 is shown to lighten the report. Indeed, in this case each voltage lags its proper current by around 90° .

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg at $Q_{STATCOM}^* = -1pu$ in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 95.

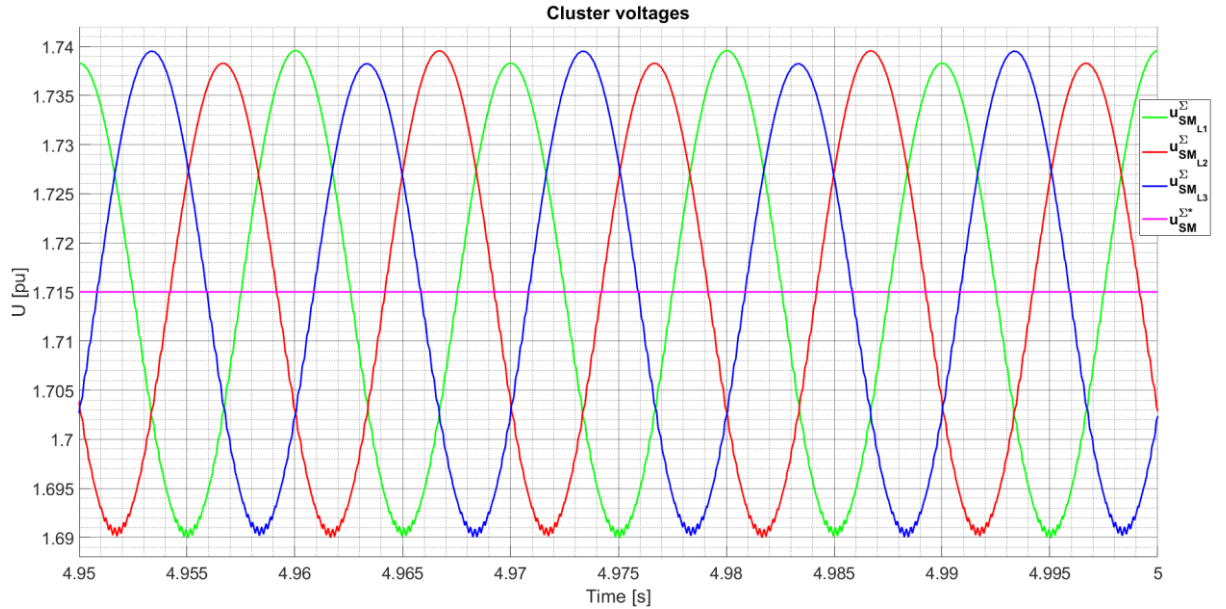


Figure 95: SSBC cluster voltage for each leg when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation

It can be seen that cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.048 pu in average. The mean value over one period of time is 1.715 pu which is equal to the reference $u_{SM_{u,L}}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_L}^{\Sigma*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation.

Finally, thanks to all the simulation results above, it is possible to validate the correct SSBC operation with $Q_{STATCOM}^* = -1pu$ in balanced grid voltage operation with the proposed control strategy.



16.2 Simulations of SSBC positive sequence capacitive current operation during one line-to-earth short-circuit (detailed results).

SSBC simulations for one line-to-earth short-circuit use the electrical schematic presented in Figure 6.

The grid voltage in simulation is applied as in Figure 11. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 4. SSBC STATCOM exchanges $Q_{STATCOM}^* = +1\text{pu}$ (or $Q_{STATCOM}^* = -1\text{pu}$). Then, when time = 0.0484 s the one line-to-earth short-circuit appears on phase L1 meaning the grid voltage $u_{gsL1} = 0\text{ pu}$ and the other phase voltage amplitude increase. It can be seen a transient for around three periods. And then the one line-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(\text{steady state}) = 0\text{ pu}$
- $u_{gsL2}(\text{steady state}) = 1.710\text{ pu}$
- $u_{gsL3}(\text{steady state}) = 1.714\text{ pu}$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

This section focuses only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 12 shows steady-state unbalanced grid voltages during one line-to-earth short-circuit applied on SSBC STATCOM in simulation.

As already mentioned, during one line-to-earth short-circuit steady state STATCOM goal is to exchange positive sequence current (inductive or capacitive) of 1pu with the grid.

Firstly, we present the results when positive sequence capacitive current ($I_{h1}^{++}=1\text{pu}$ capacitive) is exchanged between SSBC and grid. The currents exchanged are shown in Figure 96.

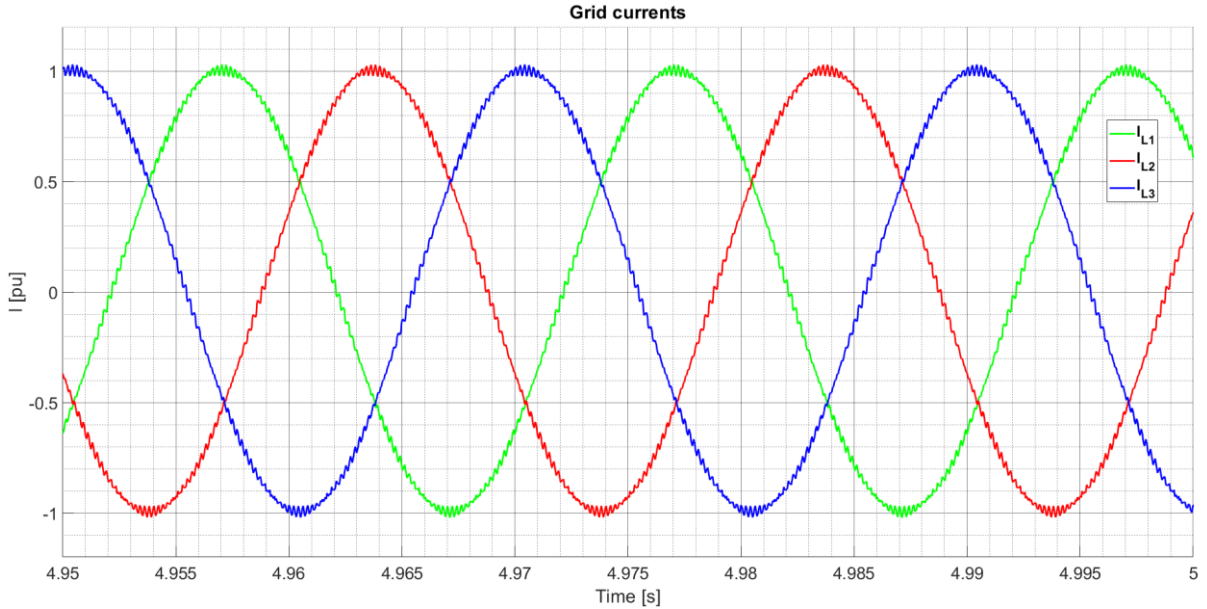


Figure 96: SSBC grid currents when $I_{h1}^{++}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state in simulation

In Figure 96, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.9\%$
- $THDi_{L2}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.9\%$
- $THDi_{L3}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.9\%$



Compared to grid voltage balanced state, THD($I_{h1}^{+*} = 1pu$ capacitive and L1 in SC) remains globally the same. One line-to-earth short-circuit does not really affect the harmonics quality of the signal.

The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

- $\hat{I}_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 1.000 pu$
- $\hat{I}_{h1}^{-}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 0.000 pu$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 0.0\%$. It confirms that the currents provided by the SSBC prototype are well balanced with the setpoint $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the SSBC exchanges fundamental positive sequence inductive reactive power with the grid. During one line-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^{+}$) is equal to 0.986 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^{+} = -89.6^{\circ}$. Fundamental positive sequence active and reactive powers are calculated with (4) and (6).

- $P_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 0.007 pu$
- $Q_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = -0.987 pu$

SSBC converter exchanges Q_{h1}^{+} in great majority meaning that it continues to operate as a balanced STATCOM. In addition, Q_{h1}^{+} is very close to the base power value because positive sequence of voltage and current are dominant on their negative sequence.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^{\Sigma}$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg with $I_{h1}^{+*}=1pu$ capacitive in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 97.

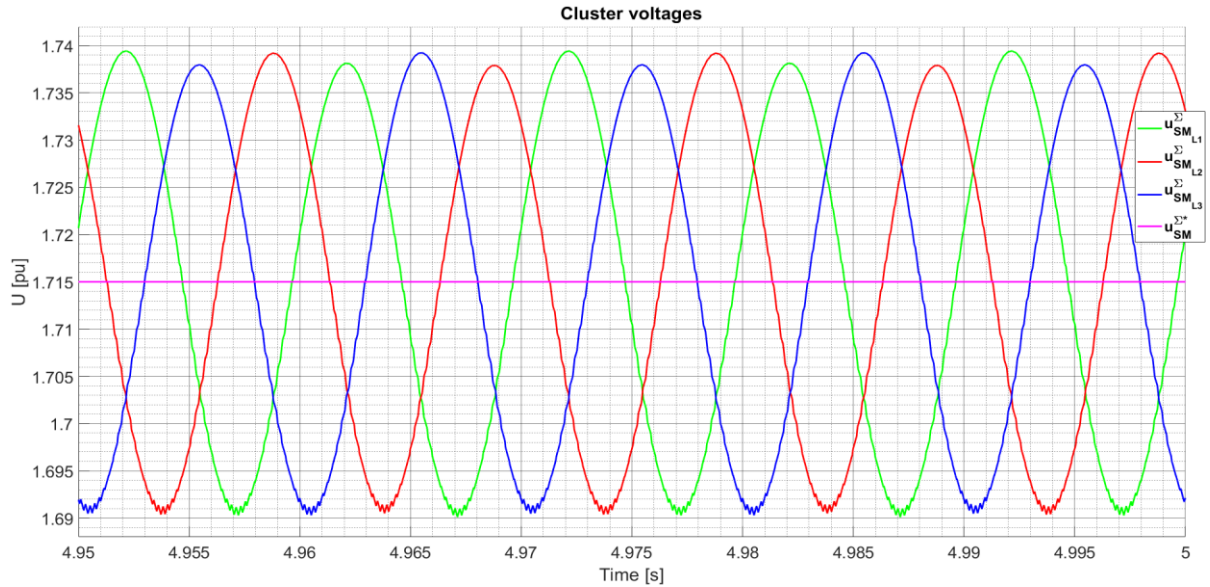


Figure 97: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state in simulation

It can be seen that cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.048 pu in average. The mean value over one period of time is 1.715 pu which is equal to the reference $u_{SM_{u,L}}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_L}^{\Sigma*}$ and so that internal stability is guaranteed when $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state in simulation.



It is important also to verify the STATCOM is able to withstand the transient of one line-to-earth short-circuit. Grid currents during this transient are shown in Figure 98.

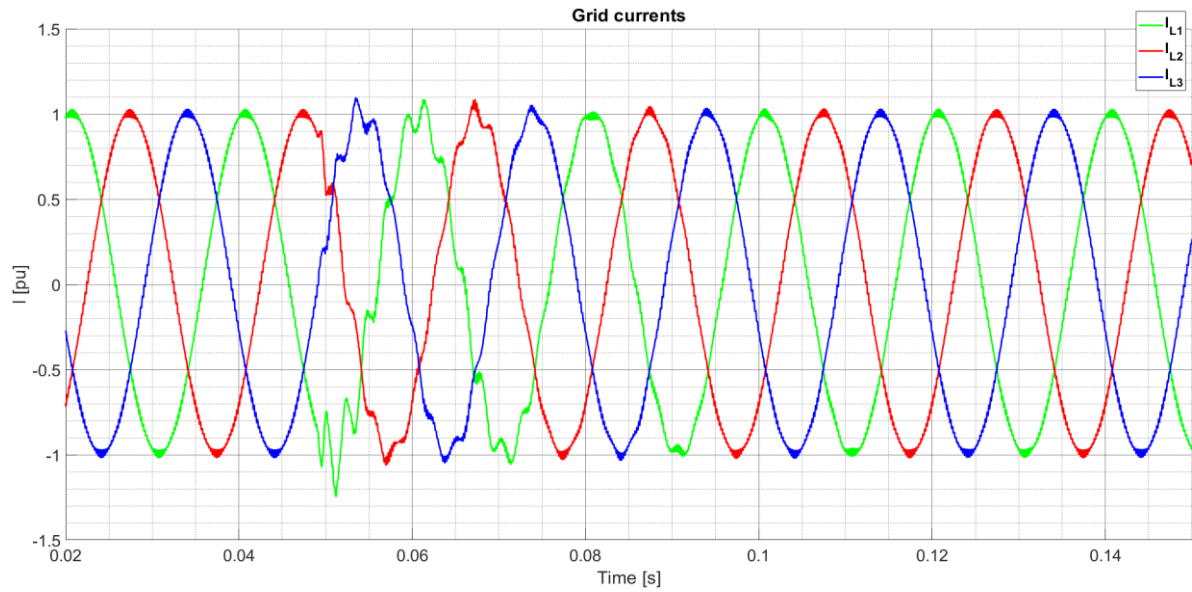


Figure 98: SSBC grid currents when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit transient in simulation

As it can be seen in Figure 98, grid currents continue to follow the $I_{h1}^{+*}=1\text{pu}$ capacitive reference during the transient. However, at the beginning of the transient (at 0.0484 s), oscillations occur going until -1.248 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.

Figure 99 shows the internal cluster voltages during this transient.

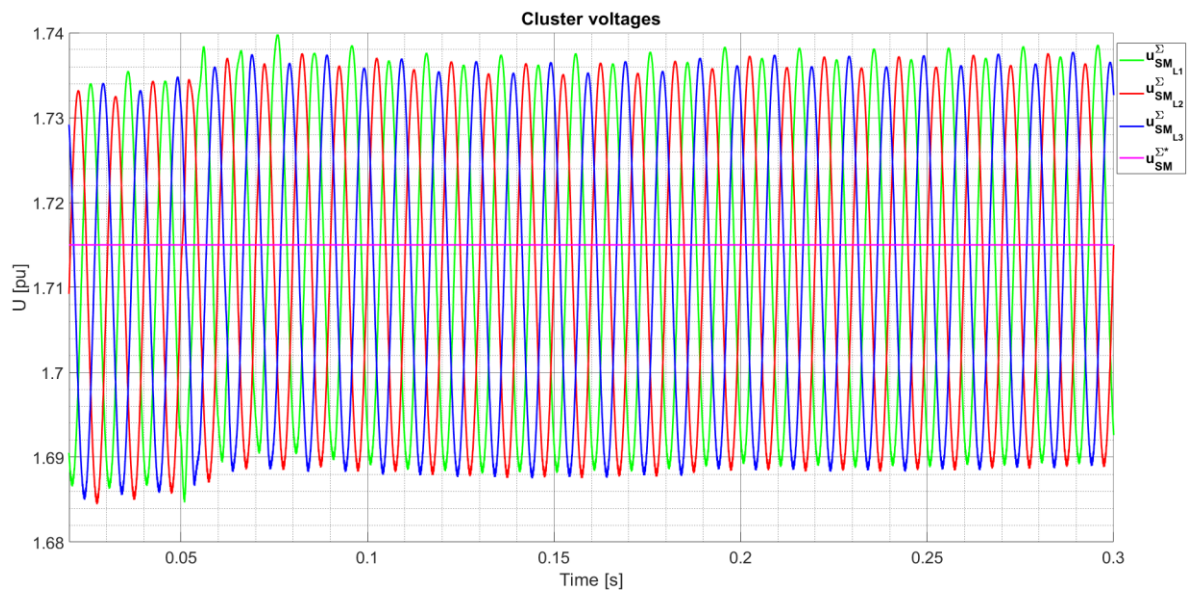


Figure 99: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit transient in simulation

Cluster voltages contain also an additional oscillation but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 1.740 pu. Cluster voltages are weakly impacted during this transient and remain stable. These results imply that the SSBC STATCOM with this control strategy is also able to withstand the transient of one line-to-earth short-circuit.

Finally, it is possible to validate the correct SSBC operation when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit with the proposed control strategy.



16.3 Simulations of SSBC positive sequence capacitive current operation during two lines-to-earth short-circuit (detailed results).

SSBC simulations for two lines-to-earth short-circuit use the electrical schematic presented in Figure 6.

The grid voltage in simulation is applied as in Figure 17. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 4. SSBC STATCOM exchanges $Q_{STATCOM}^* = +1\text{pu}$ or $Q_{STATCOM}^* = -1\text{pu}$. Then, when time = 0.0484 s the two lines-to-earth short-circuit appears on phases L1 and L2 meaning the grid voltages $u_{gsL1} = 0\text{ pu}$ as well as $u_{gsL2} = 0\text{ pu}$. In the same time, phase voltage L3 amplitude increases. It can be seen a transient for around three periods. Then the two lines-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(\text{steady state}) = 0\text{ pu}$
- $u_{gsL2}(\text{steady state}) = 0\text{ pu}$
- $u_{gsL3}(\text{steady state}) = 1.476\text{ pu}$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

This section focuses only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 18 shows steady-state unbalanced grid voltages during two lines-to-earth short-circuit applied on SSBC STATCOM in simulation.

As already mentioned, during two lines-to-earth short-circuit steady state STATCOM goal is to exchange positive sequence current (inductive or capacitive) of 1pu with the grid.

Firstly, we present the results when positive sequence capacitive current ($I_{h1}^{++}=1\text{pu}$ capacitive) is exchanged between SSBC and grid. The currents exchanged at the end of the short-circuit are shown in Figure 100.

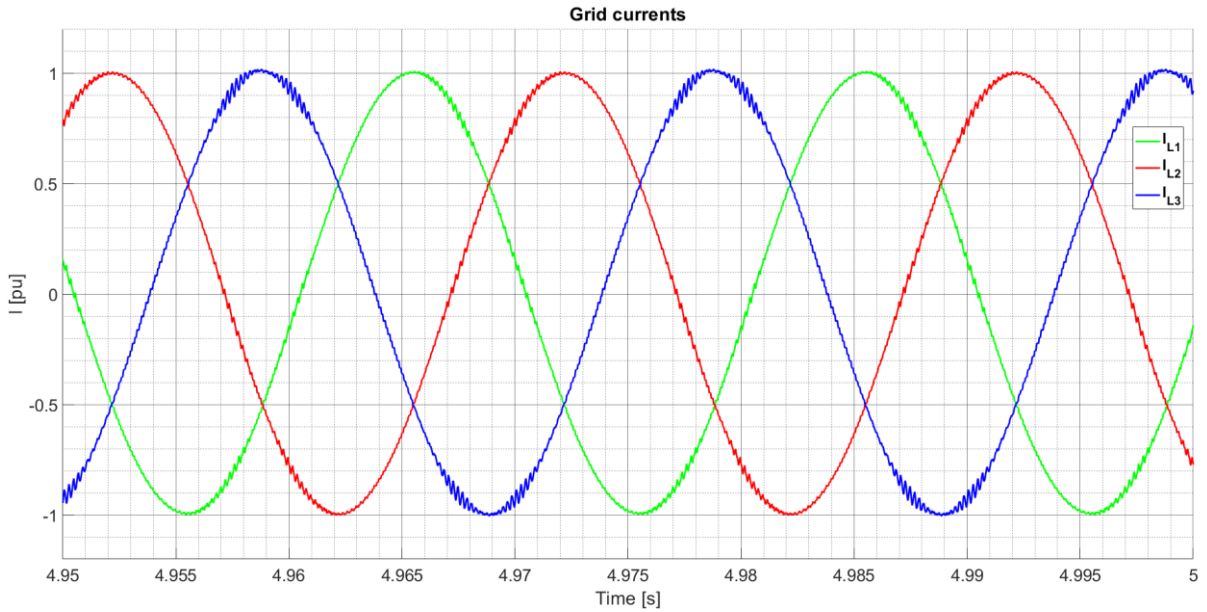


Figure 100: SSBC grid currents when $I_{h1}^{++}=1\text{pu}$ capacitive at the end of two lines-to-earth short-circuit in simulation

In Figure 100, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 1.9\%$
- $THDi_{L2}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 1.9\%$



$$- THDi_{L3}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 2.0 \%$$

Compared to grid voltage balanced state, $THD(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC)$ remains globally the same. Two lines-to-earth short-circuit does not really affect the harmonics quality of the signal.

The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

$$\begin{aligned} - \hat{I}_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) &= 1.000 \text{ pu} \\ - \hat{I}_{h1}^{-}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) &= 0.000 \text{ pu} \end{aligned}$$

This implies Current Unbalance Factor (CUF) $= \frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 0.0\%$. It confirms that the currents provided by the SSBC prototype are well balanced with the setpoint $I_{h1}^{+*}=1pu$ capacitive during two lines-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the SSBC exchanges fundamental positive sequence capacitive reactive power with the grid. During two lines-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^{+}$) is equal to 0.492 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^{+} = -89.2^{\circ}$. It is then possible to calculate the powers:

$$\begin{aligned} - P_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) &= 0.007 \text{ pu} \\ - Q_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) &= -0.492 \text{ pu} \end{aligned}$$

SSBC converter exchanges Q_{h1}^{+} in great majority meaning that it continues to operate as a balanced STATCOM. However, as mentioned earlier in the report, Q_{h1}^{+} is half of the base power value because positive sequence of voltage is half of the base value and positive sequence of current is voluntarily kept to 1 pu inductive to avoid high currents in the converter during this short-circuit state.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each leg ($u_{SM_L}^{\Sigma}$) are regulated to oscillate around the cluster voltage reference ($u_{SM_L}^{\Sigma*}$) equal to 1.715 pu. Cluster voltage for each leg with $I_{h1}^{+*}=1pu$ capacitive in simulation and the reference $u_{SM_L}^{\Sigma*}$ are shown in Figure 101.

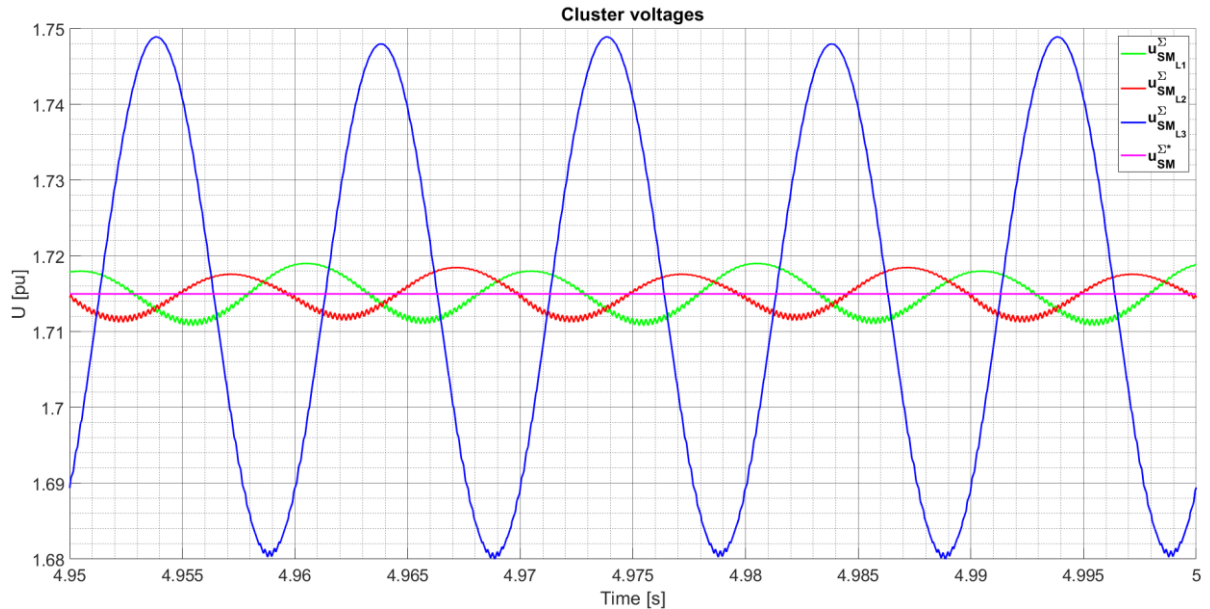


Figure 101: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive at the end of two lines-to-earth short-circuit in simulation

It can be seen that the average value over the last period of time is still 1.715 pu for each leg which is equal to the reference $u_{SM_{u,l}}^{\Sigma*}$. So, cluster voltages remain stable at the end of the 5s short circuit. Even better, this state could be hold permanently.



It is important to mention that peak-to-peak amplitudes are unbalanced between legs. The with peak-to-peak amplitude of each leg is:

- $u_{SML1pk-pk}^{\Sigma} = 0.008 \text{ pu}$
- $u_{SML2pk-pk}^{\Sigma} = 0.007 \text{ pu}$
- $u_{SML3pk-pk}^{\Sigma} = 0.069 \text{ pu}$

The peak-to-peak amplitude of L3 leg is 1.44 times higher than the balanced case. It has to be taken in consideration during the design phase of the converter. It is worth to mention that peak-to-peak amplitude of other legs are 6 times lower than the balanced case which is a positive behaviour for the converter.

We can conclude that cluster voltages are balanced around the reference value u_{SML}^{+*} with reasonable ripples amplitude. It means internal stability is guaranteed when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit steady-state in simulation.

It is important also to verify the STATCOM is able to withstand the transient of two lines-to-earth short-circuit. Grid currents during this transient are shown in Figure 102.

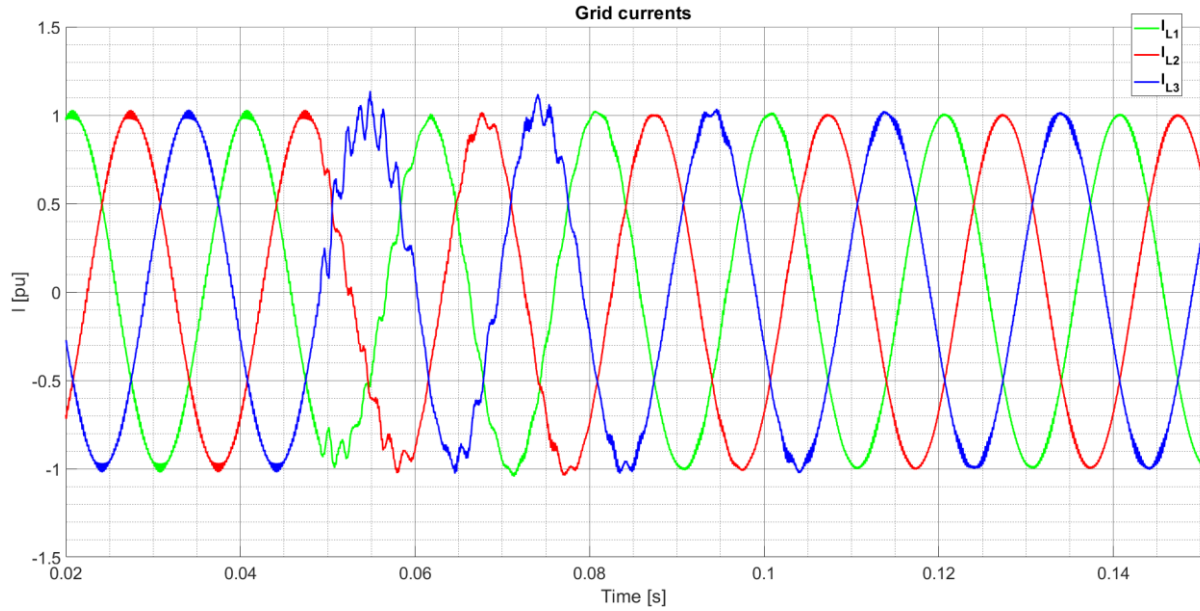


Figure 102: SSBC grid currents when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit transient in simulation

As it can be seen in Figure 102, grid currents continue to follow the $I_{h1}^{+*}=1\text{pu}$ capacitive reference during the transient. However, at the beginning of the transient (at 0.0484 s), oscillations occur going until 1.137 pu (phase L3). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.

Figure 103 shows the internal cluster voltages during this transient.

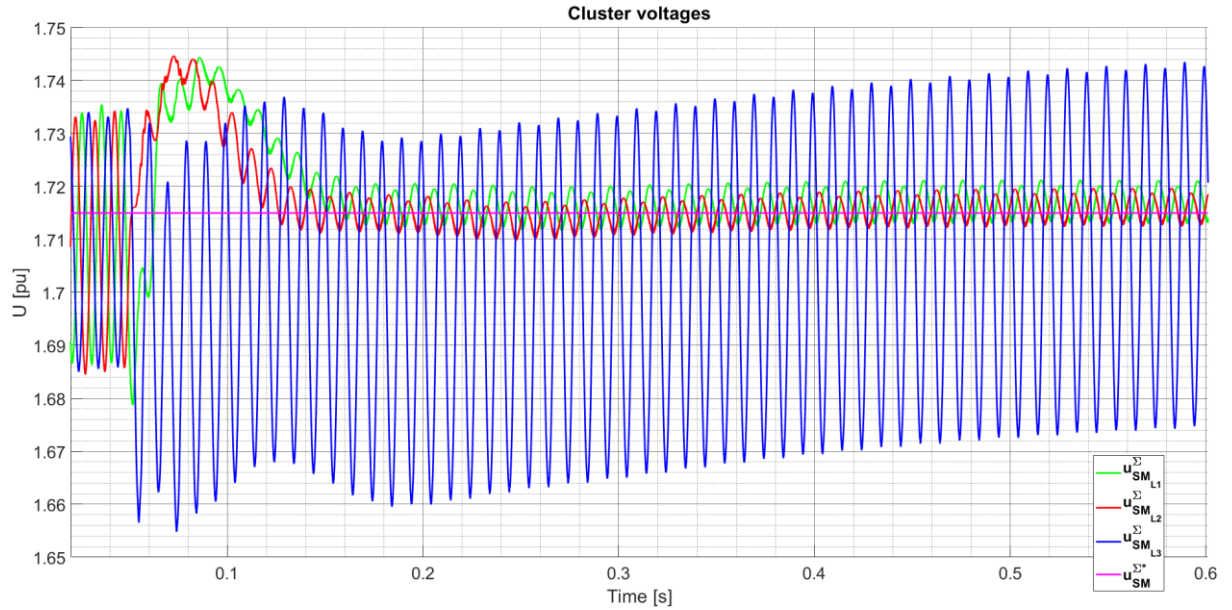


Figure 103: SSBC cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit transient in simulation

Cluster voltages contain also an additional oscillation but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 1.745 pu. Cluster voltages are notably impacted during the first 50ms of the transient and then return to stable state. These results imply that the SSBC STATCOM with this control strategy is also able to withstand the transient of two lines-to-earth short-circuit. However, the voltages reached during the transient has to be considered in the converter design stage.

Finally, it is possible to validate the correct SSBC operation when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit with the proposed control strategy.



16.4 DSCC capacitive operation simulation with balanced voltages (detailed results)

In this simulation, grid voltages (u_{gs}) are balanced 50 Hz sinusoidal waveforms with peak value of 1 pu. They are visible in Figure 7. When reactive power reference is set to $Q_{STATCOM}^* = -1$ pu (capacitive), grid currents are well balanced with Current Unbalance Factor (CUF) = $\frac{I^-}{I^+} =$ of 0.0%. Their fundamental peak value are all of 1.000 pu. These three balanced currents exchanged between DSCC converter and grid are visible in Figure 104. THD of the currents of all phases are 1.0 % in the simulation for balanced grid voltages.

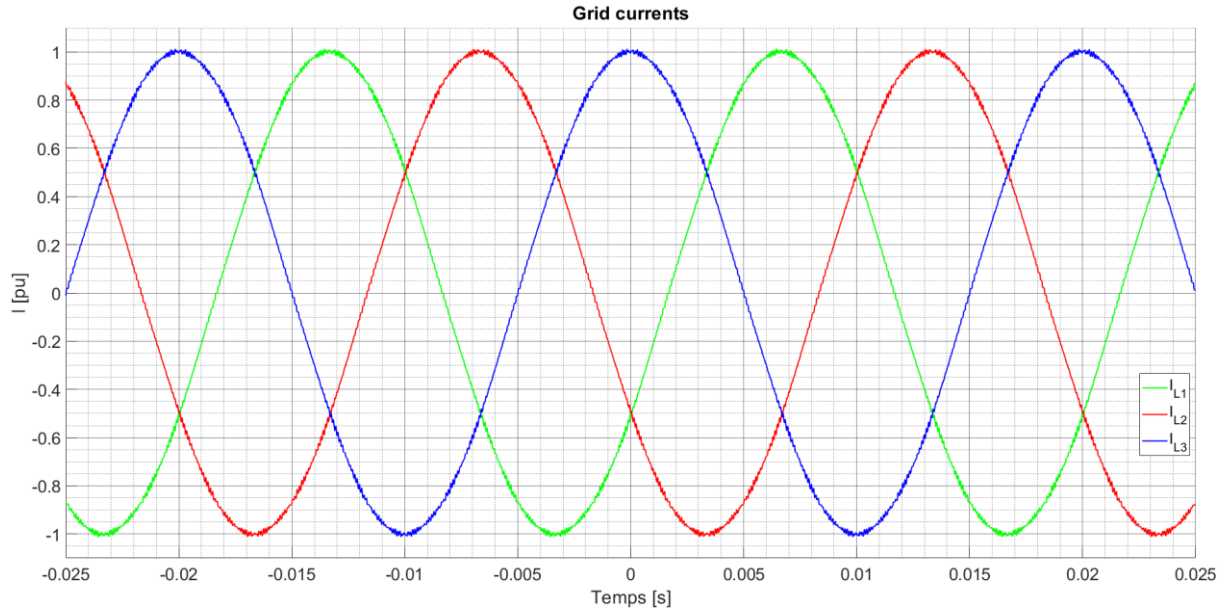


Figure 104: DSCC grid currents when $Q_{STATCOM}^* = -1$ pu and grid voltages are balanced in simulation

Due to their very low THD, currents and voltages are considered purely 50 Hz signals (without harmonics), active and reactive powers are calculated via equations (1) and (2):

- $P_{h1}(Q^* = -1 \text{ pu simulation balanced voltages}) = 0.007 \text{ pu}$
- $Q_{h1}(Q^* = -1 \text{ pu simulation balanced voltages}) = -1.000 \text{ pu}.$

(Powers are calculated with voltage and current accuracy taken at mA and mV.)

The relative deviation between reference value and measurement value is:

- $\Delta_Q(Q^* = -1 \text{ pu simulation balanced voltages}) = 0.0 \text{ \%}.$

Figure 105 shows that the fundamental grid voltage L3 is lagging its fundamental current by 89.6° . With the current convention chosen, a negative reactive power means the converter works as a capacitor. A pure reactive power device would have 90° phase shift between current and voltage but the converter includes also losses which are purely active power P_{h1} .

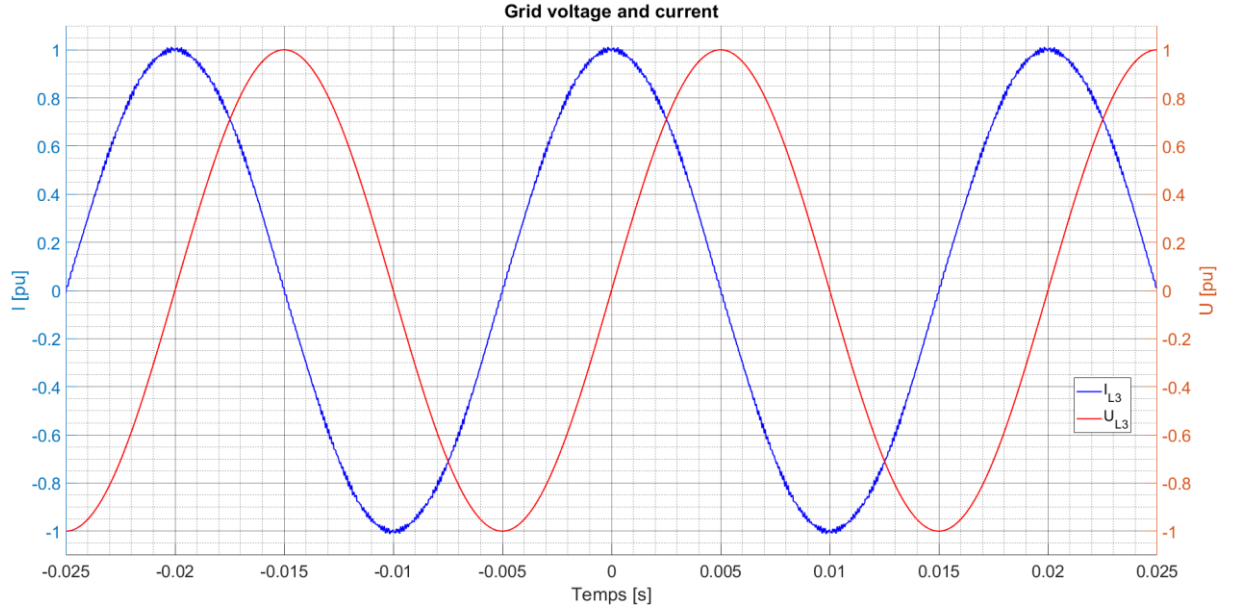


Figure 105: DSCC grid voltage and current of phase L3 when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation

Given that the 3 currents are 120° phase shifted as well as the voltages, only Figure 105 is shown to lighten the report. Indeed, in this case each voltage leads its proper current by around 90° too.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SMu,l}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SMu,l}^{\Sigma*}$) equal to 2.45 pu. The upper arm cluster voltage for each leg at $Q_{STATCOM}^* = -1pu$ in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 106.

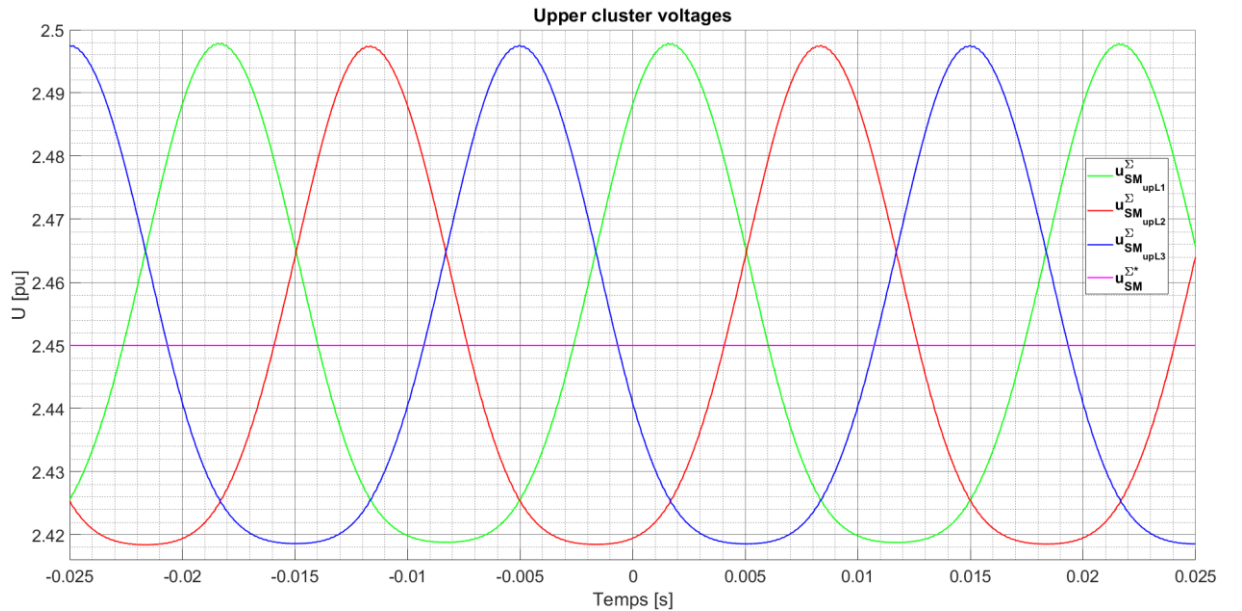


Figure 106: DSCC upper arm cluster voltage for each leg when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu. The mean value over one period of time is 2.450 pu which is equal to the reference $u_{SMu,l}^{\Sigma*}$.

As well, the lower arm cluster voltage for each leg at $Q_{STATCOM}^* = -1pu$ in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 107.

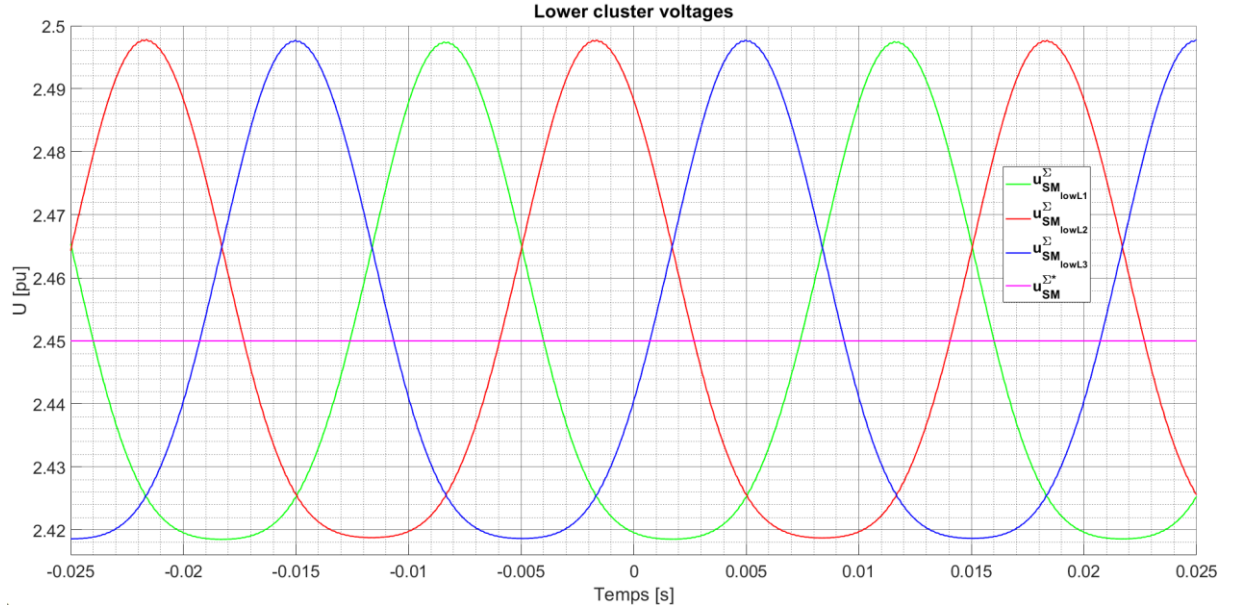


Figure 107: DSCC lower arm cluster voltage for each leg when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu as well. The mean value over one period of time is 2.450 pu which is also equal to the reference $u_{SMu,l}^{\Sigma^*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SMu,l}^{\Sigma^*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced in simulation.

Finally, thanks to all the simulation results above, it is possible to validate the correct DSCC operation with $Q_{STATCOM}^* = -1pu$ in balanced grid voltage operation with the proposed control strategy.



16.5 Simulations of DSCC positive sequence capacitive current operation during one line-to-earth short-circuit (detailed results).

DSCC simulations for one line-to-earth short-circuit use the electrical schematic presented in Figure 23.

The grid voltage in simulation is applied as in Figure 11. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 8. DSCC STATCOM exchanges $Q_{STATCOM}^* = +1\text{pu}$ (or $Q_{STATCOM}^* = -1\text{pu}$). Then, when time = 0.0484 s the one line-to-earth short-circuit appears on phase L1 meaning the grid voltage $u_{gsL1} = 0\text{ pu}$ and the other phase voltage amplitude increase. It can be seen a transient for around three periods. And then the one line-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(\text{steady state}) = 0\text{ pu}$
- $u_{gsL2}(\text{steady state}) = 1.710\text{ pu}$
- $u_{gsL3}(\text{steady state}) = 1.714\text{ pu}$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. In our study, to go further, the one line-to-earth short-circuit is maintained for 1 minute to evaluate STATCOM behaviour in this operating point. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

When this one line-to-earth short-circuit occurs, the goal for DSCC STATCOM is to continue to exchange the same positive sequence capacitive current with the grid.

In this section, we focus only on the unbalanced grid voltage state given that balanced grid voltage state results were validated in the previous sections. Figure 12 shows steady-state unbalanced grid voltages during one line-to-earth short-circuit applied on DSCC STATCOM in simulation.

Firstly, we present the results when positive sequence capacitive current ($I_{h1}^{++}=1\text{pu}$ capacitive) is exchanged between DSCC and grid. The currents exchanged are shown in Figure 108.

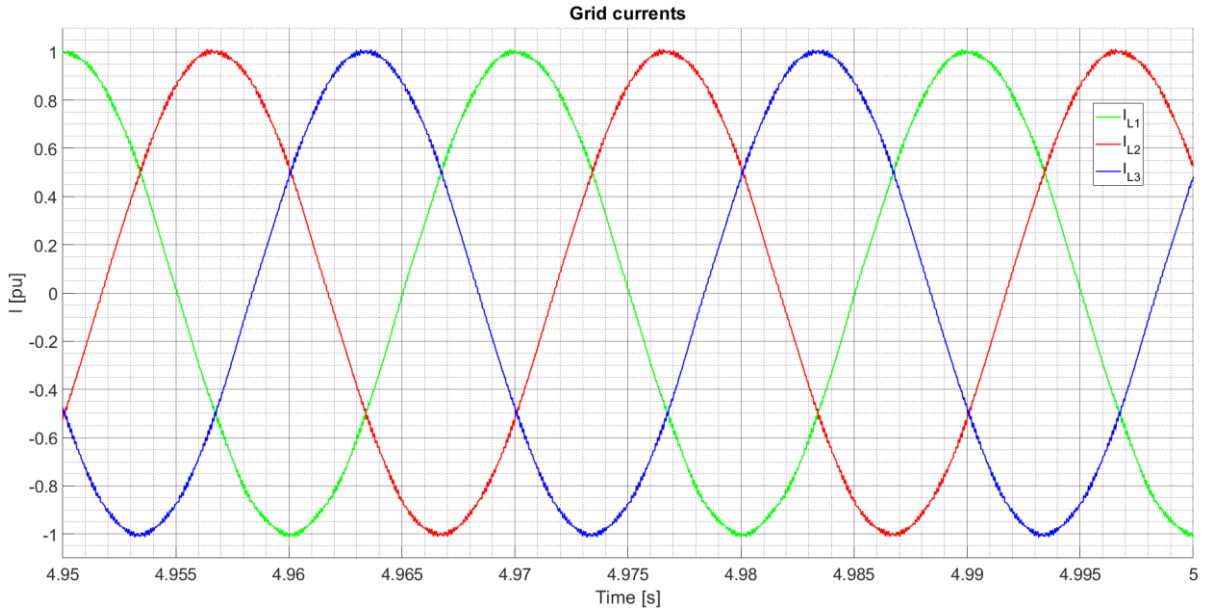


Figure 108: DSCC grid currents when $I_{h1}^{++}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state in simulation

In Figure 108, it can be seen that the currents are 50 Hz sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.0\%$
- $THDi_{L2}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.0\%$
- $THDi_{L3}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.0\%$



Compared to grid voltage balanced state, THD($I_{h1}^{+*} = 1pu$ capacitive and L1 in SC) remains globally the same. One line-to-earth short-circuit does not really affect the harmonics quality of the signal.

The fundamental RMS value of positive and negative sequence grid currents (which are very close to RMS value of the entire signal thanks to low THD) given by simulation are:

- $\hat{I}_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 1.000 pu$
- $\hat{I}_{h1}^{-}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 0.000 pu$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 0.0\%$. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the DSCC exchanges fundamental positive sequence capacitive reactive power with the grid. During one line-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^{+}$) is equal to 0.986 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^{+} = -90.4^{\circ}$. It is then possible to calculate the powers:

- $P_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = 0.007 pu$
- $Q_{h1}^{+}(I_{h1}^{+*} = 1pu \text{ capacitive and L1 in SC}) = -0.987 pu$

DSCC converter exchanges Q_{h1}^{+} in great majority meaning that it continues to operate as a balanced STATCOM. In addition, Q_{h1}^{+} is very close to the base power value because positive sequence of voltage and current are dominant on their negative sequence.

Figure 109 and Figure 110 present the current and its respective voltage for L2 and L3.

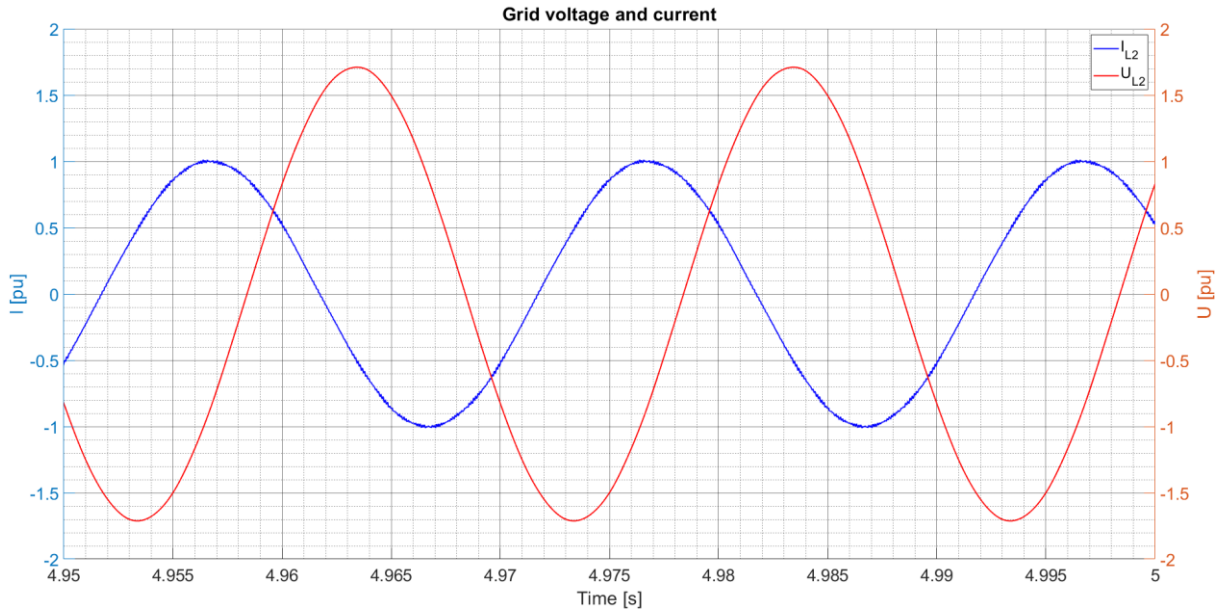


Figure 109: DSCC grid voltage and current of phase L2 when $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state in simulation

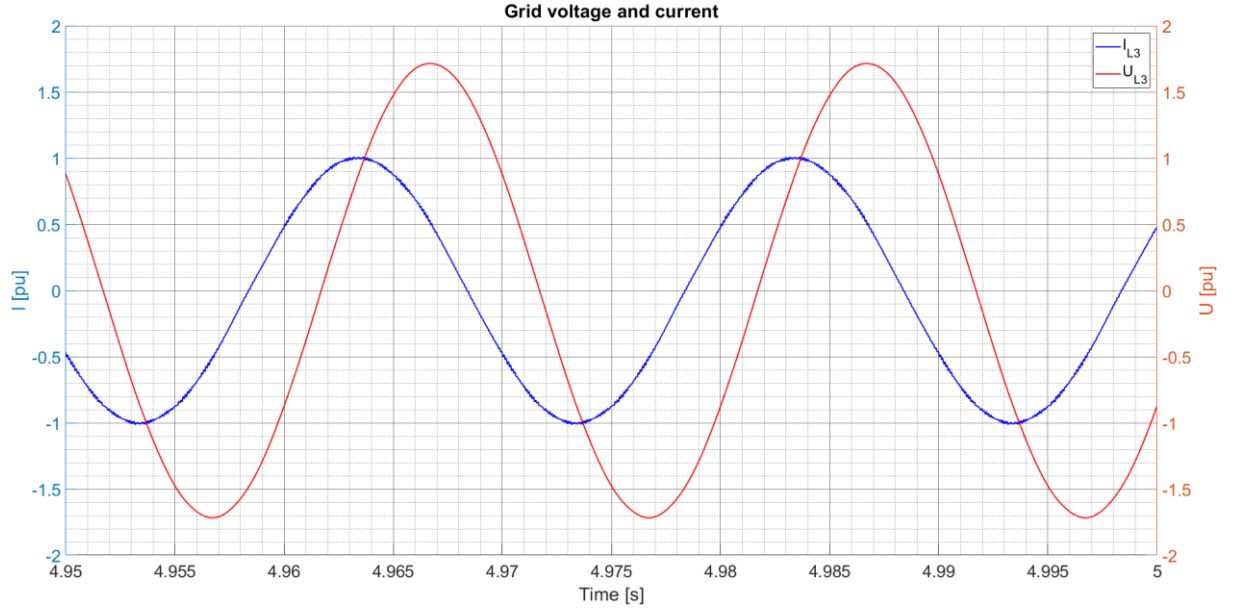


Figure 110: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state in simulation

Simulation gives us the displacement angle between voltage and current for each phase:

- $\theta_{h1L2}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = -119.7^\circ$
- $\theta_{h1L3}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = -59.8^\circ$

These displacement angles are used as references for the comparison with experimental measurements. Indeed, the power quality analyser measures this displacement angle.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SMu,l}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SMu,l}^{\Sigma*}$) equal to 2.45 pu. The upper arm cluster voltage for each leg with $I_{h1}^{+*}=1\text{pu}$ capacitive in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 111.

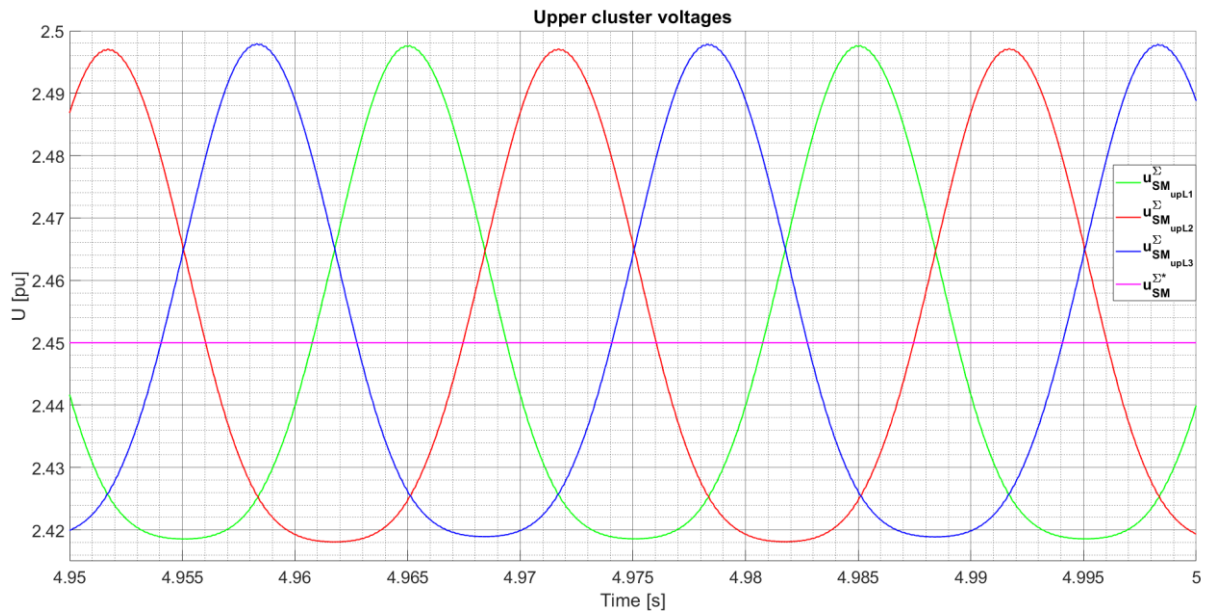


Figure 111: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state in simulation



It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu. The mean value over one period of time is 2.450 pu which is equal to the reference $u_{SMu,l}^{\Sigma*}$.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*}=1$ pu capacitive in simulation and the reference $u_{SMu,l}^{\Sigma*}$ are shown in Figure 112.

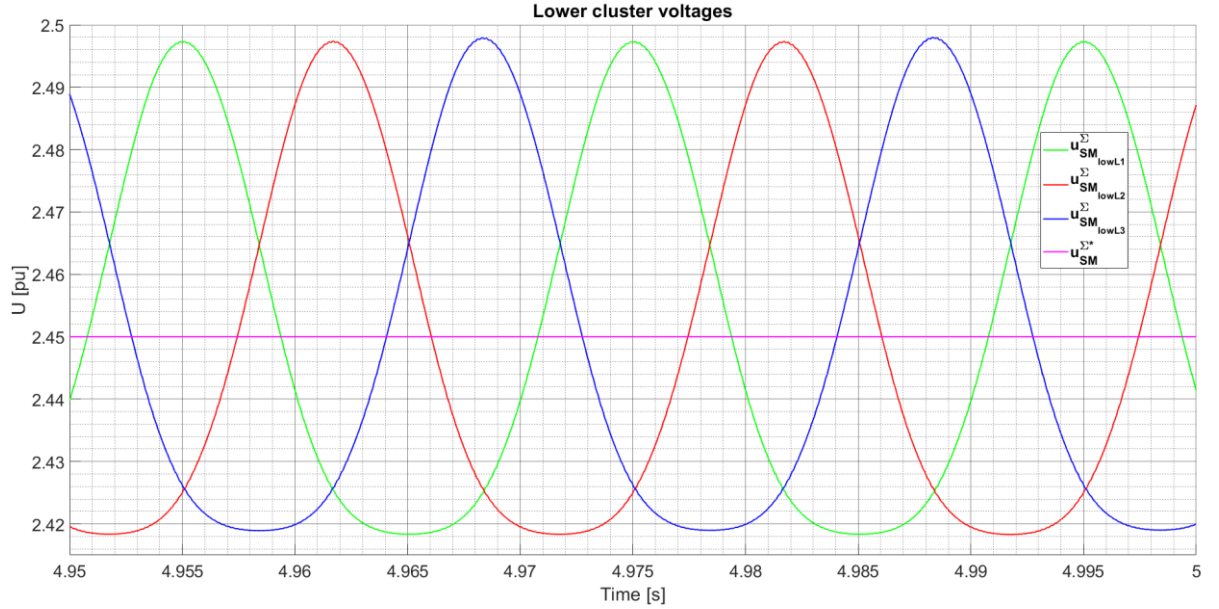


Figure 112: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*}=1$ pu capacitive during one line-to-earth short-circuit steady-state in simulation

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.079 pu. The mean value over one period of time is 2.450 pu which is equal to the reference $u_{SMu,l}^{\Sigma*}$.

We can conclude that cluster voltages are balanced around the reference value $u_{SMu,l}^{\Sigma*}$ and so that internal stability is guaranteed when $I_{h1}^{+*}=1$ pu capacitive during one line-to-earth short-circuit steady-state in simulation.

It is important also to verify the STATCOM is able to withstand the transient of one line-to-earth short-circuit. Grid currents during this transient are shown in Figure 113.

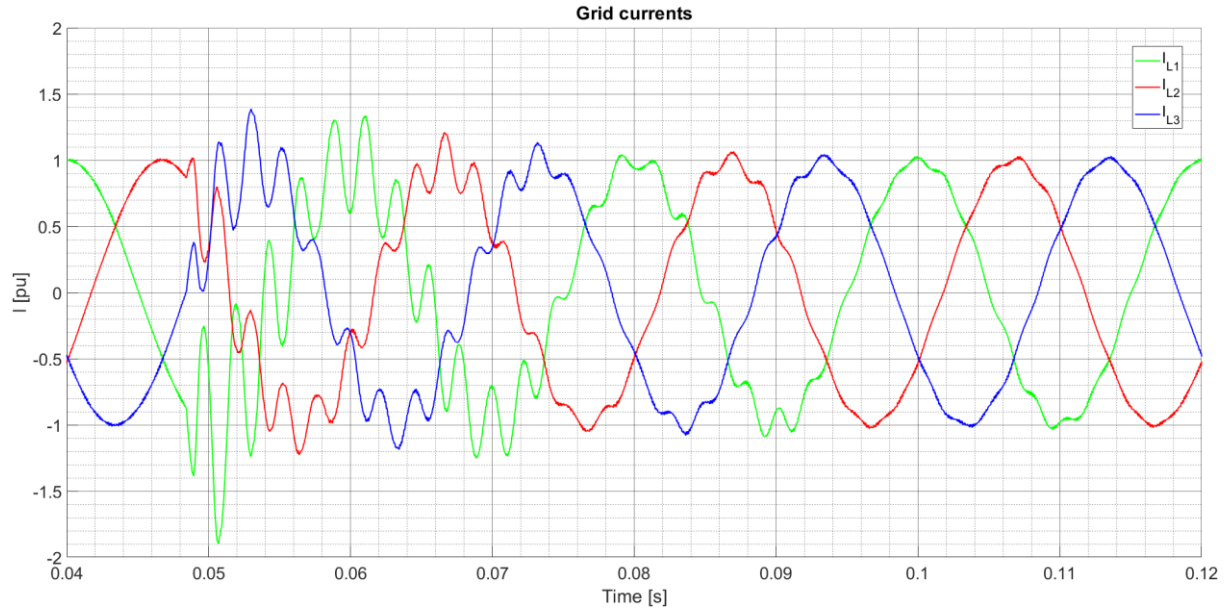


Figure 113: DSCC grid currents when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit transient in simulation

As it can be seen in Figure 113, grid currents continue to follow the $I_{h1}^{+*}=1\text{pu}$ capacitive reference during the transient. However, at the beginning of the transient, important oscillations occur going until -1.896 pu (phase L1). This point is important to consider during the design stage of STATCOM. It can be noticed that the transient is absorbed in nearly 3 periods.

Figure 114 and Figure 115 show the internal cluster voltages during this transient.

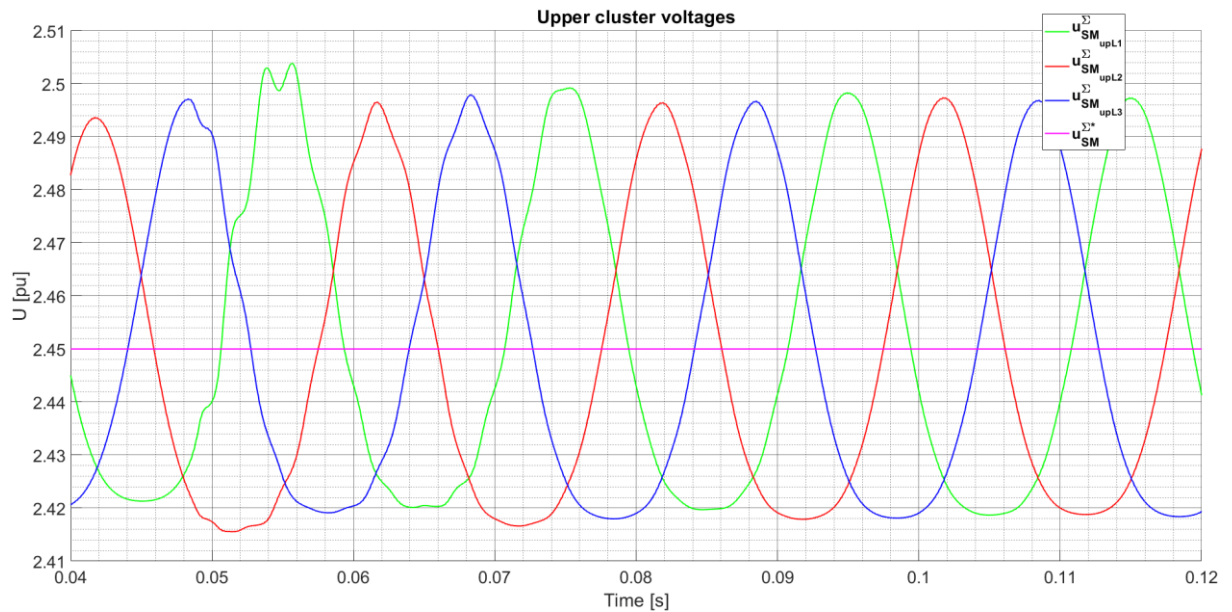


Figure 114: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit transient in simulation

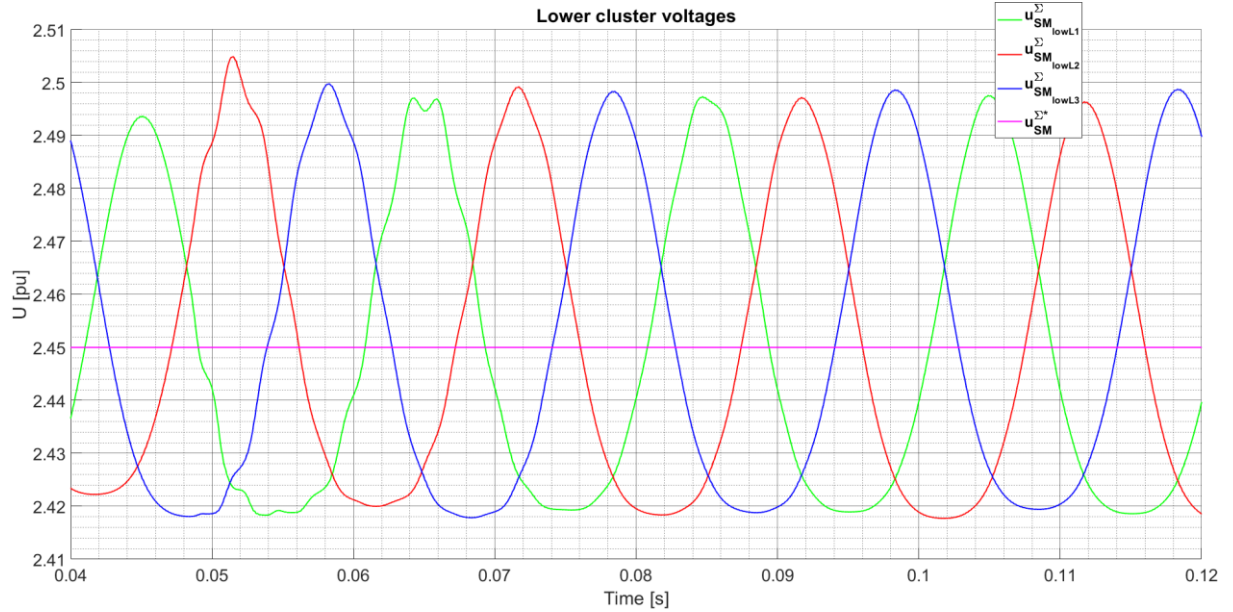


Figure 115: DSCC lower arm cluster voltage for each leg when $I_{h1}^{++}=1$ pu capacitive during one line-to-earth short-circuit transient in simulation

Cluster voltages contain also additional oscillations but remain stable, as the currents, during this transient. The maximum cluster voltage reached is 2.505 pu. Cluster voltages are less impacted than current during this transient and remain stable. These results imply that the DSCC STATCOM with this control strategy is also able to withstand the transient of one line-to-earth short-circuit.

Finally, it is possible to validate the correct DSCC operation to exchange $I_{h1}^{++}=1$ pu capacitive with grid during one line-to-earth short-circuit in simulation with the proposed control strategy.



16.6 Simulations of DSCC positive sequence capacitive current operation during two lines-to-earth short-circuit (detailed results).

It is important to remind that two lines-to-earth short-circuit directly at STATCOM input is the worst voltage grid unbalanced state for the STATCOM and converters in general. DSCC simulations for two lines-to-earth short-circuit use the electrical schematic presented in Figure 23.

The grid voltage in simulation is applied as in Figure 17. At the beginning of this simulation, grid voltages are balanced and the simulation parameters used are the same as in Table 8. DSCC STATCOM exchanges $Q_{STATCOM}^* = +1pu$ or $Q_{STATCOM}^* = -1pu$. Then, when time = 0.0484 s the two lines-to-earth short-circuit appears on phases L1 and L2 meaning the grid voltages $u_{gsL1} = 0 pu$ as well as $u_{gsL2} = 0 pu$. In the same time, phase voltage L3 amplitude increases. It can be seen a transient for around three periods. Then the two lines-to-earth short-circuit steady state voltage is reached. The steady state phase voltages are the following:

- $u_{gsL1}(steady\ state) = 0 pu$
- $u_{gsL2}(steady\ state) = 0 pu$
- $u_{gsL3}(steady\ state) = 1.476 pu$

In general, short-circuit in the network are cleared in maximum 5s. It means the STATCOM has to continue to operate during this time until the fault is cleared. The voltage amplitudes applied are based on the SIL network case study (see Table 3). As well, the phase displacement between phase voltages are modified (see Table 3).

The grid currents results when positive sequence inductive current ($I_{h1}^{++}=1pu$ inductive) is exchanged between DSCC and grid at the end of short circuit are shown in Figure 116.

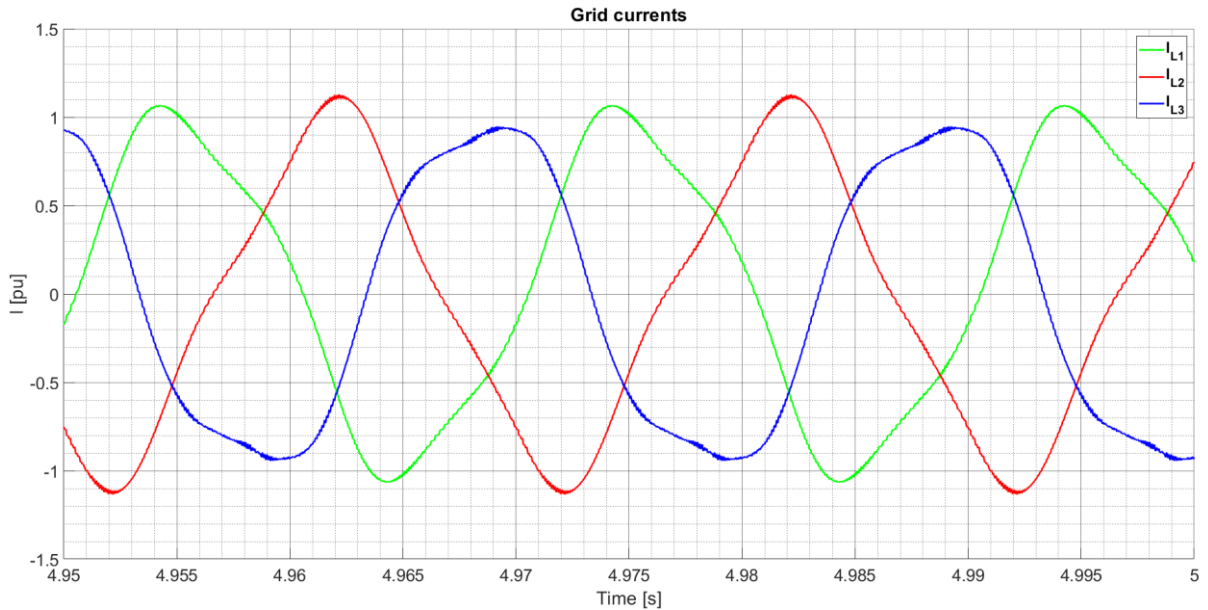


Figure 116: DSCC grid currents when $I_{h1}^{++}=1pu$ capacitive at the end of two lines-to-earth short-circuit steady-state in simulation

In Figure 116, it can be seen that the currents are 50 Hz distorted sinusoids. The simulations give the currents THD in steady-state for each phase:

- $THDi_{L1}(I_{h1}^{++} = 1pu\ capacitive\ and\ L1 + L2\ in\ SC) = 12.7\ \%$
- $THDi_{L2}(I_{h1}^{++} = 1pu\ capacitive\ and\ L1 + L2\ in\ SC) = 12.6\ \%$
- $THDi_{L3}(I_{h1}^{++} = 1pu\ capacitive\ and\ L1 + L2\ in\ SC) = 13.2\ \%$

Contrary to grid voltage balanced state, $THDi(I_{h1}^{++} = 1pu\ capacitive\ and\ L1 + L2\ in\ SC)$ is quite high but lower than inductive case. The third harmonic (150 Hz) is the most important with around 13% of the fundamental value followed by the fifth harmonic (250 Hz) with around 0.8% of the fundamental value. Other harmonics are negligible with less than 0.5% of the fundamental value. Two lines-to-earth short-



circuit has a quite important impact on the quality of the currents. This is due to converter topology and control which has to keep the converter stable. To solve this issue, additional techniques in the control or filters could be used to attenuate the harmonics. However, given that two lines-to-earth short-circuit are uncommon and do not last more than few seconds, it does not bring any significant added value for the overall STATCOM operation (mainly balanced network operation). As a remark, the internal instability is not responsible for this amount of THDi because the internal state in this case is far from instability.

The fundamental RMS value of positive and negative sequence grid currents given by simulation are:

- $\hat{I}_{h1}^+ (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 1.000 pu$
- $\hat{I}_{h1}^- (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.000 pu$

This implies no imbalance is seen at fundamental frequency. The converter regulates well the current to provide only 50 Hz positive sequence current. But the third harmonic brings notable negative sequence. The overall Current Unbalance Factor (CUF) is:

$$- \quad CUF(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = \frac{I_{rms}^-}{I_{rms}^+} = \frac{0.056}{1.003} * 100 = 5.6 \%$$

This value is negligible considering the grid voltage short circuit state (VUF = 100%).

All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*}=1pu$ capacitive in spite of the distortion which is notable during two line-to-earth short-circuit steady-state in simulation.

The second goal is now to verify the DSCC exchanges fundamental positive sequence capacitive reactive power with the grid. During two lines-to-earth short-circuit steady-state, the rms value of fundamental positive sequence voltage ($U_{rms_{h1}}^+$) is equal to 0.492 pu (see Table 3). Simulation results give the fundamental positive sequence phase shift between voltages and currents: $\theta_{h1}^+ = -88.5^\circ$. It is then possible to calculate the powers:

- $P_{h1}^+ (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.012 pu$
- $Q_{h1}^+ (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = -0.492 pu$

DSCC converter exchanges Q_{h1}^+ in great majority meaning that it continues to operate mainly as a balanced capacitive STATCOM. However, as mentioned earlier in the report, Q_{h1}^+ is half of the base power value because positive sequence of voltage is half of the base value and positive sequence of current is voluntarily kept to 1 pu capacitive to avoid high current value in the prototype. Other components of active and reactive powers are not the point of interest in our application. But it is important to mention that these components add notable ripples to the overall powers which are not desired in normal operation.

To confirm the capacitive operation of the converter, Figure 117 presents the current and its respective voltage for L3.

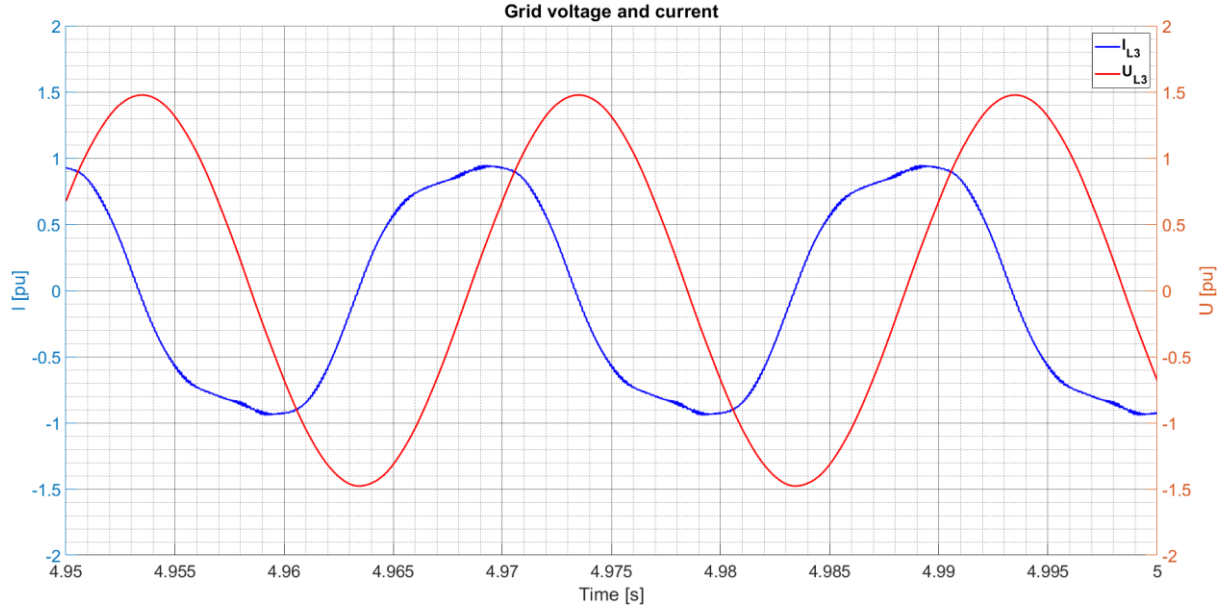


Figure 117: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit steady-state in simulation

Simulation gives us the displacement angle between voltage and current for phase L3:

$$\theta_{h1L3}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 89.2^\circ$$

This displacement angle is used as reference for the comparison with experimental measurements. It confirms the current is leading the voltage meaning capacitive operation.

It is also important to verify the STATCOM is able to withstand the transient of two lines-to-earth short-circuit. Grid currents during this transient are shown in Figure 118.

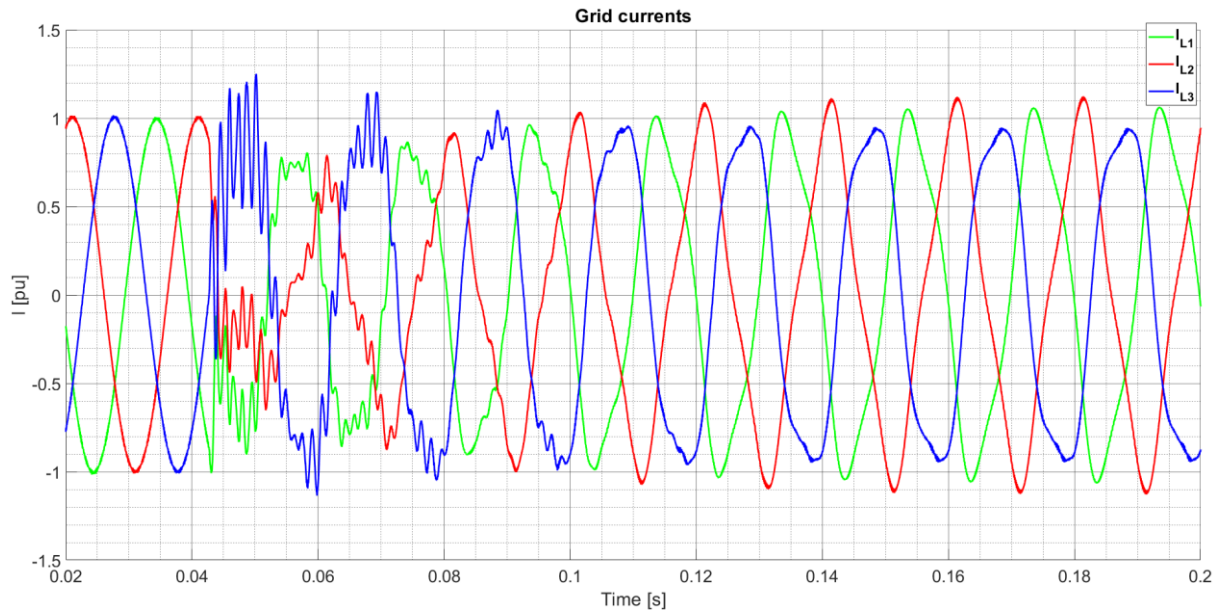


Figure 118: DSCC grid currents when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit transient in simulation

As it can be seen in Figure 118, grid currents continue to follow the $I_{h1}^{+*}=1\text{pu}$ capacitive reference during the transient. However, at the beginning of the transient (at 0.0484 s), oscillations occur going until 1.251 pu (phase L3). It can be noticed that the transient is absorbed in nearly 3 periods.

During the 5 seconds of two lines-to-earth short-circuit, the transient and steady-state currents exchanged with the grid in simulation confirm correct capacitive operation of the STATCOM.



However, as explained above, cluster voltages are slowly moving away from their reference ($u_{SM_{u,l}}^{\Sigma*} = 2.45 \text{ pu}$). The upper arm cluster voltage for each leg with $I_{h1}^{+*}=1\text{pu}$ capacitive in simulation and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 119.

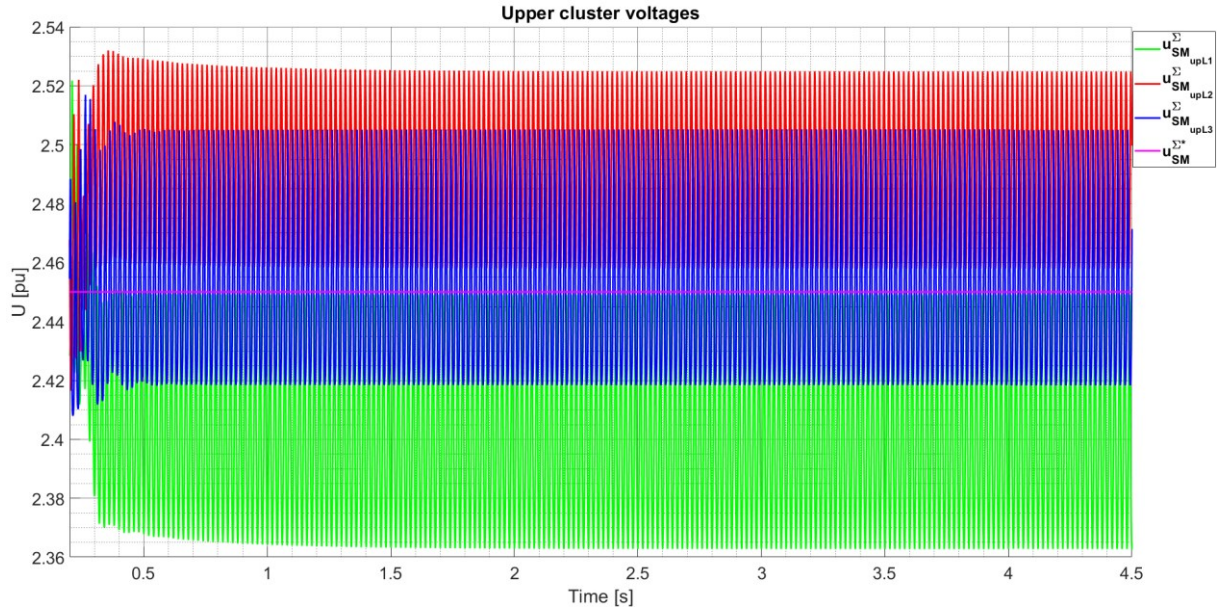


Figure 119: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during two lines-to-earth short-circuit in simulation

In Figure 119, L1 and L2 upper cluster voltages are very slowly decreasing while L3 is decreasing even more slowly. We can notice that in this time interval, upper cluster voltages are almost stable.

The final value before 5s of short-circuit are shown in Figure 120.

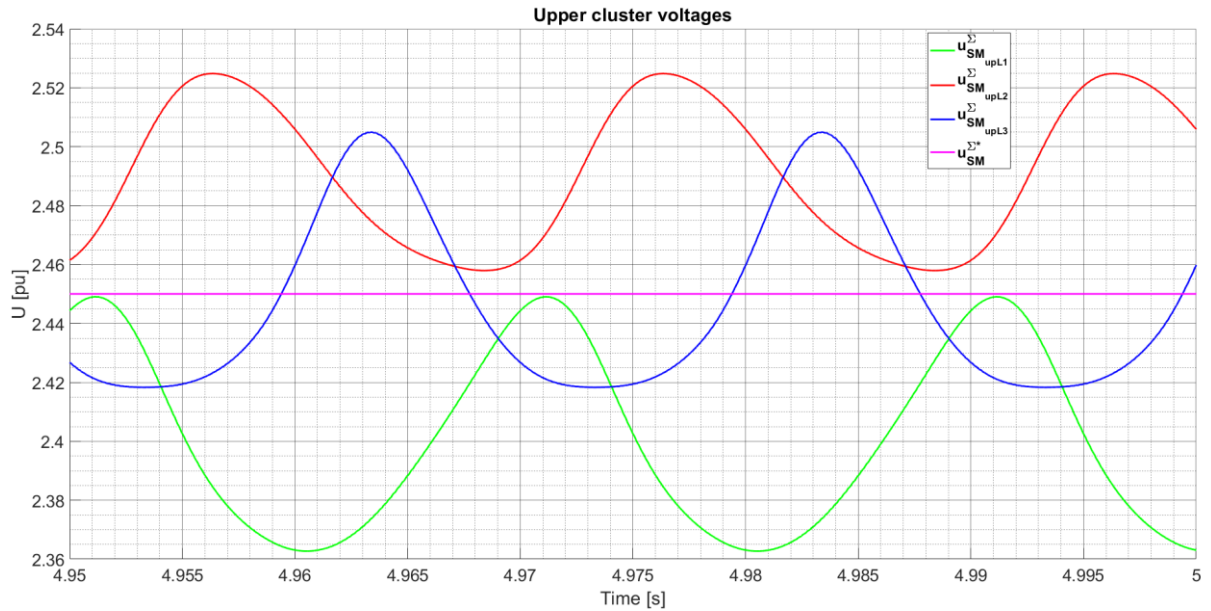


Figure 120: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive at the end of two lines-to-earth short-circuit in simulation

As it can be seen, after 5 seconds of short-circuit, their peak-to-peak amplitudes are:

$$- u_{SM_{upL1pp}}^{\Sigma}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.086 \text{ pu}$$



- $u_{SM_{upL2pp}}^{\Sigma}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.067 pu$
- $u_{SM_{upL3pp}}^{\Sigma}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.087 pu$

Ripple amplitudes are maximum 1.1 times higher than the balanced case (phase L3) but stay reasonable for STATCOM hardware safety operation.

It can also be noted that L3 phase stay around the setpoint value but L2 and L1 phases do not have the same average value. This internal unbalance between phases is not an issue for the overall internal operation.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*}=1pu$ capacitive in simulation and the reference $u_{SM_{u,l}}^{+*}$ are shown in Figure 121.

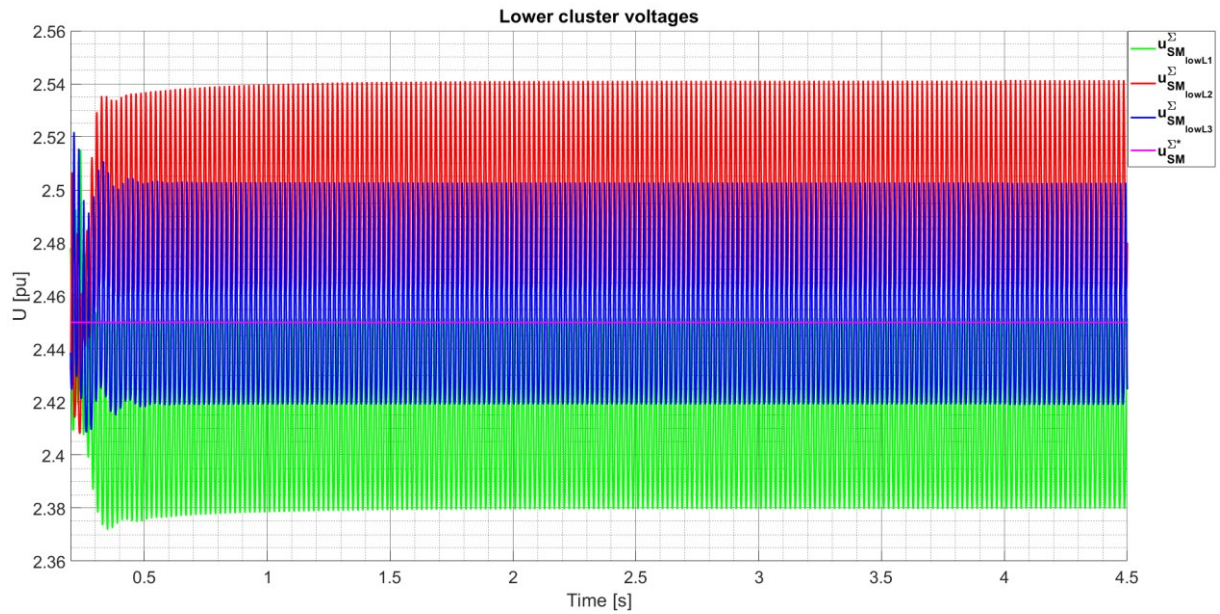


Figure 121: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive during two lines-to-earth short-circuit in simulation

In Figure 121, L1 and L2 lower cluster voltages are very slowly decreasing while L3 is decreasing even more slowly. We can notice that in this time interval, lower cluster voltages are almost stable.

The final value before 5s of short-circuit are shown in Figure 122.

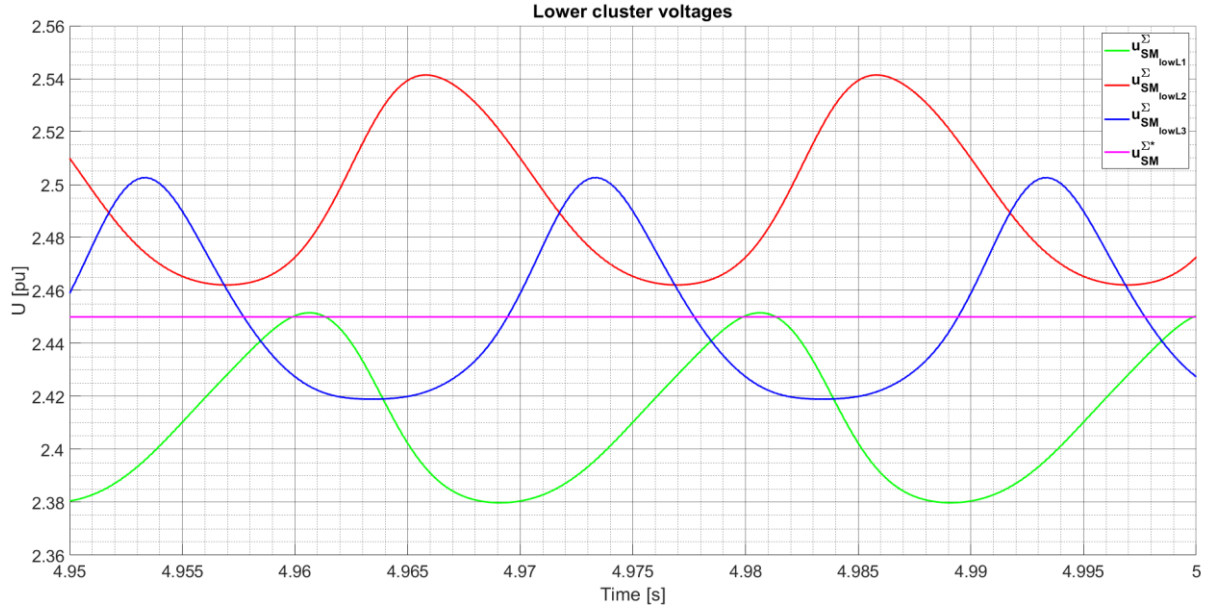


Figure 122: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive at the end of two lines-to-earth short-circuit in simulation

As it can be seen, after 5 seconds of short-circuit, their peak-to-peak amplitudes are:

- $u_{SM_{lowL1pp}}^{\Sigma} (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.072 pu$
- $u_{SM_{lowL2pp}}^{\Sigma} (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.079 pu$
- $u_{SM_{lowL3pp}}^{\Sigma} (I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.084 pu$

Ripple amplitudes are maximum 1.06 times higher than the balanced case (phase L3) but stay reasonable for STATCOM hardware safety operation.

It can also be noted that L3 phase stay around the setpoint value but L2 and L1 phases do not have the same average value. This internal unbalance between phases is not an issue for the overall internal operation.

As already mentioned, in the extreme case of two lines-to-earth short-circuit at STATCOM input, the control strategy proposed in this project does not allow to maintain a permanent internal stability of the cluster voltages. The arm energy balancing controller of each leg cannot be regulated to zero. As a consequence, the upper and lower cluster voltage of each arm are respectively increasing and decreasing. However, after 5 seconds of short-circuit (very high time duration in power systems), simulation results show that internal unbalance is reasonable to continue to exchange correct currents with the grid while insuring the internal safety of the DSCC. Indeed, maximum cluster voltage reached (phase L2) is 2.541pu which is 0.091pu over the reference value. Dividing this value by 5 gives maximum voltage increase for each capacitor in the arm: 0.018 pu. This small increase compared to the nominal voltage value (3.7% of relative deviation) means the DSCC do not need to be disconnected for safety reason. Indeed, this increase do not impact significantly the design of the capacitors of the DSCC.

Finally, all simulation results of this section confirm DSCC correct operation of the converter to exchange positive sequence capacitive current ($I_{h1}^{+*}=1pu$ capacitive) during 5s of two lines-to-earth short-circuit with the proposed control strategy.



16.7 DSCC capacitive operation tests with balanced voltages (detailed results)

Thanks to $Q_{STATCOM}^* = -1 \text{ pu}$ tests realised according to the protocol mentioned in 4.3.10.1, it is possible to fully analyse the DSCC prototype results and to compare it with the simulation results.

The grid simulator voltages during $Q_{STATCOM}^* = -1 \text{ pu}$ are visible in Figure 123.

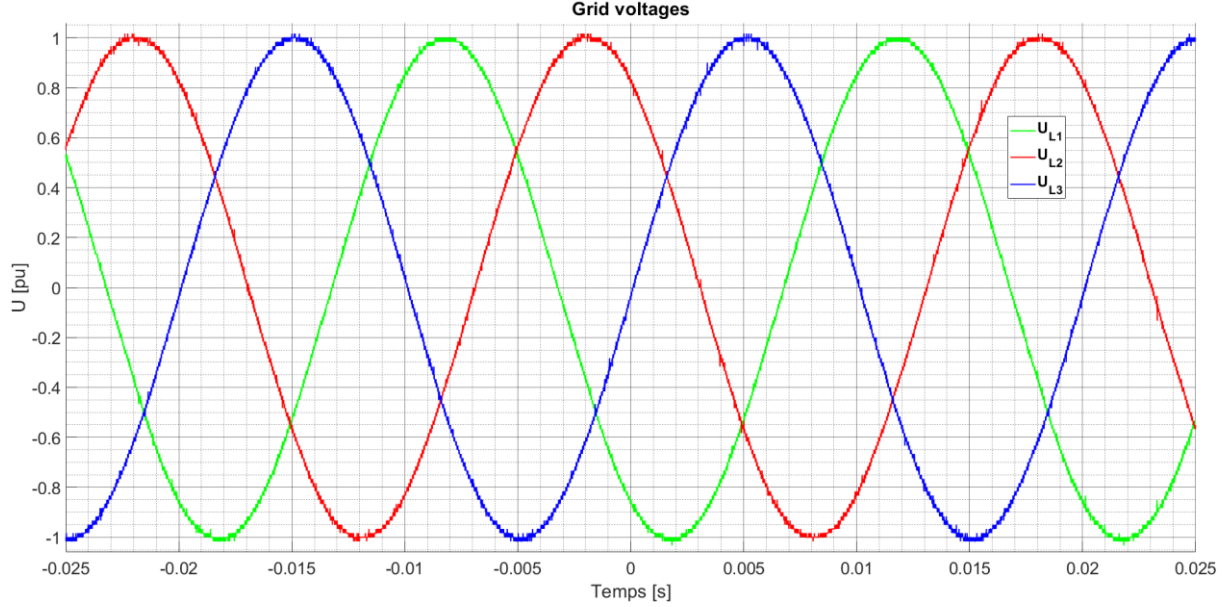


Figure 123: Balanced grid voltages of grid simulator during $Q_{STATCOM}^* = -1 \text{ pu}$ tests

On Figure 123, it can be seen that the voltages are 50 Hz sinusoids. The 50 Hz frequency average over one-minute test is confirmed by power quality analyser measurements. The power quality analyser gives the same voltage THD for each phase: 0.3%. The fundamental RMS value of grid voltages (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values are given in pu:

- $\hat{U}_{L1h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.000 \text{ pu}$
- $\hat{U}_{L2h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.000 \text{ pu}$
- $\hat{U}_{L3h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.000 \text{ pu}$

The fundamental displacement angles are given below:

- $\varphi_{uL1 \rightarrow uL2}(Q^* = -1 \text{ pu test balanced voltages}) = -120^\circ$
- $\varphi_{uL1 \rightarrow uL3}(Q^* = -1 \text{ pu test balanced voltages}) = +120^\circ$

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 0.03%. These results confirm that the grid simulator provides balanced voltages to the DSCC prototype when $Q_{STATCOM}^* = -1 \text{ pu}$. Voltages are equal to 1 pu because the STATCOM operates as a capacitor. Then it compensates the inductive reactive power of the cables and inductors of the testing circuit presented in Figure 43. The grid voltage is then increased to its nominal level in this case.

With $Q_{STATCOM}^* = -1 \text{ pu}$, grid currents waveforms are shown in Figure 124.

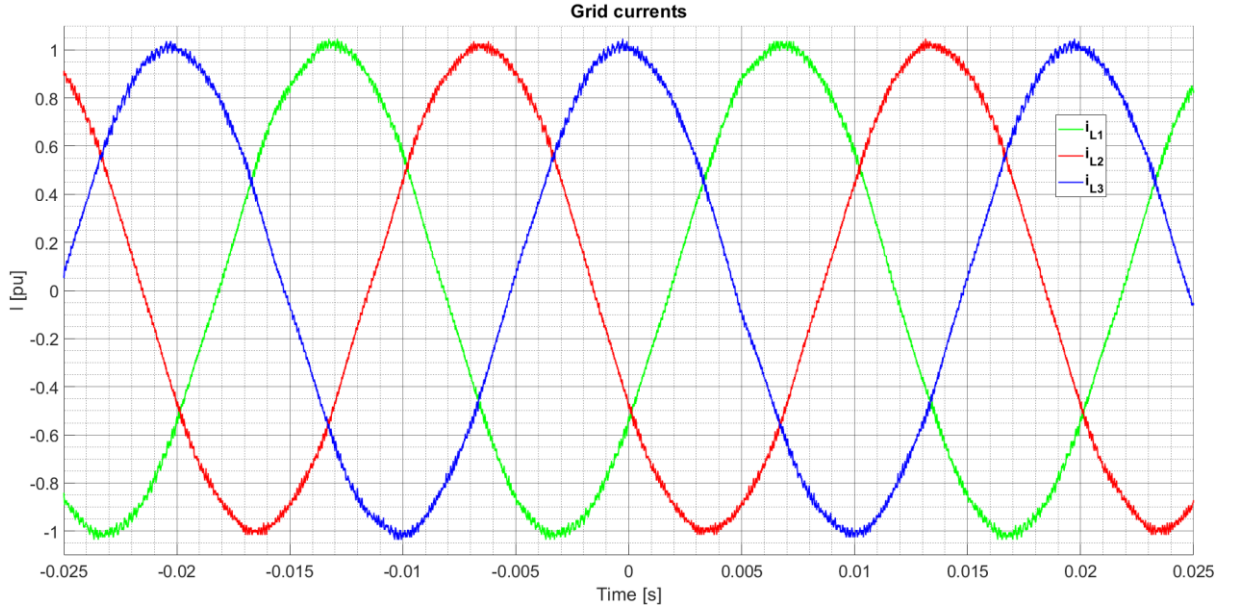


Figure 124: DSCC grid currents when grid voltages are balanced during $Q_{STATCOM}^* = -1 \text{ pu}$ test

On Figure 124, it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD in one-minute average for each phase:

- $THDi_{L1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.2\%$
- $THDi_{L2}(Q^* = -1 \text{ pu test balanced voltages}) = 1.3\%$
- $THDi_{L3}(Q^* = -1 \text{ pu test balanced voltages}) = 1.3\%$

Compared to simulation results, THD maximum increase is of 0.3%. This difference is negligible. This is mainly due to measurement noise and non-ideal components characteristics.

The fundamental RMS value of grid currents (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values in one-minute average are given in pu:

- $\hat{I}_{L1h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.022 \text{ pu}$
- $\hat{I}_{L2h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.018 \text{ pu}$
- $\hat{I}_{L3h1}(Q^* = -1 \text{ pu test balanced voltages}) = 1.002 \text{ pu}$

The fundamental displacement angles are given below:

- $\varphi_{iL1 \rightarrow iL2}(Q^* = -1 \text{ pu test balanced voltages}) = -120^\circ$
- $\varphi_{iL1 \rightarrow iL3}(Q^* = -1 \text{ pu test balanced voltages}) = +120^\circ$

Furthermore, power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^+(Q^* = -1 \text{ pu test balanced voltages}) = 1.013 \text{ pu}$
- $\hat{I}_{h1}^-(Q^* = -1 \text{ pu test balanced voltages}) = 0.007 \text{ pu}$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.7\%$ which is negligible. These second elements confirm again that the current provided by the DSCC prototype is well balanced in case of grid voltages balanced when $Q_{STATCOM}^* = -1 \text{ pu}$ which is one of the two goals needed to validate the correct STATCOM operation.

It is also important to verify that the reactive power is exchanged correctly. During the one-minute test where $Q_{STATCOM}^* = -1 \text{ pu}$, the average power values measured via the power quality analyser over this period in steady state are:



- $Q_{h1}^+(Q^* = -1pu \text{ test balanced voltages}) = -1.013 pu$
- $P_{h1}^+(Q^* = -1pu \text{ test balanced voltages}) = 0.022 pu$
- $P(Q^* = -1pu \text{ test balanced voltages}) = 0.022 pu$

The relative deviation between reactive power reference and measurement is equal to $\Delta_Q(Q^* = -1pu \text{ test balanced voltages}) = 1.3 \%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator.

Active powers (= losses for STATCOM) are negligible compared to reactive power exchanged with the grid. Given that the currents and voltages are well balanced, it can be noted that $P_{h1}^+ = P$ is a good approximation. It is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(Q^* = -1pu \text{ test balanced voltages}) = 214 \%$. This is because, the simulation was not performed to precisely represent the prototype losses (cables, losses of components, components imperfection). It would have required an important additional work that was impossible to fulfil in the timeline of the project. However, the aim of the simulation was to design a STATCOM control strategy able to follow a reactive power reference as well as maintaining the internal behaviour stable. The results shown in this section confirm the correct operation of the converter to follow a reactive power setpoint. It means the simulation reached its goal which was to provide an operational control strategy for the STATCOM.

To confirm STATCOM inductive reactive power exchanged Figure 125, Figure 126 and Figure 127 show each corresponding phase current and voltage.

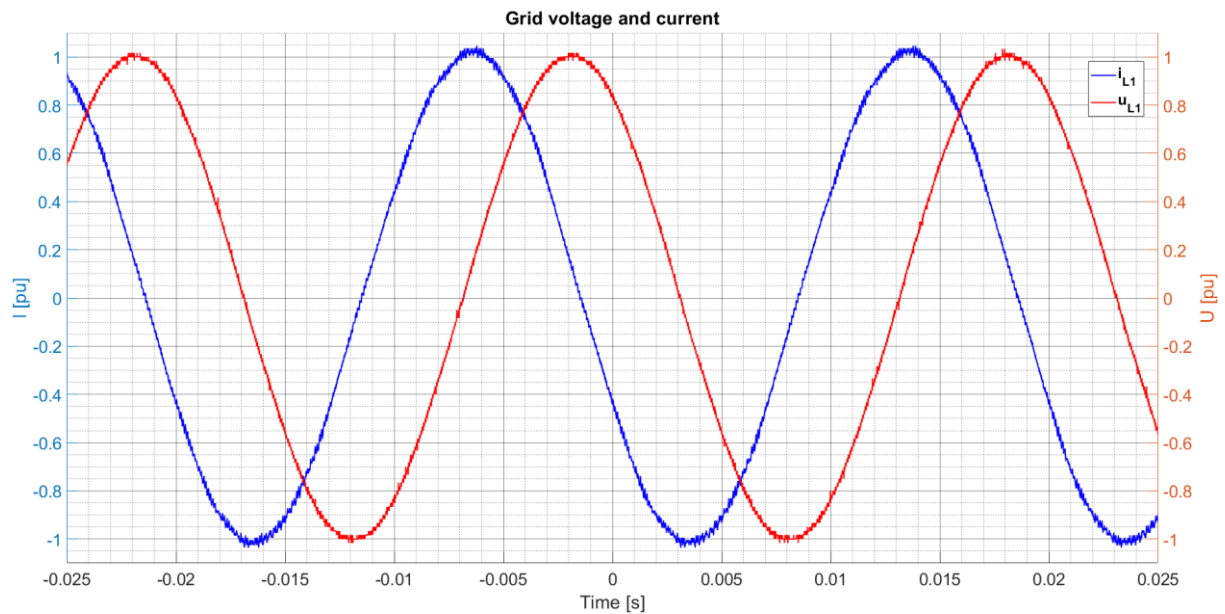


Figure 125: DSCC grid voltage and current of phase L1 when grid voltages are balanced during $Q_{STATCOM}^* = -1pu$ test (second test configuration)

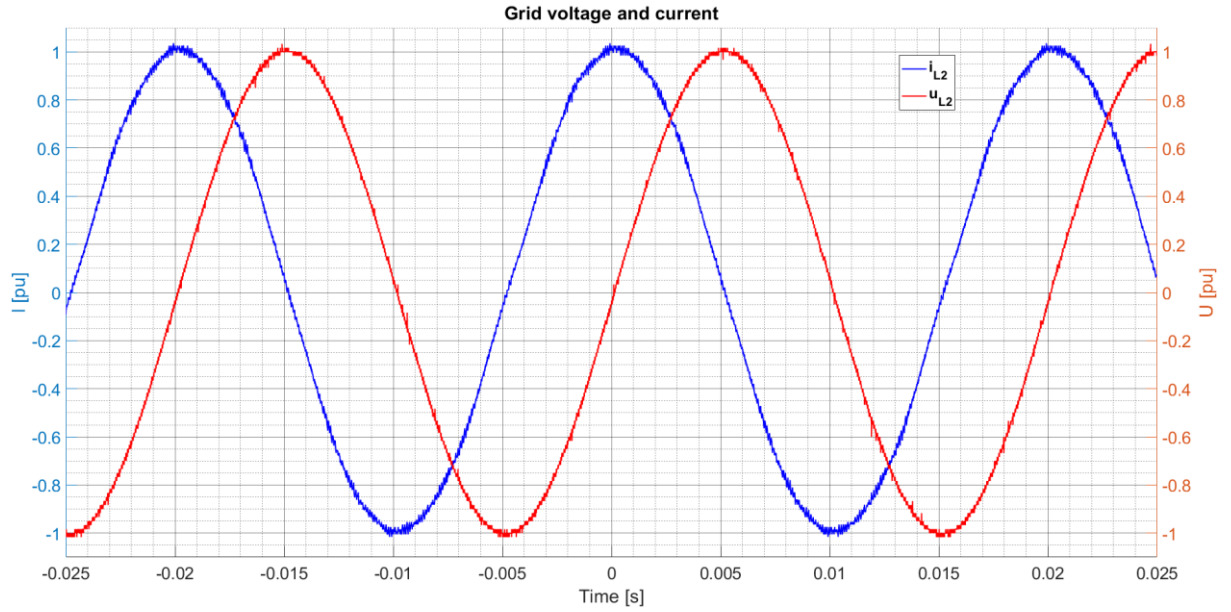


Figure 126: DSCC grid voltage and current of phase L2 when grid voltages are balanced during $Q_{STATCOM}^* = -1\text{pu}$ test (second test configuration)

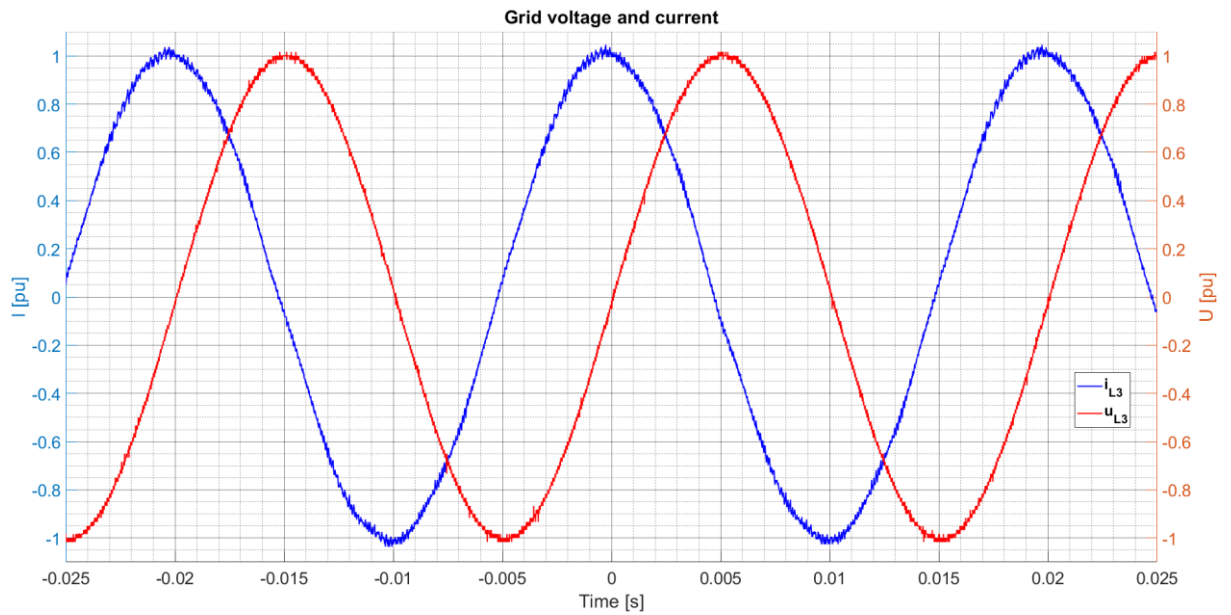


Figure 127: DSCC grid voltage and current of phase L3 when grid voltages are balanced during $Q_{STATCOM}^* = -1\text{pu}$ test (first test configuration)

It can be seen that the currents are leading their respective voltage by nearly 90° as a capacitor. The phase shift difference between the measurements and 90° corresponds to the active power losses of the DSCC STATCOM. Again, the phase shift difference compared to 90° is higher than in simulations due to higher losses of the real prototype.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SM_{u,l}}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_{u,l}}^{\Sigma*}$) equal to 2.45 pu (as in simulation). The upper arm cluster voltage for each leg at $Q_{STATCOM}^* = -1\text{pu}$ recorded by the DSCC prototype and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 128.

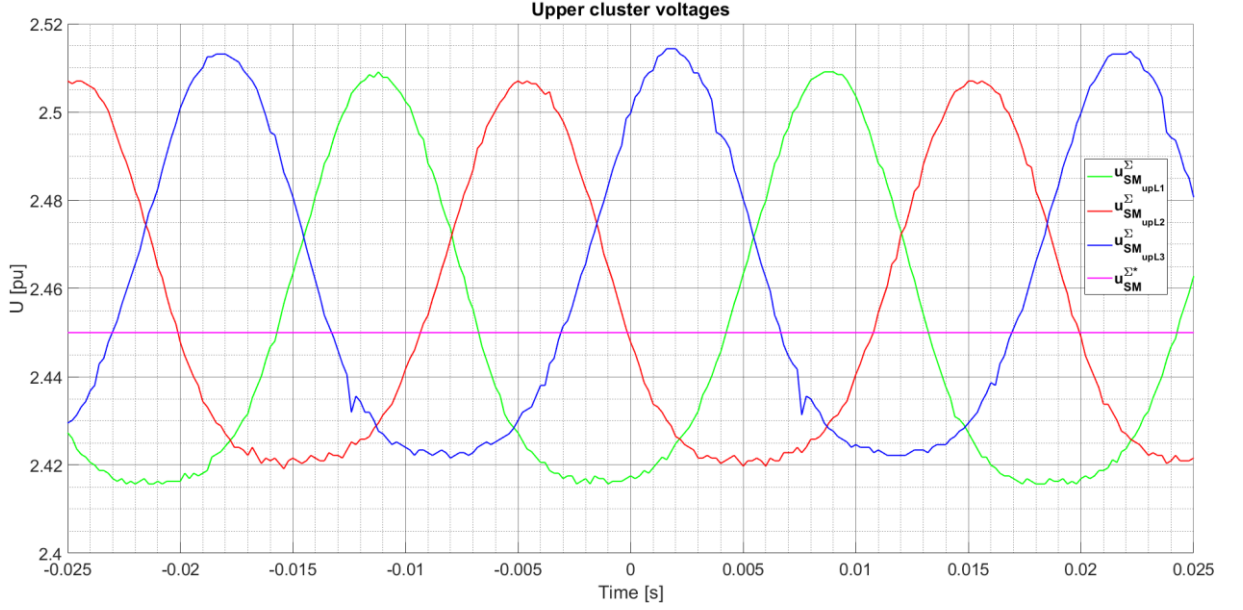


Figure 128: DSCC upper arm cluster voltage for each leg when grid voltages are balanced during $Q_{STATCOM}^* = -1pu$ test

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.090 pu in average. The peak-to-peak amplitude of prototype is 1.14 times higher than in simulation. This difference is acceptable. It is due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{upL1}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.451 pu$
- $\overline{u_{SM_{upL2}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.454 pu$
- $\overline{u_{SM_{upL3}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.459 pu$

The highest relative deviation between reference value $u_{SM_{u,l}}^{\Sigma*}$ and the three $\overline{u_{SM_{up}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{up}}^{\Sigma}}}(Q^* = -1pu \text{ simulation balanced voltages}) = 0.4\%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference. Small differences between phases are also due to small inequalities of physical components between phases (principally SM capacitances, arm inductance and overall arm resistance).

As well, the lower arm cluster voltage for each leg at $Q_{STATCOM}^* = -1pu$ recorded by the DSCC prototype and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 129.

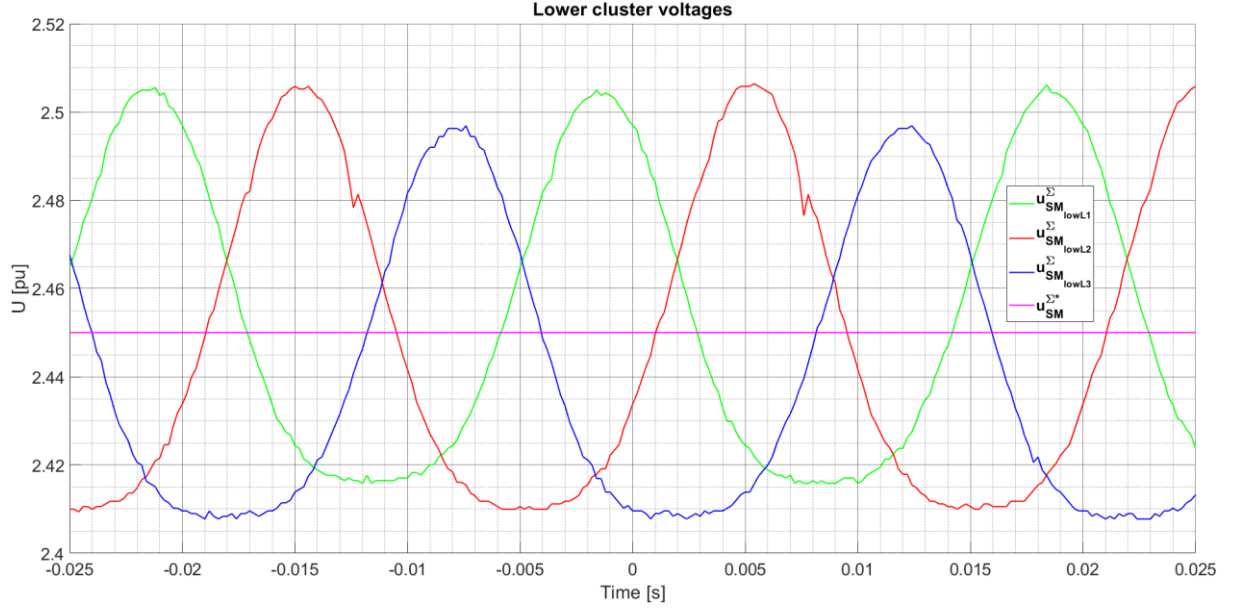


Figure 129: DSCC lower arm cluster voltage for each leg when grid voltages are balanced during $Q_{STATCOM}^* = -1pu$ test

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.091 pu in average. The peak-to-peak amplitude of prototype is 1.15 times higher than in simulation. This difference is acceptable. It is due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{lowL1}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.451 \text{ pu}$
- $\overline{u_{SM_{lowL2}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.448 \text{ pu}$
- $\overline{u_{SM_{lowL3}}^{\Sigma}}(Q^* = -1pu \text{ test balanced voltages}) = 2.443 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{\Sigma*}$ and the three $\overline{u_{SM_{low}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{low}}^{\Sigma}}}(Q^* = -1pu \text{ simulation balanced voltages}) = 0.3 \%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference. Small differences between phases are also due to small inequalities of physical components between phases (principally SM capacitances, arm inductance and overall arm resistance).

On both Figure 128 and Figure 129 some small spikes are sometimes visible. These spikes correspond to hardware measurement error that can occur for one sample as well as for $Q_{STATCOM}^* = +1pu$ test. The error is always less than 0.008 pu which is negligible. This is why the results are still coherent. It is worth to be noted that this is not due to physical principle of the DSCC. Indeed, as it can be seen in simulation, these spikes are not present.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_{u,l}}^{\Sigma*}$ and so that internal stability is guaranteed when $Q_{STATCOM}^* = -1pu$ and grid voltages are balanced. Furthermore, the test results confirm the simulation correctness.

In case of grid voltage balanced, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange -1 pu positive sequence reactive power with the grid simulator while maintaining the internal behaviour stable. In addition, except for DSCC converter losses (see above in this section), test results precisely match the simulation results and THD of the currents are small enough not to disturb correct grid operations.



16.8 Test of DSCC positive sequence capacitive current operation during one line-to-earth short-circuit (detailed results)

The results for $I_{h1}^{++}=1\text{pu}$ capacitive operation under one line-to-earth short-circuit grid voltages are presented below. Given that transient results are similar to the $I_{h1}^{++}=1\text{pu}$ inductive case, transient results are not presented to lighten the report content. So, the one line-to-earth short-circuit steady-state results are then presented.

The grid simulator voltages during $I_{h1}^{++}=1\text{pu}$ capacitive operation are visible in Figure 130.

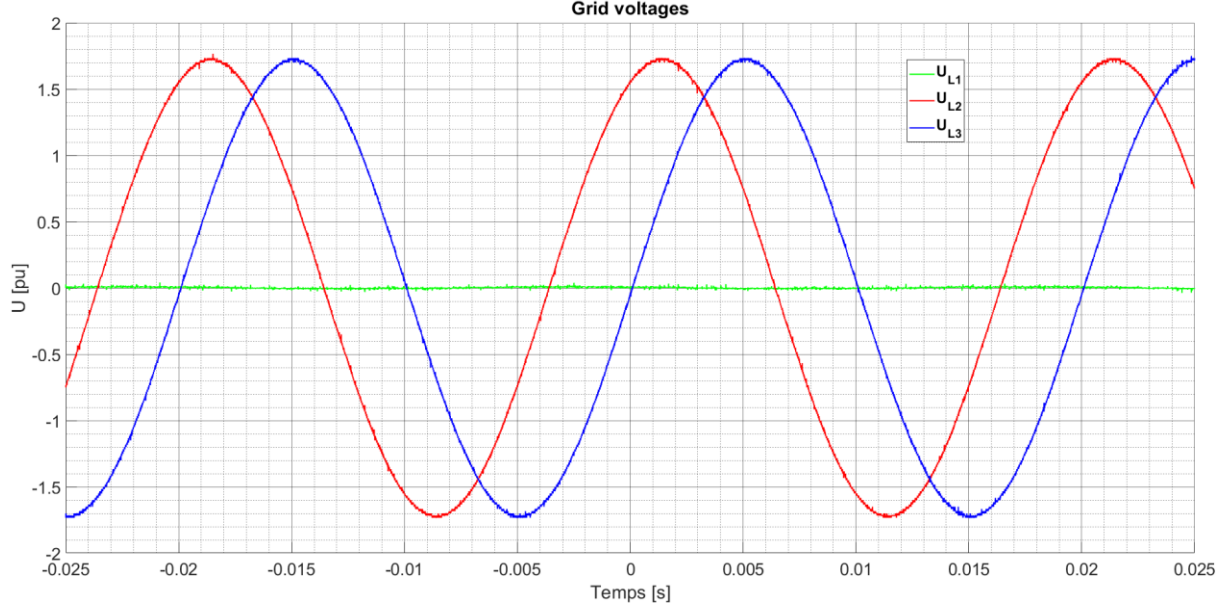


Figure 130: Steady-state unbalanced one line-to-earth short-circuit grid voltages during $I_{h1}^{++}=1\text{pu}$ capacitive test

On Figure 130, it can be seen that the voltages are 50 Hz sinusoids unbalanced. The 50 Hz frequency average over one-minute test is confirmed by power quality analyser measurements. The power quality analyser gives the voltage THD in steady-state for each phase:

- $THDu_{L1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 22.2 \%$
- $THDu_{L2}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 0.2 \%$
- $THDu_{L3}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 0.2 \%$

The high THDu of phase L1 is due to the very low voltage amplitude which is not a constant zero. However, with important amplitudes, THDu of L2 and L3 are very low.

The fundamental RMS value of grid voltages are given by the power quality analyser. The corresponding peak values are given in pu:

- $\hat{U}_{L1h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 0.006 \text{ pu}$
- $\hat{U}_{L2h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.725 \text{ pu}$
- $\hat{U}_{L3h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 1.723 \text{ pu}$

Compared to simulation, it can be seen that $\hat{U}_{L1h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC})$ is not completely null. This is due to the fact the grid simulator is not a perfect device. It has an internal impedance which is never null. Given that current is still exchanged, it creates a residual voltage. The 0.006 pu value is considered negligible. Relative deviation compared to simulation value are given for phase L2 and L3:

- $\Delta\hat{U}_{L2h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 0.9\%$
- $\Delta\hat{U}_{L3h1}(I_{h1}^{++} = 1\text{pu capacitive and L1 in SC}) = 0.5\%$

These relative deviations confirm the correct operation of the grid simulator to provide the correct amplitude for phase L2 and L3.



The fundamental displacement angles between phase voltages are given below:

- $\varphi_{uL1 \rightarrow uL2}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = -77^\circ$
- $\varphi_{uL1 \rightarrow uL3}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = -137^\circ$
- $\varphi_{uL2 \rightarrow uL3}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = -60^\circ$

Displacement angle between L2 and L3 is the only one comparable with value of Table 3, because L1 is considered null in theory. The relative deviation is 0.9%. This small difference with theory is mainly explained by the precision of grid simulator and power quality accuracy.

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 0.4%. The relative deviation with the value in Table 3 is equal to 33%. This deviation stays reasonable for small values like this.

Apart from phase L1 which is slightly different compared to simulation, the correct operation of the grid simulator to provide the one line-to-earth short-circuit with $I_{h1}^{+*} = 1pu \text{ capacitive}$ is confirmed.

Grid currents waveforms during $I_{h1}^{+*} = 1pu$ capacitive operation are visible in Figure 131.

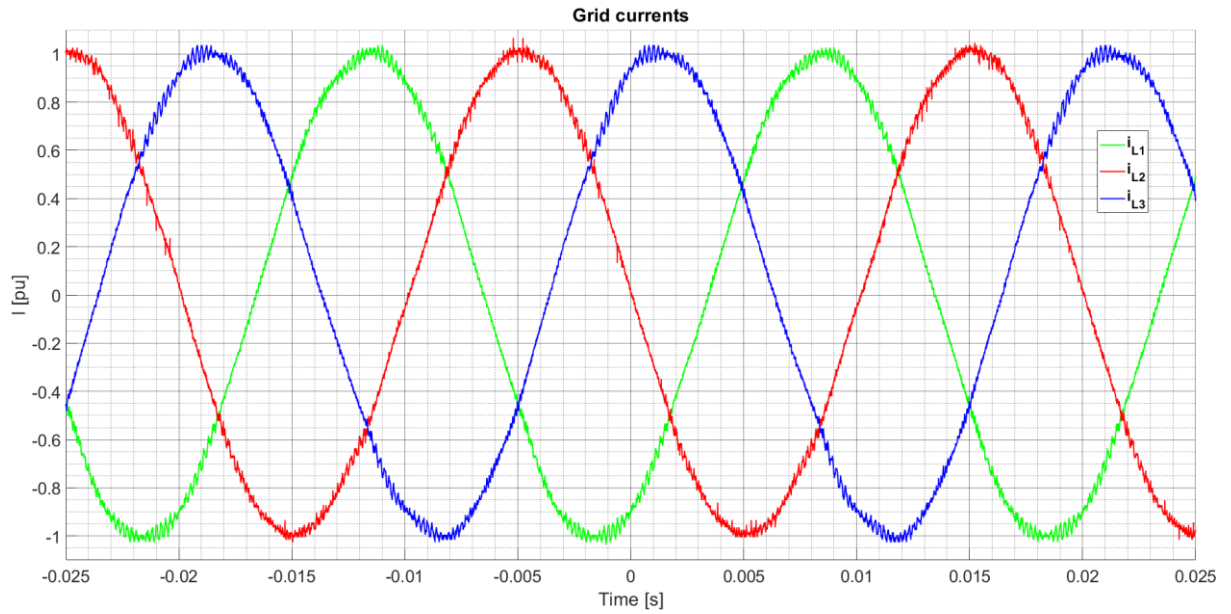


Figure 131: DSCC steady-state unbalanced one line-to-earth short-circuit grid currents during $I_{h1}^{+*} = 1pu$ capacitive test

On Figure 131 it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD in one-minute average for each phase:

- $THDi_{L1}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.4\%$
- $THDi_{L2}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.8\%$
- $THDi_{L3}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 2.0\%$

Compared to simulation results, THD maximum increase is of 1%. This difference is negligible. This is mainly due to measurement noise and non-ideal components characteristics. It means one line-to-earth short-circuit is not degrading significantly the THD of the currents.

The fundamental RMS value of grid currents (which are very close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values in one-minute average are given:

- $\hat{I}_{L1h1}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.022 \text{ pu}$
- $\hat{I}_{L2h1}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.018 \text{ pu}$
- $\hat{I}_{L3h1}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.003 \text{ pu}$

The same amplitudes as the to $Q_{STATCOM}^* = -1pu$ balanced voltage test are measured. Fundamental RMS value of grid currents are not affected by the one line-to-earth short-circuit.



The fundamental displacement angles are given below:

- $\varphi_{iL1 \rightarrow iL2}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = -120^\circ$
- $\varphi_{iL1 \rightarrow iL3}(I_{h1}^{+*} = 1pu \text{ inductive and } L1 \text{ in } SC) = +120^\circ$

A relative deviation of 0% compared to 120° is measured which confirm currents are balanced.

Furthermore, power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^+(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 1.012 pu$
- $\hat{I}_{h1}^-(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 0.008 pu$

This implies Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^-}{\hat{I}_{h1}^+} = 0.8 \%$ which is negligible. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state test.

The second goal is now to verify the DSCC exchanges fundamental positive sequence capacitive reactive power with the grid. The power quality analyser measures the fundamental 3-phase reactive power (Q_{h1}^+) as well as the 3-phase fundamental active power (P_{h1}^+). During the one-minute test with the setpoint $I_{h1}^{+*}=1pu$ capacitive, the average power values measured via the power quality analyser over this period in steady state are:

- $Q_{h1}^+(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = -1.006 pu$
- $P_{h1}^+(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 0.022 pu$

The relative deviation between fundamental reactive power reference and measurement is equal to $\Delta_{Q_{h1}^+}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 0.6 \%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator. It can be noted, that compared to balanced voltage test results, as in simulation, the fundamental reactive power has slightly decreased due to positive sequence voltage amplitude without real impact on the reactive power exchange.

Fundamental active power stays equal to the one in the case of grid voltages balanced. It is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 214 \%$. This is because, the simulation was not performed to precisely represent the prototype losses (cables, losses of components, components imperfection). It would have required an important additional work that was impossible to fulfil in the timeline of the project. However, the aim of the simulation was to design a STATCOM control strategy able to follow a reactive power reference as well as maintaining the internal behaviour stable. The results shown in this section confirm the correct operation of the converter to follow a reactive power setpoint with this control strategy.

Figure 132 and Figure 133 show each corresponding phase current and voltage for L2 and L3.

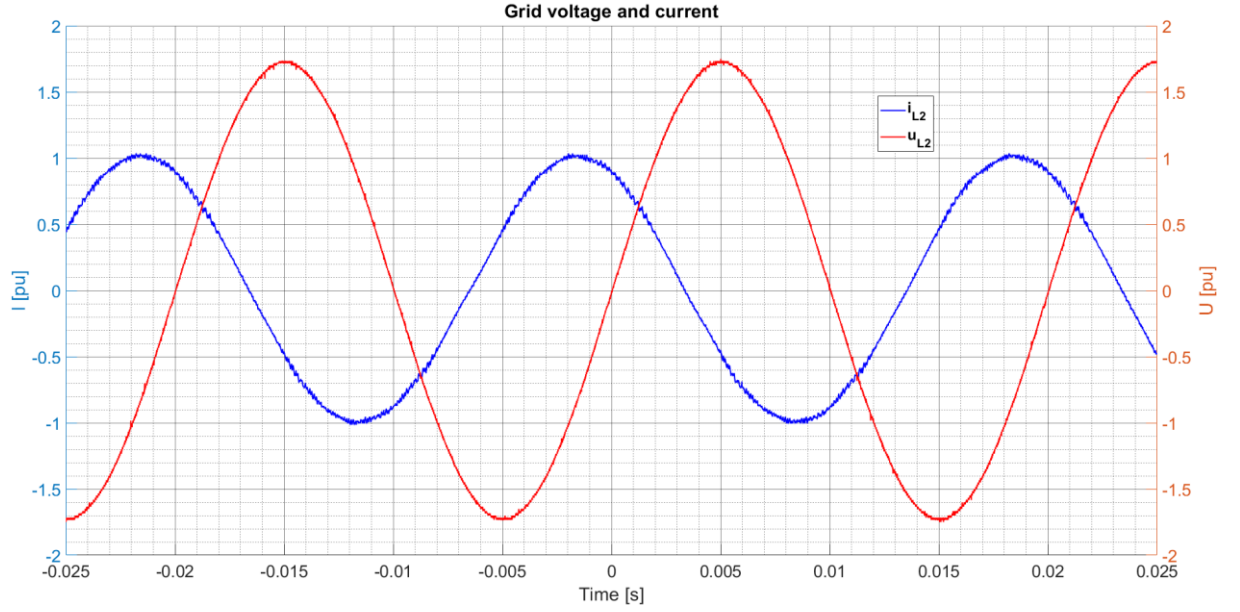


Figure 132: DSCC grid voltage and current of phase L2 when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state test

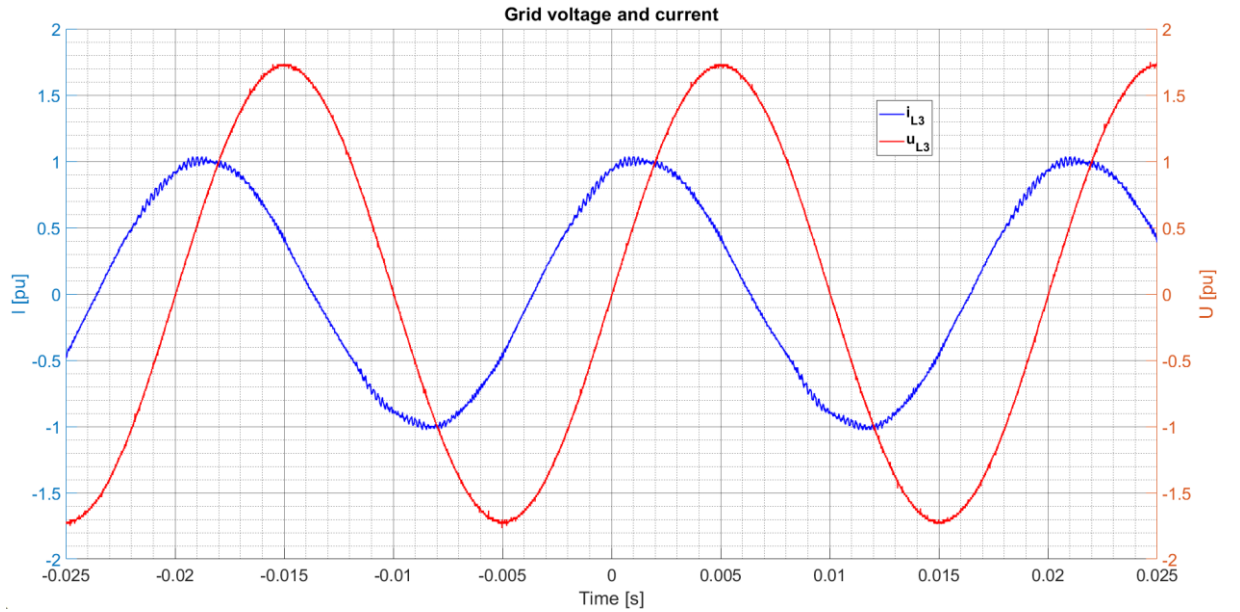


Figure 133: DSCC grid voltage and current of phase L3 when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state test

Firstly, the experimental waveforms in Figure 132 and Figure 133 are very similar to the simulation waveforms in Figure 34 and Figure 35. Secondly, the power quality analyser gives us the displacement angle between voltage and current for each phase (1° accuracy):

- $\theta_{h1L2}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = -119^\circ$
- $\theta_{h1L3}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = -59^\circ$

Their relative deviation compared to simulation displacement angle are:

- $\Delta_{\theta_{h1L2}}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = 0.6\%$
- $\Delta_{\theta_{h1L3}}(I_{h1}^{+*} = 1\text{pu capacitive and L1 in SC}) = 1.3\%$



The displacement angles are very close to the one of the corresponding simulations (less than 1° of difference). It confirms again the correct STATCOM operation. As a remark, the current is leading the voltage confirming the STATCOM is exchanging capacitive reactive power.

It is also important to confirm internal balance of SM voltages during this exchange of reactive power. Cluster voltage of each arm in each leg ($u_{SM_{u,l}}^\Sigma$) are regulated to oscillate around the cluster voltage reference ($u_{SM_{u,l}}^{\Sigma*}$) equal to 2.45 pu (as in simulation). The upper arm cluster voltage for each leg with $I_{h1}^{+*}=1\text{pu}$ capacitive recorded by the DSCC prototype and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 134.

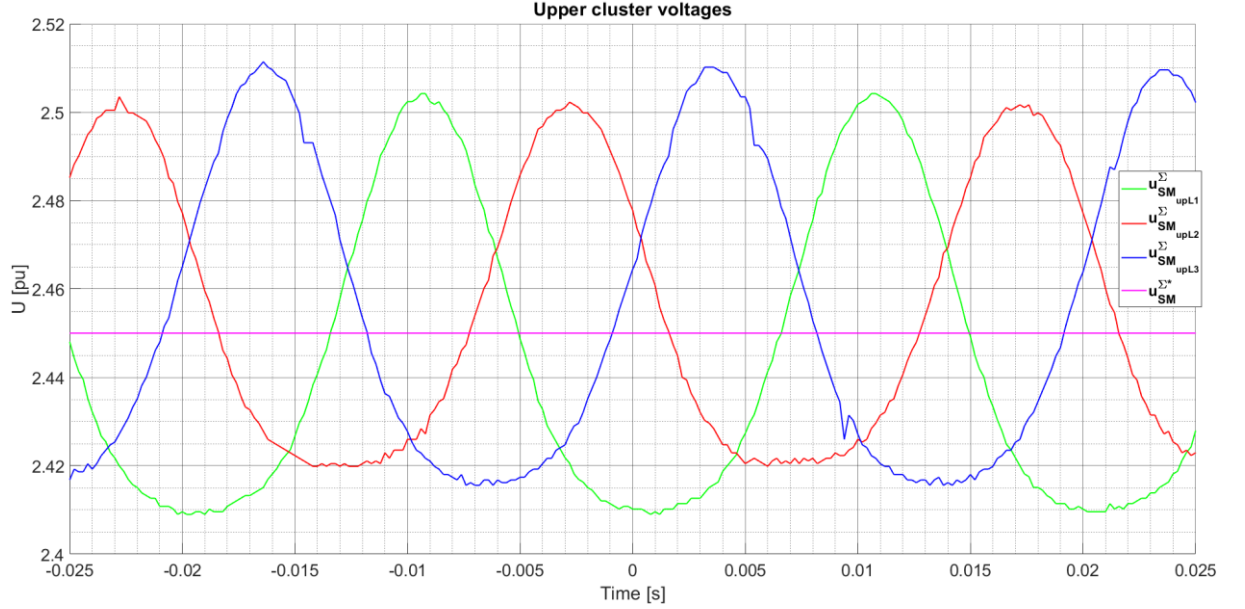


Figure 134: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1\text{pu}$ capacitive during one line-to-earth short-circuit steady-state test

It can be seen that upper arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.090 pu in average. The peak-to-peak amplitude of prototype is 1.14 times higher than in simulation. This difference is acceptable. It is mainly due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{upL1}}^\Sigma}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 \text{ in } SC) = 2.447 \text{ pu}$
- $\overline{u_{SM_{upL2}}^\Sigma}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 \text{ in } SC) = 2.452 \text{ pu}$
- $\overline{u_{SM_{upL3}}^\Sigma}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 \text{ in } SC) = 2.453 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{\Sigma*}$ and the three $\overline{u_{SM_{up}}^\Sigma}$ is equal to: $\Delta_{\overline{u_{SM_{up}}^\Sigma}}(I_{h1}^{+*} = 1\text{pu capacitive and } L1 \text{ in } SC) = 0.1\%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference.

As well, the lower arm cluster voltage for each leg with $I_{h1}^{+*}=1\text{pu}$ capacitive recorded by the DSCC prototype and the reference $u_{SM_{u,l}}^{\Sigma*}$ are shown in Figure 135.

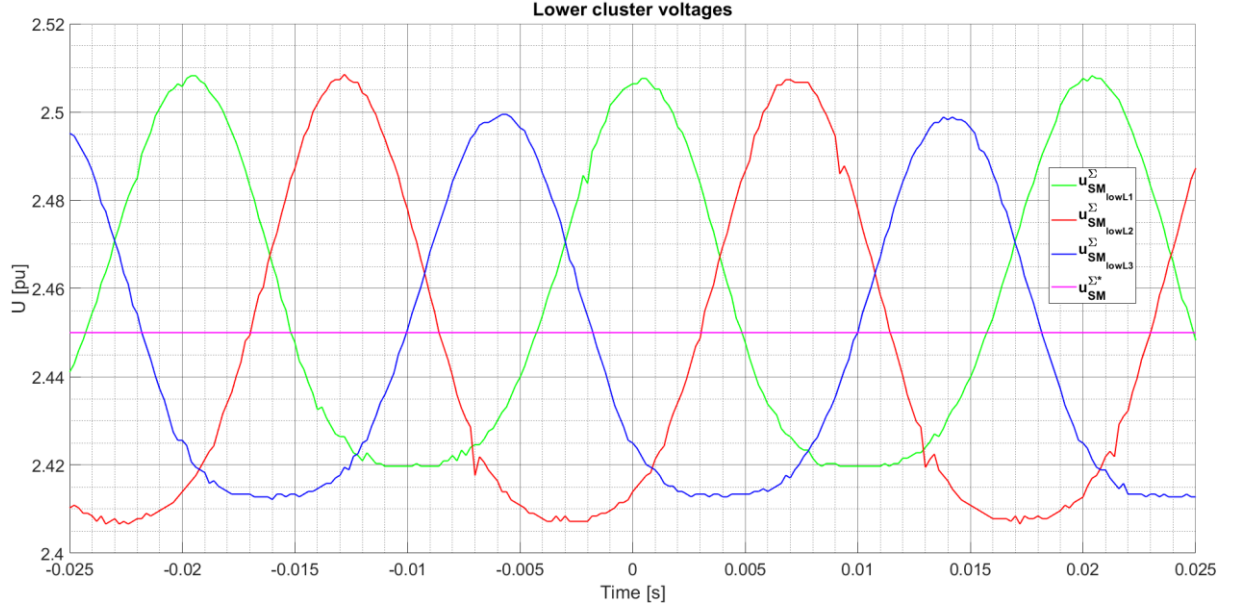


Figure 135: DSCC lower arm cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive during one line-to-earth short-circuit steady-state test

It can be seen that lower arm cluster voltage for each leg oscillates with peak-to-peak amplitude of 0.091 pu in average. The peak-to-peak amplitude of prototype is 1.15 times higher than in simulation. This difference is acceptable. It is due to the measurement accuracy and non-ideal components characteristics.

For each leg, the mean value over one period of time are:

- $\overline{u_{SM_{lowL1}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 2.454 \text{ pu}$
- $\overline{u_{SM_{lowL2}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 2.447 \text{ pu}$
- $\overline{u_{SM_{lowL3}}^{\Sigma}}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 2.447 \text{ pu}$

The highest relative deviation between reference value $u_{SM_{u,l}}^{\Sigma*}$ and the three $\overline{u_{SM_{low}}^{\Sigma}}$ is equal to: $\Delta_{\overline{u_{SM_{low}}^{\Sigma}}}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 \text{ in } SC) = 0.2 \%$. This highest relative deviation is very small, meaning that the cluster voltages follow their reference.

On both Figure 134 and Figure 135, some small spikes are sometimes visible. These spikes correspond to hardware measurement error that can occur for one sample. After many investigations, HEIG team did not succeed to correct these momentary errors. The error is always less than 0.007 pu which is negligible. This is why the results are still coherent. It is worth to be noted that this is not due to physical principle of the DSCC. Indeed, as it can be seen in simulation, these spikes are not present.

We can conclude that cluster voltages are balanced around the reference value $u_{SM_{u,l}}^{\Sigma*}$ and so that internal stability is guaranteed with $I_{h1}^{+*} = 1pu \text{ capacitive}$ during one line-to-earth short-circuit steady-state. Furthermore, the test results confirm the simulation correctness.

In case of one line-to-earth short-circuit steady-state, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence capacitive current with the grid simulator while maintaining the internal behaviour stable permanently. In addition, except for DSCC converter losses (see above in this section), test results precisely match the simulation results and THD of the currents are small enough not to disturb even more grid operation.

The verification of the correct current exchanged during transient operation for the case $I_{h1}^{+*} = 1pu \text{ capacitive}$ was done and results are conclusive as for the inductive tests. They are not presented to lighten the content of the report.



16.9 Test of DSCC positive sequence capacitive current operation during two lines-to-earth short-circuit (detailed results)

The grid simulator voltages during $I_{h1}^{++}=1\text{pu}$ capacitive operation are visible in Figure 136.

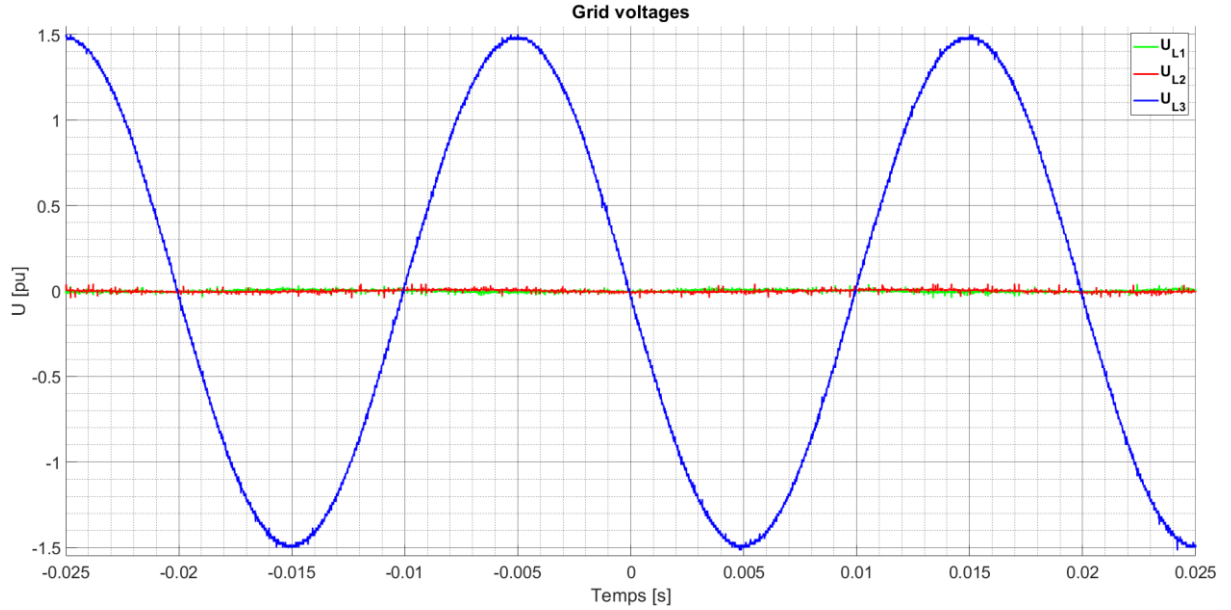


Figure 136: Steady-state unbalanced two lines-to-earth short-circuit grid voltages during $I_{h1}^{++}=1\text{pu}$ capacitive test

In Figure 136, it can be seen that the voltages are 50 Hz sinusoids unbalanced. The 50 Hz frequency is confirmed by power quality analyser measurements. The power quality analyser gives the voltage THD in steady-state for phase L3 (the one of interest) which is small:

$$- \quad THDu_{L3}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.2 \%$$

The fundamental RMS value of grid voltages are given by the power quality analyser. The corresponding peak values are given in pu:

$$\begin{aligned} - \quad \hat{U}_{L1h1}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) &= 0.006 \text{ pu} \\ - \quad \hat{U}_{L2h1}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) &= 0.006 \text{ pu} \\ - \quad \hat{U}_{L3h1}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) &= 1.487 \text{ pu} \end{aligned}$$

Relative deviation compared to simulation value is given for phase L3:

$$- \quad \Delta \hat{U}_{L3h1}(I_{h1}^{++} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.7\%$$

These relative deviations confirm the correct operation of the grid simulator to provide the correct amplitude for L3 while the others are close to 0 pu amplitude.

The VUF ($\frac{U^-}{U^+}$) measured via the power quality analyser is equal to 99.7%. The relative deviation with the value in Table 3 is equal to 0.3%, a very good result.

The correct operation of the grid simulator to provide the two lines-to-earth short-circuit with $I_{h1}^{++} = 1\text{pu capacitive}$ is confirmed.

Grid currents waveforms during $I_{h1}^{++}=1\text{pu}$ capacitive operation are visible in Figure 137.

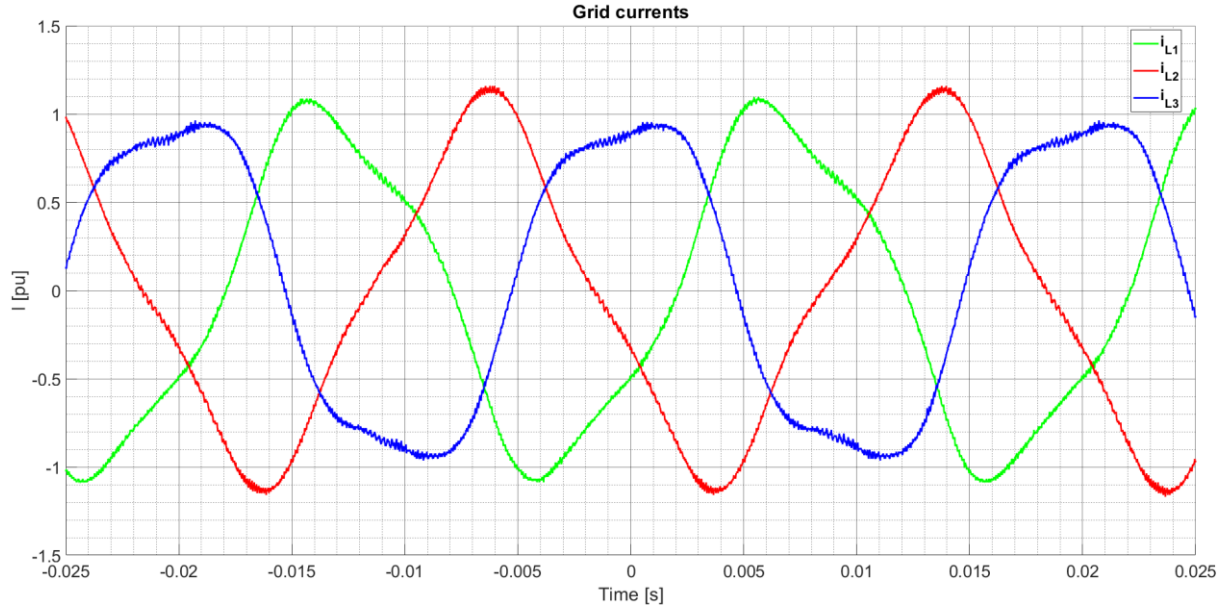


Figure 137: DSCC steady-state unbalanced two lines-to-earth short-circuit grid currents during $I_{h1}^{+}=1\text{pu}$ capacitive test

In Figure 137, it can be seen that the currents are 50 Hz sinusoids. The power quality analyser gives the currents THD for each phase:

- $THDi_{L1}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 15.2\%$
- $THDi_{L2}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 14.1\%$
- $THDi_{L3}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 15.8\%$

Compared to simulation results, THD maximum increase is of 2.6%. This difference is negligible. The same remark can be made as in simulation. THD is importantly increased during two lines-to-earth short-circuit. Currents exchanged are still 50Hz dominant but with important distortion.

The fundamental RMS value of grid currents (which are close to RMS value of the entire signal thanks to low THD) are given by the power quality analyser. The corresponding peak values are given:

- $\hat{I}_{L1_{h1}}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 1.027 \text{ pu}$
- $\hat{I}_{L2_{h1}}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 1.020 \text{ pu}$
- $\hat{I}_{L3_{h1}}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.995 \text{ pu}$

A maximum relative deviation of 2.6% between test and simulation is measured. This difference is reasonable to consider correct amplitude of the fundamental currents exchanged

Power quality analyser gives the fundamental positive and negative sequence amplitude of currents:

- $\hat{I}_{h1}^{+}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 1.014 \text{ pu}$
- $\hat{I}_{h1}^{-}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.010 \text{ pu}$

This implies fundamental Current Unbalance Factor (CUF) = $\frac{\hat{I}_{h1}^{-}}{\hat{I}_{h1}^{+}} = 1.0 \%$ which is negligible. All the results above mentioned confirm that the currents provided by the DSCC prototype are well balanced with the setpoint $I_{h1}^{+}=1\text{pu}$ capacitive during two lines-to-earth short-circuit steady-state test.

The second goal is now to verify the DSCC exchanges fundamental positive sequence capacitive reactive power with the grid. The power quality analyser measures the fundamental 3-phase reactive power (Q_{h1}^{+}) as well as the 3-phase fundamental active power (P_{h1}^{+}). During the test with the setpoint $I_{h1}^{+}=1\text{pu}$ capacitive, the average power values measured via the power quality analyser over this period in steady state are:

- $Q_{h1}^{+}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = -0.503 \text{ pu}$
- $P_{h1}^{+}(I_{h1}^{+} = 1\text{pu capacitive and } L1 + L2 \text{ in } SC) = 0.023 \text{ pu}$



The relative deviation between simulation and measurement is equal to $\Delta_{Q_{h1}^+}(I_{h1}^{++} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 2.2 \%$. This relative deviation is small enough to consider the STATCOM exchanges the correct positive sequence reactive power to the grid simulator. It can be noted, that compared to balanced voltage test results, as in simulation, the fundamental reactive power has been decreased by a half compared to balanced conditions as expected.

Fundamental active power stays almost equal to the one in the case of grid voltages balanced. As a consequence, it is important to note the relative deviation between simulation value and measurement value: $\Delta_{P_{simu-test}}(I_{h1}^{++} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 91.7 \%$. This is because, the simulation was not performed to precisely represent the prototype losses (cables, losses of components, components imperfection). It would have required an important additional work that was impossible to fulfil in the timeline of the project. However, the aim of the simulation was to design a STATCOM control strategy able to follow a reactive power reference as well as maintaining the internal behaviour stable. The results shown in this section confirm the correct operation of the converter to follow a reactive power setpoint with this control strategy.

Test results during transient operation for the case $I_{h1}^{++} = 1pu \text{ capacitive}$ are compared to simulation. Grid voltages during transient are shown in Figure 138.

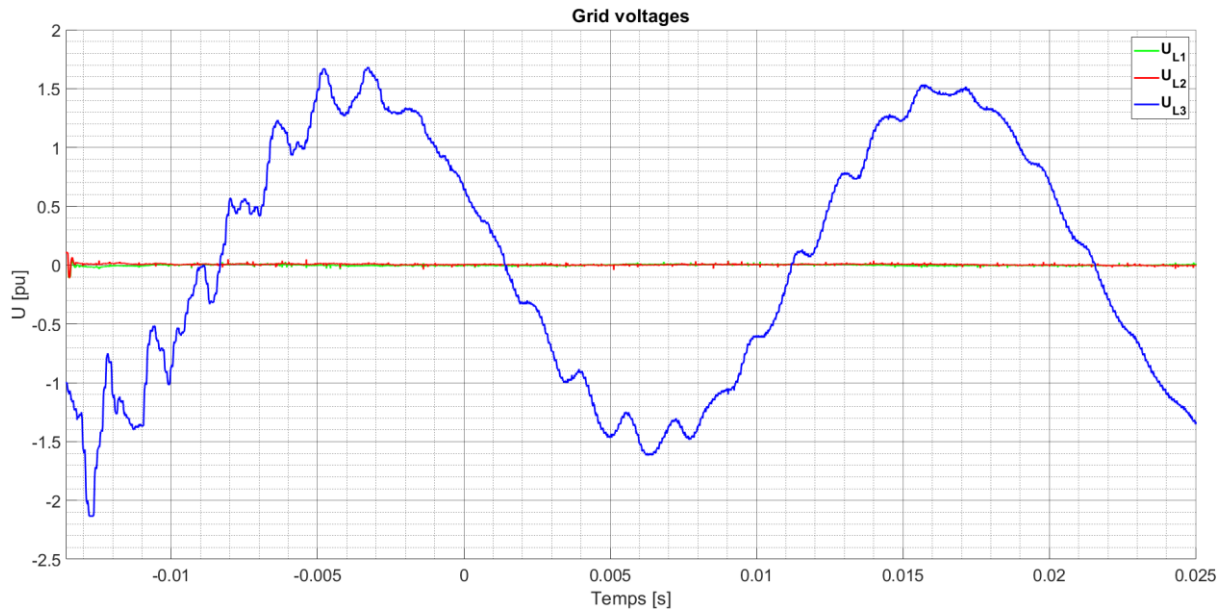


Figure 138: DSCC grid voltages when $I_{h1}^{++}=1pu$ capacitive during two lines-to-earth short-circuit transient in test

The measured voltages visible in Figure 138 are highly corresponding with the simulation transient voltages in Figure 17. The voltage during the transient is the same as the one in simulation. The grid currents exchanged between DSCC prototype and grid simulator during this transient are shown in Figure 139.

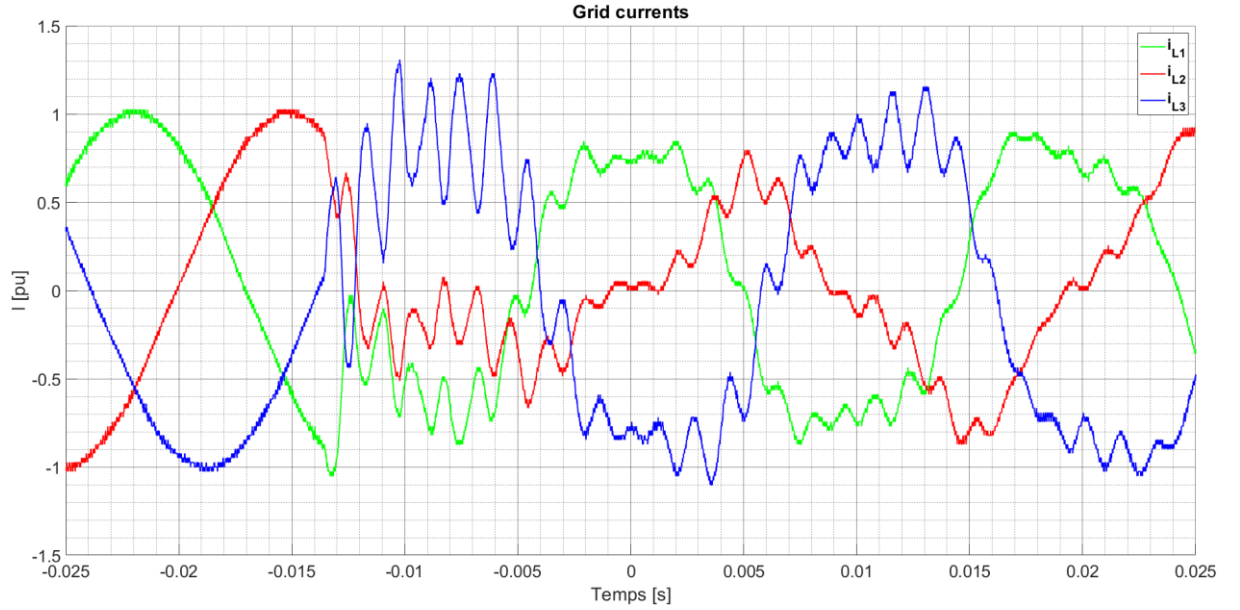


Figure 139: DSCC grid currents when $I_{h1}^{**}=1pu$ capacitive during two lines-to-earth short-circuit transient in test

If we compare Figure 139 with simulation results in Figure 118, it can be seen that current waveforms are highly similar. The maximum current reached is 1.308 pu which is 1.05 times more than in the simulation. Furthermore, grid currents continue to follow the $I_{h1}^{**}=1pu$ capacitive reference during the transient with the same oscillations as in simulation. It means DSCC prototype is dealing well with the transient.

We still need to verify internal behaviour of the DSCC. As in simulation, cluster voltages are slowly moving away from their reference ($u_{SM_{u,l}}^{*} = 2.45 pu$). The duration time of the two lines-to-earth short-circuit was 5s before one cluster voltage difference with 2.45pu setpoint reached 0.3pu. STATCOM prototype reach the limit many times faster than the simulation. This is due to the internal unbalance of the physical components (non-ideal capacitances and inductances with values different between each component). They deteriorate faster the internal imbalance of the converter. These 5s are sufficient to manage the maximum time of short circuit. It could be increased by increasing the safety limit.

The upper arm cluster voltage for each leg with $I_{h1}^{**}=1pu$ capacitive recorded by the DSCC prototype before one cluster voltage difference with 2.45pu setpoint equals 0.3pu are shown in Figure 140.

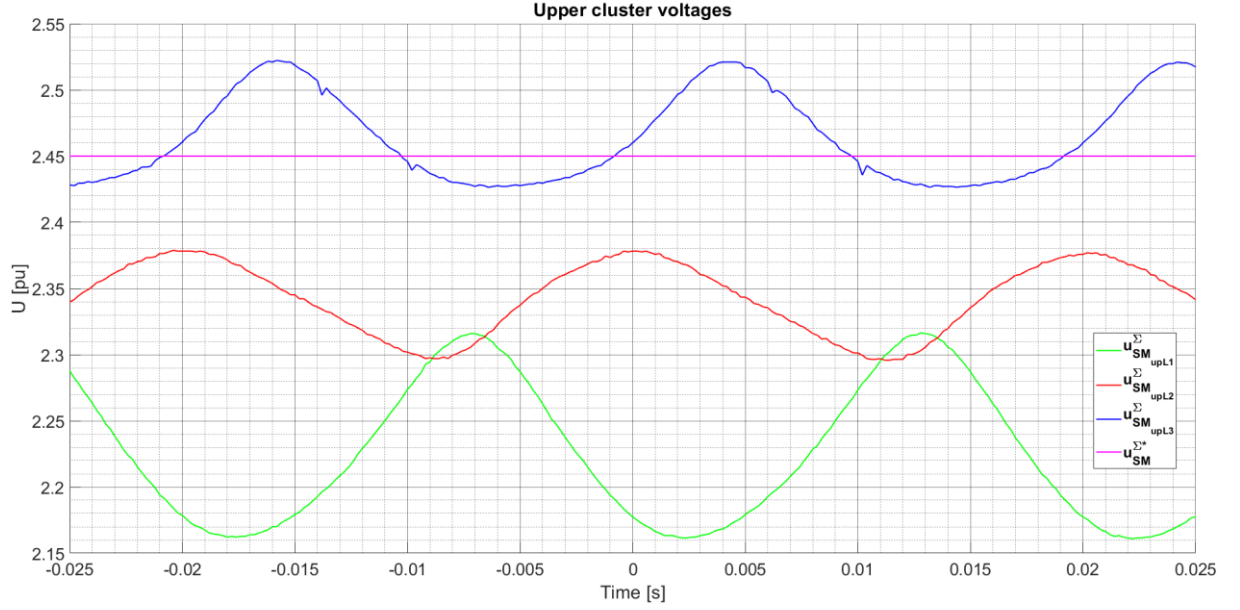


Figure 140: DSCC upper arm cluster voltage for each leg when $I_{h1}^{+*}=1pu$ capacitive at the end of two lines-to-earth short-circuit in test

As in simulation, upper cluster voltages are decreasing over the time. But the experimental upper cluster voltages are decreasing a lot faster compared to simulation due to physical differences of the components (mainly inductors and capacitors). Phase L1 and L2 average in the last period are lower than the 2.45 pu setpoint whereas in simulation, at the same interval of time, L2 average value is still higher than 2.45 pu.

The minimum value is 2.162 pu reached by L1. It can also be noted that L3 phase is the closest to the setpoint value as in simulation.

As it can be seen, their peak-to-peak amplitudes are:

- $u_{SM_{upL1pp}}^{\Sigma}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.155 pu$
- $u_{SM_{upL2pp}}^{\Sigma}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.081 pu$
- $u_{SM_{upL3pp}}^{\Sigma}(I_{h1}^{+*} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.095 pu$

It can be seen that L2 has the lowest peak-to-peak amplitude as in simulation but L1 has highest which is different from simulation but coherent regarding the inductive results. Indeed, peak-to-peak amplitudes tend to become higher than in simulation for each phase which is still the case here.

The lower arm cluster voltage for each leg with $I_{h1}^{+*}=1pu$ capacitive recorded by the DSCC prototype before one cluster voltage difference with 2.45pu setpoint equals 0.3pu are shown in Figure 141.

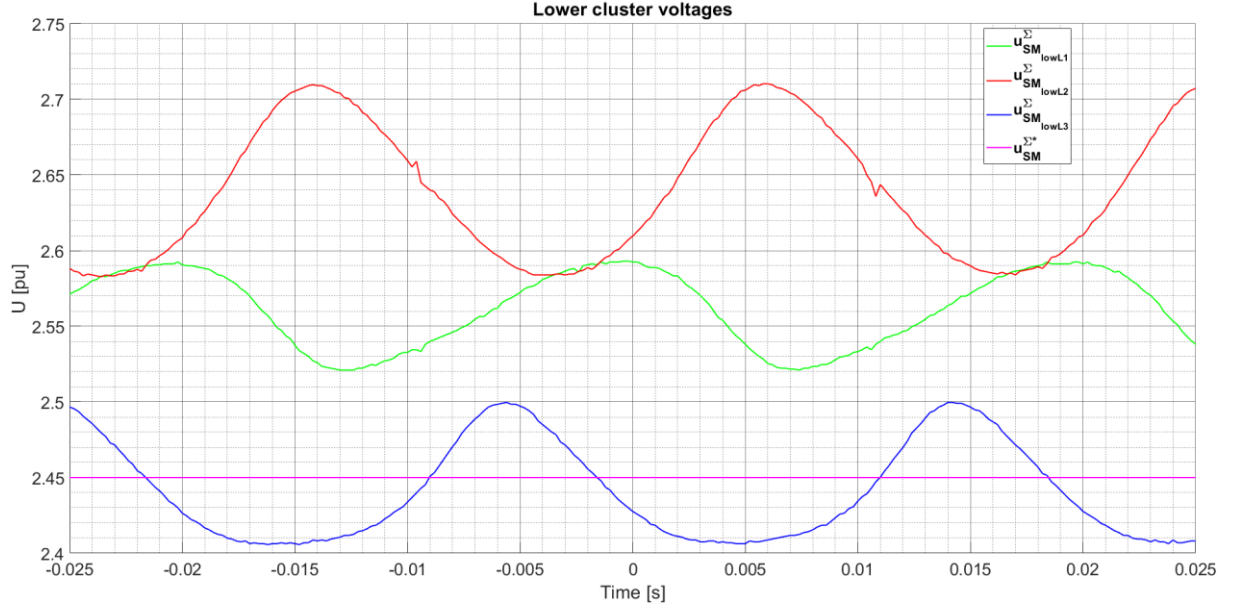


Figure 141: DSCC lower arm cluster voltage for each leg when $I_{h1}^{++}=1pu$ capacitive at the end of two lines-to-earth short-circuit in test

As in simulation, lower cluster voltages are increasing over the time. But the experimental lower cluster voltages are increasing a lot faster compared to simulation due to physical differences of the components (mainly inductors and capacitors). Phase L1 and L2 average in the last period are higher than the 2.45 pu setpoint whereas in simulation, at the same interval of time, L1 average value is still lower than 2.45 pu.

The maximum value is 2.708 pu reached by L2. It can also be noted that L3 phase is the closest to the setpoint value as in simulation.

As it can be seen, their peak-to-peak amplitudes are:

- $u_{SM_{lowL1pp}}^{\Sigma} (I_{h1}^{++} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.070 pu$
- $u_{SM_{lowL2pp}}^{\Sigma} (I_{h1}^{++} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.125 pu$
- $u_{SM_{lowL3pp}}^{\Sigma} (I_{h1}^{++} = 1pu \text{ capacitive and } L1 + L2 \text{ in } SC) = 0.094 pu$

L1 amplitude is coherent with simulation but L2 is higher than L3 contrary to simulation. However, this is coherent regarding the inductive results. Indeed, peak-to-peak amplitudes tend to become higher than in simulation for each phase which is still the case here.

As predicted by simulation, the arm energy balancing controller of each leg cannot be regulated to zero. These cluster results are quite different from simulation at the same interval of time. The main difference is the deviation speed from the setpoint which is higher in test compared to simulation. This is due to physical unbalance of the components. The same behaviour as the inductive case confirm that the capacitive results are coherent.

In case of two lines-to-earth short-circuit steady-state and transient, thanks to test results above mentioned, DSCC STATCOM prototype is able to exchange 1 pu positive sequence capacitive current with the grid simulator during 5s with safety limit of 0.3pu cluster voltage difference with 2.45pu setpoint. In addition, except for DSCC converter losses and time before reaching safety limit, test results precisely match the simulation results. It is important to mention that, as in simulation, the capacitive case is beneficial because DSCC prototype is able to work two times longer during two lines-to-earth short circuit (5 seconds against 2.5s for the inductive case).



16.10 MV/LV substations loading of “B” network for scenario 1 and 3

Substation number	Active power (P) [pu]	Reactive power (Q) [pu]
2	0.00166	0.00080
3	0.00166	0.00080
4	0.00261	0.00127
5	0.00104	0.00050
6	0.00166	0.00080
7	0.00104	0.00050
8	0.00104	0.00050
9	0.00166	0.00080
10	0.00104	0.00050
11	0.00104	0.00050
12	0.00332	0.00160
13	0.00166	0.00080
14	0.00066	0.00032
15	0.00104	0.00050
16	0.00261	0.00127
17	0.00166	0.00080
18	0.00830	0.00402
19	0.01091	0.00529
20	0.00261	0.00127
21	0.00166	0.00080
22	0.00261	0.00127
23	0.00166	0.00080
24	0.00261	0.00127
25	0.00261	0.00127
26	0.00166	0.00080
27	0.00166	0.00080
28	0.00166	0.00080
29	0.00104	0.00050
30	0.00041	0.00020
31	0.00166	0.00080
32	0.00166	0.00080
33	0.00166	0.00080
34	0.00261	0.00127
35	0.00261	0.00127
36	0.00166	0.00080



37	0.00166	0.00080
38	0.00332	0.00160
39	0.00166	0.00080

Table 39: MV/LV substations loading of "B" network for scenario 1 and 3



16.11 MV/LV substations loading of “B” network for scenario 2

Substation number	Active power (P) [pu]	Reactive power (Q) [pu]
2	0.00730	0.00354
3	0.00730	0.00354
4	0.01150	0.00557
5	0.00457	0.00221
6	0.00730	0.00354
7	0.00457	0.00221
8	0.00457	0.00221
9	0.00730	0.00354
10	0.00457	0.00221
11	0.00457	0.00221
12	0.01461	0.00708
13	0.00730	0.00354
14	0.00292	0.00142
15	0.00457	0.00221
16	0.01150	0.00557
17	0.00730	0.00354
18	0.03652	0.01768
19	0.04802	0.02325
20	0.01150	0.00557
21	0.00730	0.00354
22	0.01150	0.00557
23	0.00730	0.00354
24	0.01150	0.00557
25	0.01150	0.00557
26	0.00730	0.00354
27	0.00730	0.00354
28	0.00730	0.00354
29	0.00457	0.00221
30	0.00183	0.00088
31	0.00730	0.00354
32	0.00730	0.00354
33	0.00730	0.00354
34	0.01150	0.00557
35	0.01150	0.00557
36	0.00730	0.00354



37	0.00730	0.00354
38	0.01461	0.00708
39	0.00730	0.00354

Table 40: MV/LV substations loading of "B" network for scenario 2