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Medium-Voltage Direct-Current Energy Conversion Technologies and Systems

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Swiss Federal Office of Energy SFOE
Research Programme Electricity Technologies
CH-3003 Bern
www.bfe.admin.ch
energieforschung@bfe.admin.ch

Co-financed by:
ABB Switzerland, Medium Voltage Drives
Austrasse
CH-5300 / Turgi
http://www.abb.com

Agent:
Power Electronics Laboratory, EPFL
Station 11
CH-1015 / Lausanne
http://pel.epfl.ch

Author:
Prof. Drazen Dujic, Power Electronics Laboratory, EPFL, drazen.dujic@epfl.ch
Dr. Francisco Freijedo, Power Electronics Laboratory, EPFL, francisco.freijedo@epfl.ch

SFOE head of domain: Dr Michael Moser, michael.moser@bfe.admin.ch
SFOE programme manager: Roland Brüniger, roland.brueniger@brueniger.swiss
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Summary

Despite benefiting from AC systems for more than a century, there are applications where DC technology is preferred and is already deployed or considered. Potentials and benefits are largely unexplored in the medium voltage (MV) domain due to lack of available high-power conversion and protection technologies for DC. Project focus was on novel, compact and highly efficient power electronic conversion technologies for MVDC applications that provide benefits on the system level. System level stability studies are used to aid system design and ensure safe and reliable operation.

To enable deployment of MVDC power distribution networks, various conversion and protection technologies have to be developed from the scratch or adapted from the existing MVAC systems. While the existing MVAC distribution grids are widely spread, both in utility and industrial applications, MVDC power distribution networks are currently considered for some specific applications, such as: electric ship distribution, photovoltaic and wind plants collection grids, data centres, etc. Industry is currently at the stage of feasibility assessment, which provides great research opportunities to define and shape further developments in the area.

While the focus of the research activities in the first year of the project was mostly on development of enabling conversion technologies suitable for MVDC, the second year focus has been on performance verifications and translation of concepts towards the working prototype. In addition, system level stability studies have opened several other research directions related to active impedance/admittance shaping through control means, as well as area of real time impedance/admittance measurements for medium voltage systems. The last year has been focusing on the key activities that allow us to consider that we reach the main objectives of the project. In that sense, the format of this report has been elaborated to show, objective by objective how the milestones of the project have been achieved.

Industrially sponsored part of the project, has moved its initial focus from high power marine electrical systems, towards the more generic MVDC architectures, inspired by other industrial installations involving multiple high power sources and loads, interconnected by MVDC electrical power distribution.

SCCER-FURIES research activities related to MVDC-LVAC conversion have led to a proposal of a Galvanically Isolated Modular Converter (GIMC) characterized by single stage, galvanically isolated converter relying on the modular multilevel converter principles. Since SCCER round 1 of financing is over and considering lack of dedicated funds for hardware demonstrators, GIMC prototype has not been completely finalized. We are continuing our activities within the SCCER round 2 of financing, where platform will be finalized (largely thanks to our internal funds), and be used to support activities related to high power DC-DC conversion based on GIMC platform. SNSF NRP70 part of the research related to MVDC-LVDC conversion, resulted in development of a concept of Multiport Energy Gateway (MEG) – a modular and isolated multiport DC-DC converter that integrates distributed storage elements. Prototype is currently being assembled for the final testing and demonstration of developed principles. The SNSF project Solid State Resonant Conversion (SSRC) with focus on the high power DC-DC conversion using Integrated Gate Commutated Thyristors (IGCT), has developed high power test setup, and we are actively gathering experimental data. All these research activities require galvanic isolation by means of medium frequency transformers, and receive support from internally funded research activities in this domain.

Several research papers have been either already published or submitted, as provided in the list at the end of a report.

Contents

List of abbreviations

SFOE	Swiss Federal Office of Energy
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
DC	Direct Current
AC	Alternating Current
LVDC	Low Voltage Direct Current
MVDC	Medium Voltage Direct Current
HVDC	High Voltage Direct Current
PV	Photovoltaic
DSO	Distribution System Operator
PEL	Power Electronics Laboratory
GIMC	Galvanically Isolated Modular Converter
MEG	Multiport Energy Gateway
MMC	Modular Multilevel Converter
IGCT	Integrated Gate Commutated Thyristor
SFOE	Swiss Federal Office of Energy

1 Introduction

This final report provides an overview of research results obtained under the framework of the project "**Medium-Voltage Direct-Current Energy Conversion Technologies and Systems**". Over the last three years, while working on various aspects associated with MVDC applications, we could observe increased interests into this topic worldwide. Both industry and academia are actively working to provide technological solutions that would enable deployment of the MVDC power distribution networks into the future energy systems. Thanks to the SFOE funding, we were able to closely interlink several research activities, funded from various sources, and amplify the impact and of our research work and make technical proposals more valuable to the potential receivers and user of technology.

2 Context

2.1 Background

DC technologies are increasingly being considered for new installations or as retrofit options for the existing ones. This is, predominantly, possible thanks to advances in power electronics and possibilities to carry out very efficiently process of electrical energy conversion. Increased deployment of photovoltaic energy generation is a typical example where primary DC source of energy (PV panel) must be connected to the existing AC grid through a PV inverter (power electronics converter performing DC-AC conversion). Grouping this renewable generation into larger power clusters (the same applies for wind generation) enables creation of DC power collection and distribution networks that would be interfaced to the existing AC systems. In particular, MVDC power distribution networks are the main interest of this project and development of enabling technologies continues to be one of the main research strands of Power Electronics Laboratory.

2.2 Motivation of the project

Motivation to focus on the MVDC technologies and system can be explained in several different ways.

LVDC technologies are already deployed in several industrial applications and great deal of conversion and protection equipment is commercially available. New installations require detailed system engineering and planning, and performances could be further increased through new developments. HVDC technologies, characteristics for bulk power transmission, are as well commercially available and deployed around the world for bridging large distances between generation and consumption. These high power technologies represent a niche segment of the power system, and relatively modest research and development efforts are present in Switzerland (e.g. ABB's HVDC business is located in Sweden, Siemens's HVDC business is located in Germany, GE's HVDC business (former ALSTOM Grid) is located in UK).

MVDC applications (generally by MVDC we consider DC voltages from 1.5kV to 50kV) and thus technologies are still in an early phase and will require several years of continuous development before we start seeing larger deployments. MV levels are normally associated with DSO business, and represent significant market segment in Switzerland. While the AC technologies (transformers, inverters, drives) are readily available for predefined MVAC classes, equipment or clear migration to MVDC voltage levels is still not defined or standardized. There are several demonstration projects around the world (e.g. ANGLE DC project in UK) where utilities and industrial partners are jointly working to demonstrate benefits of MVDC technologies.

For the reasons of numerous technical gaps, research problems addressed in this project were postulated in such a way to address problem at large, whenever possible, in order to provide solutions that would be applicable to a variety of applications. Nevertheless, due to favourable dynamic of changes, applications such as marine DC electric ships, were analysed in great depths, as these will likely be early adopters of MVDC technologies.

2.3 Goals

The original goals of the project are repeated here, for the sake of clarity:

1. to quantify potential and impact of MVDC systems compared to MVAC systems
2. to develop dynamic models and stability assessment tools for MVDC systems
3. to develop enabling power electronics conversion technologies
4. to demonstrate energy savings on the system level

Majority of project goals 1) - 3) has been achieved (sometimes exceeding initial expectations) as it will be presented in incoming sections. Due to delays with installation of PEL MV laboratory, goals related to effective experimental demonstration of project results 4) have been achieved using small scale prototype, something that is elaborated in incoming sections.

3 Approach and methodology

3.1 MVDC applications and systems of interest

The fact that research interest and expertise of power electronic laboratory is predominantly related to electrical energy conversion technologies, has defined the essential focus on our investigation. Since utilities are slow to adopt new technologies, and especially those requiring large infrastructural changes, other high power applications were considered.

Marine MVDC electrical distribution systems are the ones studied thoroughly in the project. Currently, state-of-the-art ships use AC distribution systems, with diesel-generator sets providing AC supply that is distributed throughout the ship to various loads (propulsion being the biggest). Replacing this AC distribution with DC is motivated by several factors:

- AC distribution requires all generators to be synchronized to the same network, preventing operation of diesel engines at optimal speed related to the actual loading conditions. This can be completely avoided by rectifying generated AC voltage and implementing electrical distribution using DC.
- Ability to run diesel engines at variable speed leads to significant fuel savings (some reports estimate saving of up to 27%)
- Use of DC distribution further improves efficiency as all reactive losses associated with AC systems are eliminated.
- Converters on the load side are somewhat simplified, especially for AC loads as only inverters are now sufficient (provided voltage coordination is correctly executed)

Despite these drivers and benefits, Marine MVDC power distribution networks are not yet a reality since conversion and protection equipment is not readily available. Nevertheless, key industrial players, such as SIEMENS and ABB, are already having multiple LVDC ships commissioned and in operation, largely thanks to the fact that LV equipment is commercially available.

Other application examples include industrial factory installations, where multiple MV large power variable speed drives are in use. In some cases, these installations are already having a form of MVDC power distribution network, in the sense that all machine inverters are connected to the same MVDC bus. It is believed that these applications may be further expanded (spatially), thus creating special MVDC power distribution networks.

By working on these applications, it is possible to propose technical solutions and technologies that will enhance or enable these applications, facing much less obstacles or hurdles compared to the case of on-shore utility applications involving DSOs. One of the primary focuses of the research studies dealing with the system level, was a question of interactions between different power electronics technologies and overall stability of the system.

3.2 MVDC conversion technologies

To enable MVDC systems, various conversion and protection equipment is required. Part of the SFOE project has looked into this and was greatly supported by other research projects in the power electronics laboratory. Provided MVDC power lines are available, they would have to be interfaced to all other possible voltage levels and types. We have addressed some type of power electronic conversions needed for future MVDC systems:

1. **MVDC – LVAC:** In the phase 1 of the SCCER-FURIES we have proposed concept of Galvanically Isolated Modular Converter (GIMC) as means to interface MVDC grids with readily available LVAC grids. In the phase 2 of the SCCER-FURIES we are continuing developments in this direction as well further expanding the focus on DC-DC conversion.
2. **MVDC – LVDC:** For the phase 2 of the SCCER-FURIES we have proposed high power conversion structure passed on use of Modular Multilevel Converter (MMC) in combination with Scott Transformer Connection (STC) for bipolar MVDC grids. A patent application has been filled on this topology, as part of the work has been carried out supported by Hyundai Electric and Energy Systems from Korea
3. **MVDC – LVDC – LVDC with integrated energy storage:** As part of the SNSF NRP 70 program, we have proposed Multiport Energy Gateway (MEG) concept of a converter that integrates energy storage elements for providing support to the MVDC and LVDC grids.
4. **MVDC- MVDC:** As part of the SNSF sponsored project we are working on a concept of high power resonant DC-DC converter based on Integrated Gate Commutated Gate (IGCT) devices and medium frequency transformers.
5. **Medium Frequency Transformers Design Optimization:** To support development of these galvanically isolated conversion structures, internally funded research activites are organized on the design optimization of medium frequency transformers.

3.3 Medium voltage power electronics laboratory

Large efforts and funds have been invested, over the last three years, to establish highly functional research facilities that are able to respond to long-term research needs in high power medium voltage electronics. While we have not yet reached 100% operational state, the majority of infrastructure work has been executed and facilities are effectively in use. Ability to carry out experimental investigations and testing in a safe and controlled environment are of high importance for future research projects. Fig.1 illustrates the present state of the MV PEL facilities.

Figure 1: Medium voltage research facility of the Power Electronics Laboratory. Test cages are equipped with relevant high power MVAC and MVDC supply lines (up to 20kV AC and up to 10kV DC).

4 Results

Summary of the results achieved over the last three years is presented hereafter, addressing each objective separately. To avoid repetition of material already presented in the previous reports, description is restricted to the most important findings and facts. However, list of publications at the end of the report includes all scientific papers published during the project, directly related to one of the objectives.

4.1 Potential and impact of MVDC systems

A comparison between MVAC and MVDC systems has been reported in our studies, including a journal paper[1] [EPFL_2018_1]. We have identified renewable distributed generation and power electronics grid interface as a good benchmark for such a benchmark study. Distribution generation based on LV electrical machine comprises wind energy, hydraulic resource, diesel generators, etc. This structure is found in multiple applications such as renewable energies, marine technology and modern traction systems, among others. Fig. 2. below shows the benchmark systems for such an evaluation.

The following benefits have been identified.

1. Enhanced efficiency of the DC conversion stage. Typical curves provided for AC full converter solution provide efficiencies of around 97%. Losses in the line step transformer, of around 1%, should also be added. On the other hand, the MVDC solution offers much better numbers, efficiencies between 98-99%, including losses in the passive rectifier and Medium Frequency Transformer (MFT) have been reported in the literature.

[1] F. D. Freijedo, E. Rodriguez-Diaz, D. Dujic, 'Stable and Passive High-Power Dual Active Bridge Converters Interfacing MVDC Grids', *IEEE Trans. Ind. Electron*, vol. 65, n. 12, pp. 9561 – 9570, 2018

2. Size, weight and cost reductions in distribution cables. For the same power level and cable technology, a bipolar DC distribution offers a 1.56 higher power density than the conventional solution based on three-phase AC system. One intuitive reason for this improvement comes from the fact that ac RMS value is √2 smaller than the peak value and meanwhile power transfer is dependent on RMS value, negative effects (e.g., losses) depends on voltage/current peak values.
3. Size, weight and cost reductions in magnetic components. MVDC power conversion stages implement a MFT to step up from LV to MV. The MFT has a much better power density than bulky 50/60 Hz line transformers. The removal of bulky components and their substitution for compact components is one key advantage of MVDC technology, which undoubtedly supports need for research efforts in the field.

The challenges for MVDC to become a reality nowadays come from the fact that enabling power electronics technology is not developed yet at an industrial level. One important technical factor that prevents key players (e.g., ABB, Siemens, GE, Hyundai, etc) to step into MVDC technology is the uncertainty in terms of dynamic interactions inside multi-terminal dc systems. At this stage, a significant part of research efforts should focus on stability studies related to objective 2 as well as on conversion technologies of the objective 3.

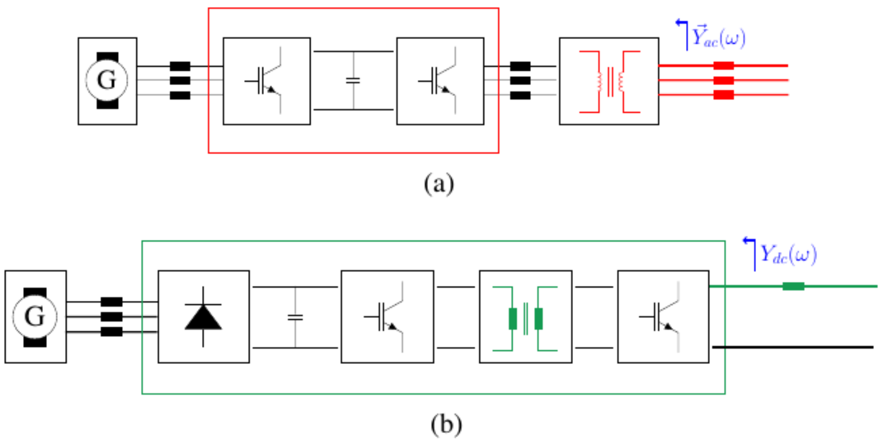

Figure 2: *A benchmark for MVAC vs MVDC comparison: distributed generation with LV electric machine and connection to MV distributon. a) conventional solution based on LVAC power electronics and bulky line step up transformer. b) solution based on a step-up DC-DC converter feeding MVDC distribution from a LVAC generator (diode rectifier is assumed for simplicity).*

4.2 Dynamic models and stability assessment tools

Besides Francisco D. Freijedo, ABB financed part of the project, which ended with the graduation of Dr. Uzair Javaid in March 2018 (he has been also hired by ABB Power Grids in Turgi). From the initial focus on marine MVDC system, the project has evolved from simplified, but insightful analysis methodology[2], to a general solution of the problem of dynamic interactions in multi-terminal MVDC grids. By the end of this project, on top of state of the art methods, we have developed a reliable methodology to assess stability of MVDC grids of any size. The proposed methodology overcomes

[2] U. Javaid, F. D. Freijedo, D. Dujic, W. van der Merwe, "Dynamic assessment of source-load interactions in marine MVDC distribution", IEEE Trans. Ind. Electron., vol. 64, n. 6, pp. 4372-4381, Jun. 2017.

shortcomings, such as lack of observability and limited scalability of simplified approaches. A journal paper including the new method has been submitted to a high impact journal[3].

Fig. 3 shows the playground of a multi-terminal MVDC grid on ship. In order to take full advantage of MVDC technology (related to objective 1), the power system distribution is made out of a long dc-cable.

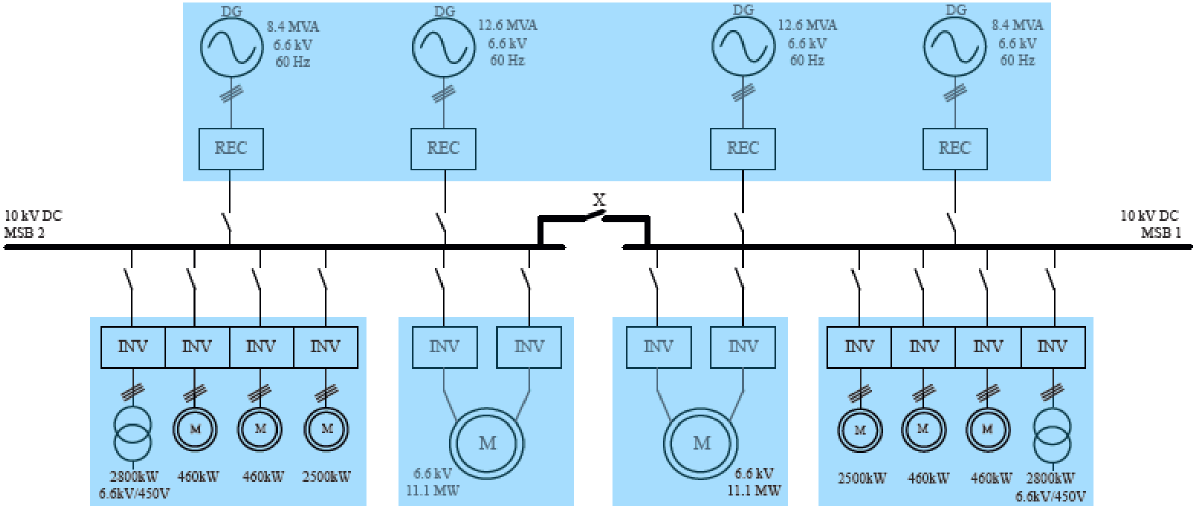

Figure 3: *Multi-terminal MVDC grid with distributed dc grids and **long dc cables***

It is found that the sizing of system capacitances and their placement play a significant role in the stability of the system. We provide a reliable tool that permits to accurately size MVDC systems, so high efficiency and reliable operation is achieved with an optimal size of components (i.e., reduced costs of installation). Some explicit results, of readiness for industry partner are: i) it is overall advantageous to place the big capacitances near to the active voltage sources, mostly in order to improve the damping of the system. The filtering effort near the loads can be relaxed. Furthermore, a very high inductance in distribution, due to a long cable effect, introduces low frequency resonances, which lead to system instability. For a given power and distances, cost-effective selection of dc-cables can be optimized.

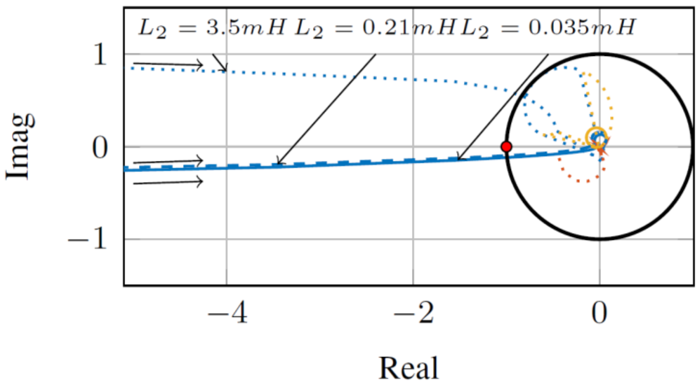

Figure 4: *Graphical solution to detect the feasibility of a MVDC grid for different **dc cables sizes***

[3] U. Javaid, F. D. Freijedo, D. Dujic, W. van der Merwe, "Stability Analysis of Multi-Port MVDC Distribution Networks for All-Electric Ships", submitted to IEEE JESTPE.

4.3 Enabling power electronics conversion technologies

Several research activities have been conducted or are still ongoing, tackling the problem of conversion technologies. In all cases focus is on MW rated power conversion that will be key enabler of MVDC systems.

Emulation of MVDC grids: The workpage devoted to the emulation of MVDC grids (e.g., long cable effects and potential resonances) has been revised, so an active solution has been found as more feasible and efficient. A solution based on power electronics has been developed and tested in a LV lab prototype, as shown in Fig. 5. Experimental results taken in the PEL LV lab prove the feasibility of the proposed technique with existing power electronics[4]. The main control parameter that limits the performance is the devices' switching frequency. Nowadays, new industrially available technologies, such as SiC, allow to work with high swiching rate and high voltage, so the proposal is also feasible for an industrial level development. Preliminary results of this study have been presented in an international conference.

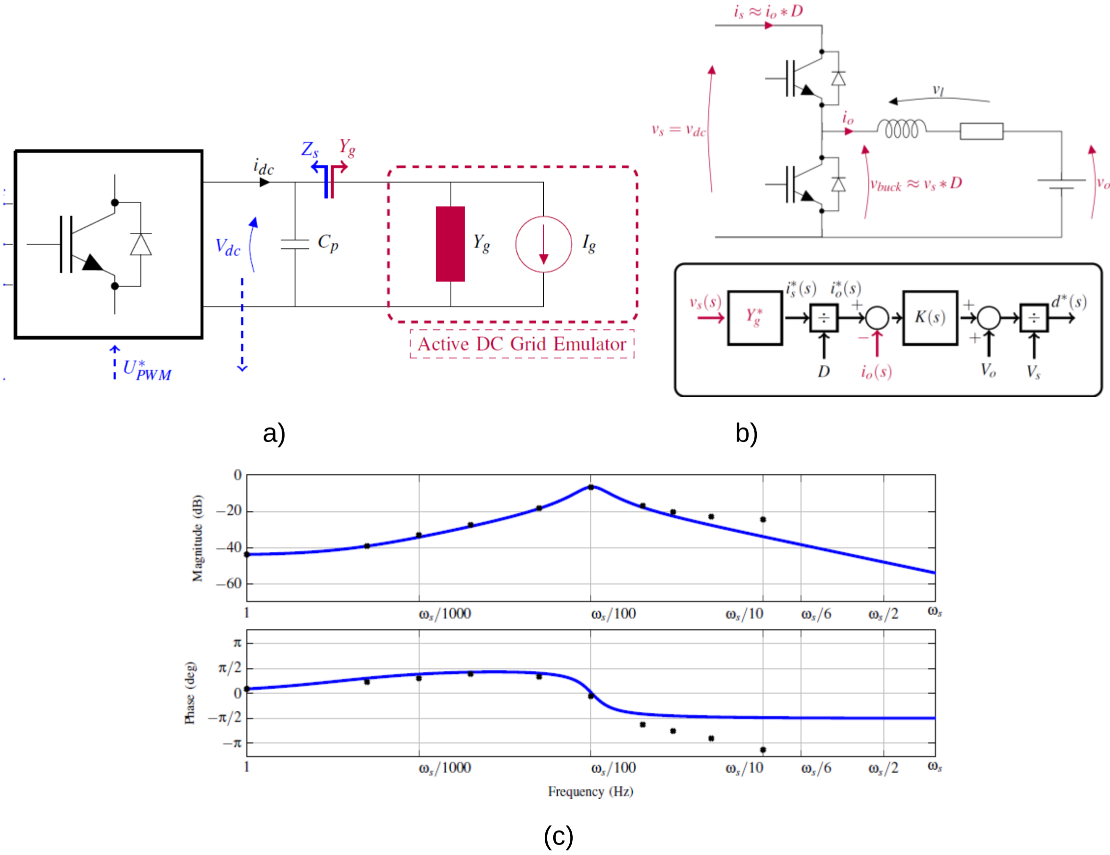

Figure 5: *Active MVDC grid emulation concept. (a) Objective: the dc grid source (i.e., the grid maker) is connected to a complex grid, modelled by an arbitrary admittance, which should be shaped according to the complex physical system to emulate. (b) a dc-dc boost power converter with detail of a plug-and-play to add grid emulation feature. (c) The theoretical curve (blue) shows the frequency response of a system with a resonance. The experimental results (dots) show the equipment is able to match the response up to 1/10 of sampling frequency.*

[4] E. Rodriguez-Diaz, F. D. Freijedo, D. Dujic, J. C. Vasquez and J. M. Guerrero, ''An Approach for the Emulation of DC Grid Admittances: Implementation on a Buck Converter'', International Power Electronics Conference-IPEC ECCE Asia, Niigata, Japan, May, 2018.

MVDC – LVAC conversion: The work on galvanically isolated modular converter (GIMC) has been finalized with graduation of PhD student Alexandre Christe, who is now with ABB Corporate Research in Sweden. The converter layout is shown in Fig.6, for which majority of hardware development has been done as elaborated in conference publications[5]. Development of the concept[6] has been supported by development of various tools[7] and identification of suitable control methods. The most important result from this work is development of modular multilevel converter sub-module which now serves as a technical platform for various other projects in the laboratory. This is illustrated in Fig. 7.

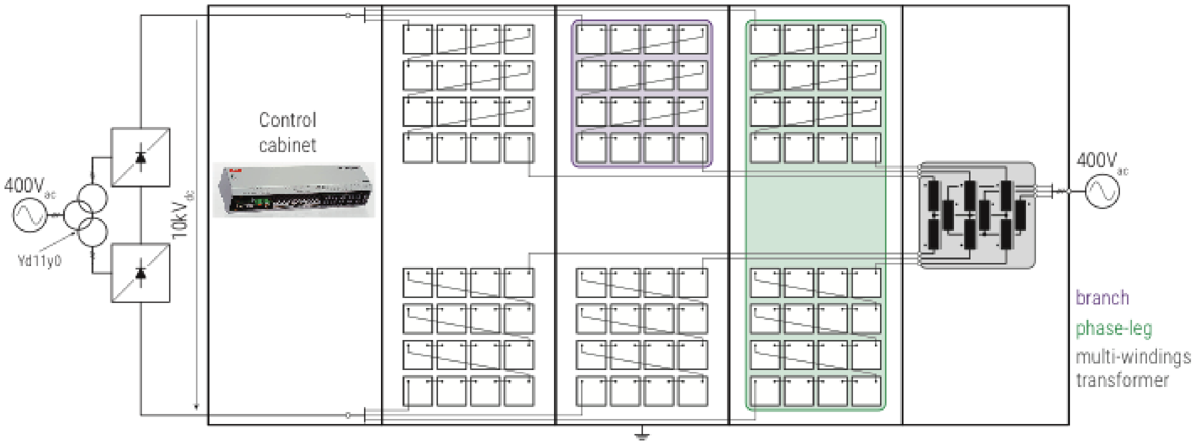

Figure 6: GIMC converter layout utilizing modular multilevel converter power stage and featuring integrated[8] multiwinding transformer.

Figure 7: MMC sub-module based on low voltage semiconductors and designed for medium voltage operation.

[5] A.Christe, E.Coulinge, D.Dujic: “Insulation coordination and dielectric design of a modular multilevel converter prototype”; The 18th European Conference on Power Electronics and Applications – EPE-ECCE Europe; September 5–9, 2016, Karlsruhe, Germany, pp.01-09.

[6] A.Christe, D.Dujic: “Galvanically isolated modular converter”, IET Journal on Power Electronics, vol. 9, Iss. 12, pp. 2318-2328, 2016.

[7] A.Christe, D.Dujic: “Virtual submodule concept for fast semi-numerical modular multilevel converter loss estimation”, IEEE Trans. On Industrial Electronics, vol. 64, no. 7, pp. 5286-5294, 2017.

[8] A.Christe, D.Dujic: “On the integration of low frequency transformer into modular multilevel converter”; The IEEE Energy Conversion Congress & Expo – ECCE; September 20–24, 2015, Montreal, Canada, pp. 3585-3592.

MVDC – LVDC: For the phase 2 of the SCCER-FURIES we have proposed high power conversion structure passed on use of Modular Multilevel Converter (MMC) in combination with Scott Transformer Connection (STC) for bipolar MVDC grids. A patent application has been filled on this topology, as part of the work has been carried out with support from Hyundai Electric and Energy Systems from Korea. More details can be found in the following conference publications[9,10]. Further developments are relying on use of MMC sub-module from Fig. 7.

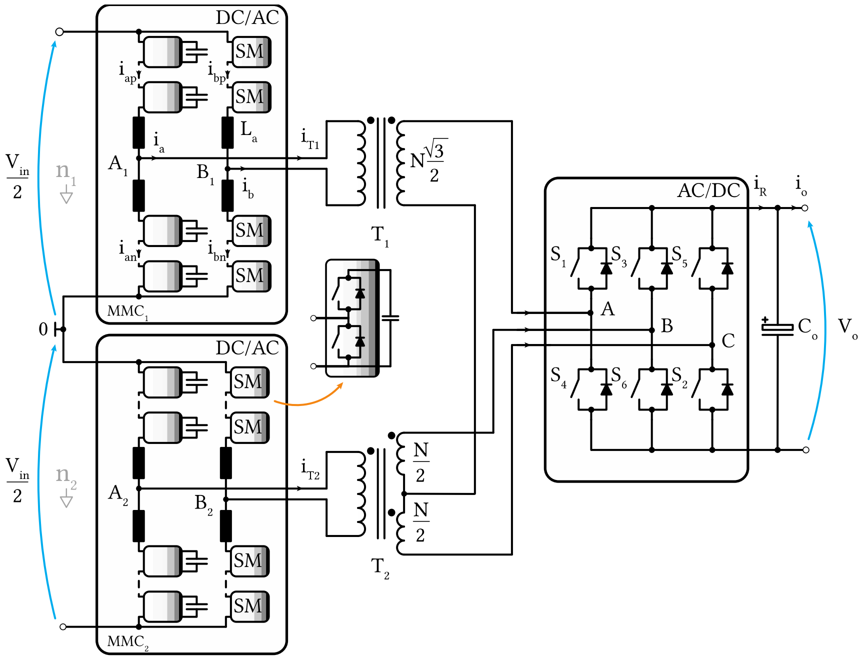

Figure 8: High power MMC-based DC-DC converter utilising Scott Transfomer Connection.

MVDC – LVDC – LVDC with integrated energy storage: Multiport Energy Gateway (MEG)[11] is a concept developed during the PhD work of Mr. Yan-Kim Tran (expected graduation in March 2019). The goal is to interface DC grids of different voltage levels and to add flexibility for energy storage integration. A multiport resonant converter has been identified as a suitable technical solution for MEG concept implementation. One main reason is the fact that the LLC resonant converter[12] is highly efficient in a wide range of power conversion set points.

A key part of the high power DC-DC operation relies on the DC-transformer operation (see next section). Currently, there is a lack of available design rules in the literature that explain the design for multiport transformers. In principle, the mathematical model is complicated, since it presents non-linearities and coupling among all the terminals[13].

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[9] S.Milovanovic, D.Dujic: "Six-step MMC-based high power DC-DC converter"; The International Power Electronics Conference – IPEC – ECCE Asia; May 20–24, 2018, Niigata, Japan, pp. 1484-1490.

[10] S.Milovanovic, D.Dujic: "MMC-based high power DC-DC converter employing Scott transformer"; The International Power Conversion and Intelligent Motion Conference – PCIM; June 5–7, 2018, Nürnberg, Germany.

[11] Y-K.Tran, D.Dujic: "A multiport medium voltage isolated DC-DC converter"; The 42nd Annual Conference of the IEEE Industrial Electronics Society – IECON; October 24–27, 2016, Florence, Italy, pp. 6983-6988.

[12] Y.K. Tran, D.Dujic, P.Barrade: "Multiport resonant DC-DC converter"; The 41st Annual Conference of the IEEE Industrial Electronics Society – IECON; November 9–12, 2015, Yokohama, Japan, pp. 3839-3844.

[13] Y-K Tran, F. D. Freijedo and D. Dujic, '' Natural Power Sharing Characteristics of Three-Port DC-DC Resonant Converters'', submitted to IEEE Tran. Power Electron.

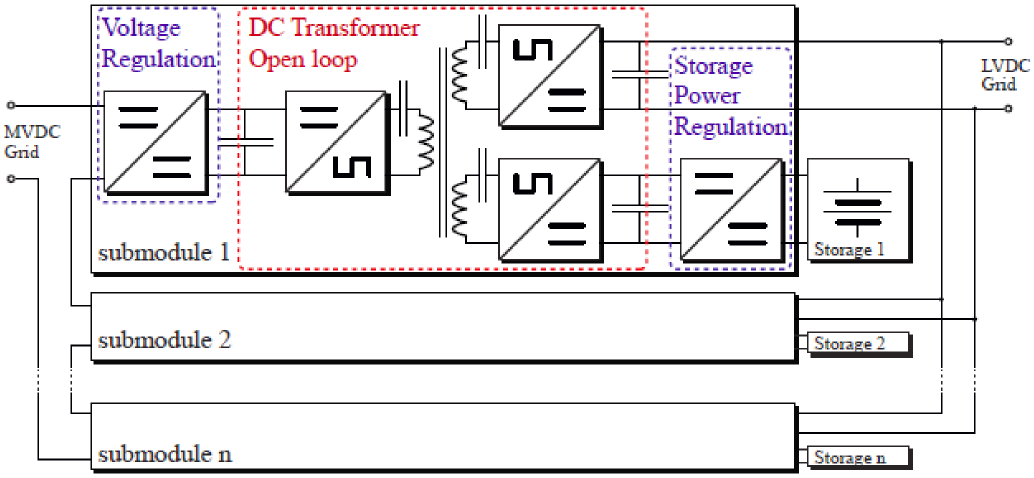


Figure 9: MEG for interfacing MVDC and LVDC grids with energy storage functionality.

MVDC - MVDC: To develop high power DC-DC converter capable of processing multi MW of power requires the use of appropriate power semiconductors. Our research activities sponsored by SNSF and in part by ABB semiconductors are focused on IGCT based resonant conversion. For the purpose of establishing operational limits of the semiconductor device, highly flexible test setup (shown in Fig. 10) has been designed, assembled and utilized for multiple experiments. Results related to low current switching conditions without preflooding[14] and with preflooding[15] of devices have been already presented at major conferences.

Figure 10: Test setup used for characterization of IGCT devices under soft switching conditions.

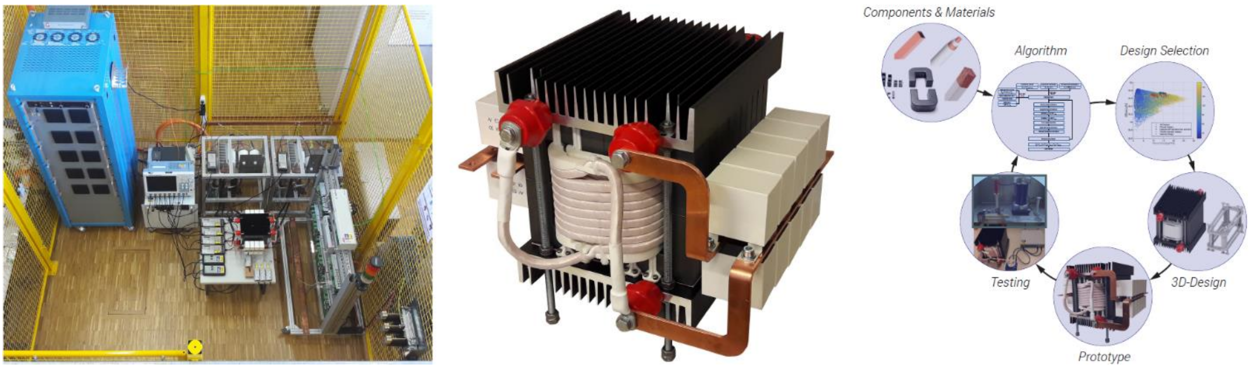
[14] D.Stamenkovic, U.R. Vemulapati, M.Rahimo, T.Stiasny, D.Dujic: “IGCT switching behaviour under low current conditions”; The International Power Conversion and Intelligent Motion Conference – PCIM; June 5–7, 2018, Nürnberg, Germany, pp. 777-782.

[15] D.Stamenkovic, U.R. Vemulapati, M.Rahimo, T.Stiasny D.Dujic: “IGCT switching behaviour under resonant mode low current conditions”; The 20th European Conference on Power Electronics and Applications – EPE-ECCE Europe; September 17–21, 2018, Riga, Latvia, pp. 1-10.

Medium Frequency Transformers Design Optimization: To support development of these galvanically isolated conversion structures, internally funded research activites are organized on the design optimization of medium frequency transformers. Thanks to the availability of high performing semiconductor devices, it is possible nowadays to process large amounts of power at high operating frequencies. Yet, in case when galvanic isolation is required, this implies the need for a transformers designed to operate at these elevated frequencies. While this has been achieved long time ago in LV applications, it is associated with many challenges when it comes to MV domain.

The main goal of this project is to accumulate the know-how and to establish a procedure for medium frequency transformer (MFT) design optimisation[16] in order to support other research activities related to isolated conversion. The associated activities performed within the last year include: thorough analysis of the current state of the art, detailed overview of available design choices in terms of materials and technologies[17], modelling of the corresponding multi-physical subsystems, development of a model-based optimisation scheme, prototyping and experimental verification, as depicted in Fig. 11c).

In terms of hardware development, the outcomes of these activities are the optimal 100kW, 10 kHz, MFT prototype, as displayed in Fig. 11b) and the resonant converter test setup capable of circulating full power, as illustrated in Fig. 11a). In terms of academic contribution, described activities have led to the development of a sophisticated design optimisation scheme and various MFT model improvements. The results of this PhD work are reflected in a journal paper[18]. Finally, the accumulated know-how was recognised as sufficiently valuable to be presented in form of a tutorial "Medium Frequency Transformer Design Optimisation" at some of the most reputable power electronics conferences worldwide: EPE'17 in Warsaw, Poland; ECCE 2017 in Cincinnati, Ohio; Ee 2017 in Novi Sad, Serbia and ICIT 2018 in Lyon, France. Presentations on developments in this project are already scheduled for the ECPE workshop "Medium Frequency Conversion for Solid State Transformers" which will be organized in Lausanne on 14th and 15th of February, and as seminar to be organize during PCIM 2019 conference in Nurnberg, Germany from 7th to 9th of May.



a) b) c)

Figure 11: a) Full power rated test resonant setup within a protective cage, b) 100kW, 10kHz, MFT prototype of the optimal design generated by developed design optimisation procedure, c) State-flow chart of the project learning cycle

[16] M.Mogorovic, D.Dujic: "Medium frequency transformer design and optimization"; The International Power Conversion and Intelligent Motion Conference – PCIM; May 16–18, 2016, Nürnberg, Germany, pp. 423-430.

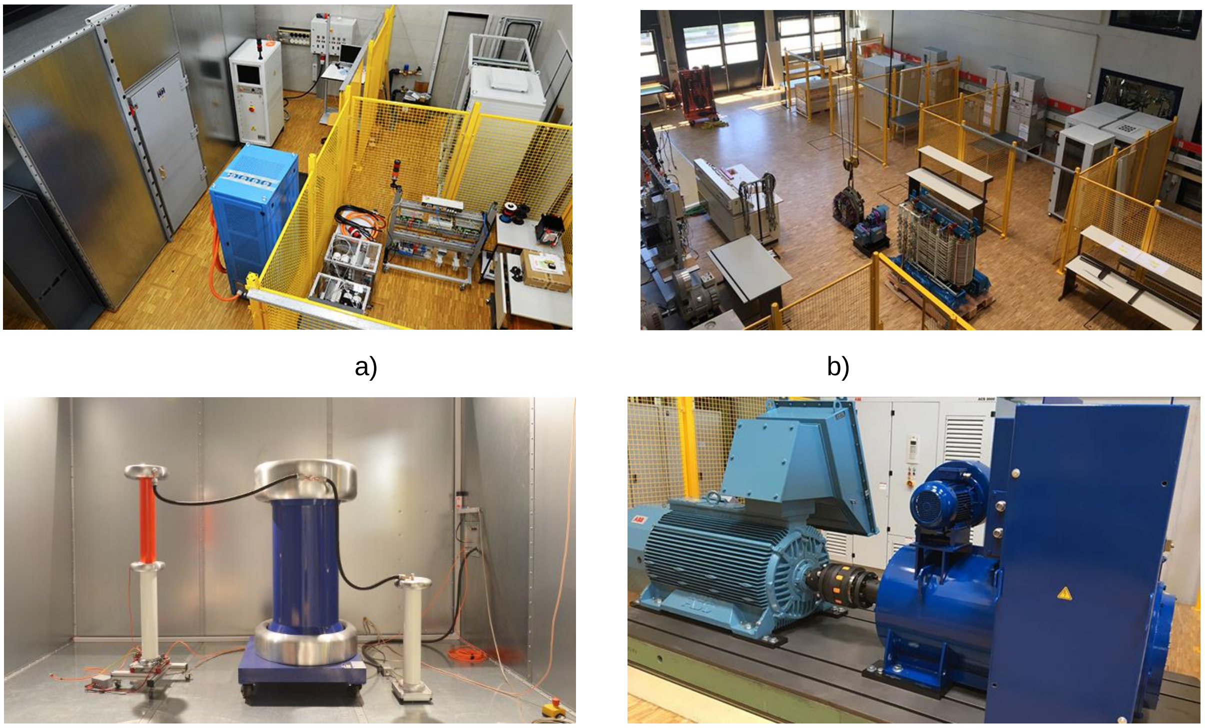
[17] M.Mogorovic, D.Dujic: "Thermal modelling and experimental verification of an air cooled medium frequency transformer"; The 19th European Conference on Power Electronics and Applications – EPE-ECCE Europe; September 11–14, 2017, Warsaw, Poland, pp. 1-9.

[18] M.Mogorovic; D.Dujic, '100kW, 10kHz Medium Frequency Transformer Design Optimization and Experimental Verification', IEEE Tran. Power Electron, (early access), 2018.

4.4 Medium voltage power electronics laboratory

Significant part of the effort, over the last three years, has been devoted to defining and establishing highly functional facilities enabling testing under realistic medium voltage conditions. During 2018 majority of the upgrade have been carried out and large portion of the work is actually finalized. Existing LV infrastructure already able to provide 1MW of power at 400V AC, has been extended by installation of three step-up transformers providing variety of voltages to the test cages (from 3.3kV AC to 20kV AC and up to 10kV DC). In addition to two test cages shown in Fig. 12a), additional four test cages are installed, as seen in Fig. 12b). For dielectric testing of various MV prototypes, high voltage test setup is available as shown in Fig. 12c). Finally, to support ongoing research activities in domain of power electronics for hydro applications, medium voltage machines (6kV, 0.5MW) are installed and soon will be connected to medium voltage drive ACS 2000, received as donation from ABB Medium Voltage Drives in Turgi.

In incoming months, Power Electronics Laboratory will reach fully functional state of its infrastructure and posses one of the best (if not the best) equipped university laboratories for medium voltage research in Europe. Project activities sponsored by SFOE were greatly helping to achieve this state and attract further funding from industry.



a) b)

c) d)

Figure 12: a) Two protective cages available since 2015 together with Faraday Cage of Partial Discharge test setup, b) Additional four test cages for medium voltage research activities, c) high voltage partial discharge test setup and d) medium voltage machine group.

5 Discussion of results

5.1 Scientific outreach

It is not easy to judge a project and its results immediately after reaching the end, as it takes some time for scientific community to react and judge the results. Yet, based on the provided summary, MVDC systems are still in infancy phase and further research (academia) and development (industry) is required.

Work related to stability of power electronics dominated MVDC systems, conducted during the project, has revealed importance of this kind of studies. Highly dynamic interactions which may occur between different elements of a system and initiated either due to resonances caused by passive elements or by interactions due to active control actions of different converters, may lead to instabilities rendering system inoperable or to deterioration of system performances below expected levels. Methods developed and tested by means of simulations are able to tackle simple as well as complex system architectures and can greatly aid system design phase. Inability to have exact parameters of various converter hardware or software elements is circumvented by performing large parameters sweeps, covering realistic operating conditions. These results have been successfully published.

When it comes to work related to conversion technologies, the majority of these projects is still ongoing and results are regularly disseminated on conferences and in journals. Two PhD students working on these projects have graduated in March 2018, producing two excellent PhD theses, available online. Power electronics laboratory will continue to focus its research effort on MVDC conversion technologies.

5.2 Industrial outreach

Initially, part of the project was co-sponsored by ABB Medium Voltage Drives. ABB part of the project is finalized and dicussions for follow up are still ongoing. PhD student that was working on this project is hired by ABB and is currently working with ABB Power Grids in Turgi, developing high power conversion solutions. In addition to sponsoring PhD project, ABB Medium Voltage Drives have donated 1MW medium voltage converter ACS2000 to the laboratory as part of ongoing support and interest into our research work.

Another part of ABB (ABB Semiconductors) is actively involved into our research activities related to soft switching of IGCT and continues to provide support in material, models and advices, whenever needed.

Work on marine electrical system has led to collaboration with Hyundai Electric and Energy System from Korea, and we have launched three projects with them. One has been finalized, and two are ongoing at the moment.

Several other industrial partners have been interested into our work on design optimization of medium frequency transformers, either as suppliers of core materials (e.g. Hitachi Metals from Japan or ThyssenKrupp from Germany), or as producers of final technology.

Dissemination of results of the projects associated with MVDC technologies has been very succefull so far and we will continue to organize educational seminars and tutorials, addressing challenges as well as opportunities in this domain. Reference list at the end includes all PEL publications relevant to the scope of the SFOE project and directly related to MVDC techologies.

6 Conclusions and outlook

Despite large effort invested into research activities, MVDC technologies require further investments, both in academia and as well in industry, in order to develop a framework, standards and de-risk investments in this field. Potentials of the technology cannot be exploited at the moment, as there is no common agreement on how to design and operate MVDC systems. Efforts to do so are evident and currently there are several working groups of CIGRE addressing various aspects of this. The principal investigator of this project is a member of working group SC6.31 dealing with “Feasibility of MVDC grids”.

Despite these challenges associated with needs of industry to find appropriate business case and return on their investments, when it comes to technological landscape, there are great opportunities. Conversion technologies are required to support MVDC deployment, and since there is a lack of standardization, certain flexibility is required when it comes down to operating voltage. This is where the majority of work is focused on modular converter topologies, capable to adapt to various MVDC voltages. Protection equipment (e.g. DC breaker) is not readily available or it is prohibitively expensive, requiring alternative ways to implement protection coordination on newly designed DC systems. Designing future MVDC system will require tools and methods to carry out stability studies and considering variety of possible system layouts, this field will require further research and developments. Finally, these new MVDC networks will require certain power flow control and coordination of a large number of power electronics converters (provided those are defined), resulting in needs of development of appropriate control schemes.

In a summary, and from an academic point of view, more work is needed to move MVDC technologies and systems into a mainstream solution ready for industrial adoption.

With several ongoing research activities related to conversion technologies and the fact that medium voltage facilities are available, research work will move from the domain of simulations into prototyping and experimental testing. This is required to validate various concepts that are thoroughly analysed and simulated already.

In some of these research prototyping efforts, final prototypes will be used as a part of laboratory infrastructure, thus supporting further research activities. Design activities carried out during the project have created various tools that are reusable and can be extended for other needs, improving the efficiency of workflow.

Industrial partners will continue to be an important part of collaborative projects, providing insights and challenges for deployment of various technologies, and we hope to start new collaborative projects already in 2019.

7 Publications

EPFL_2015_1 U.Javaid, D.Dujic, W.van-der Merwe: “MVDC marine electrical distribution: Are we ready?”; *The 41st Annual Conference of the IEEE Industrial Electronics Society – IECON*; November 9–12, 2015, Yokohama, Japan, pp. 823-828.

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EPFL_2017_3 U.Javaid, F.D.Freijedo, D.Dujic and W. van der Merwe, “Marine MVDC Multi-Phase Multi-Pulse Supply,” *IECON 2017 – 43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, 2017.

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EPFL_2016_3 A.Christe, D.Dujic: “Galvanically isolated modular converter”, *IET Journal on Power Electronics*, 2016.

EPFL_2017_4 A Christe, D Dujic: “Virtual Submodule Concept for Fast Semi-Numerical Modular Multilevel Converter Loss Estimation”, *IEEE Transactions on Industrial Electronics*, Vol.64, No.7, pp. 5286 – 5294, 2017

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