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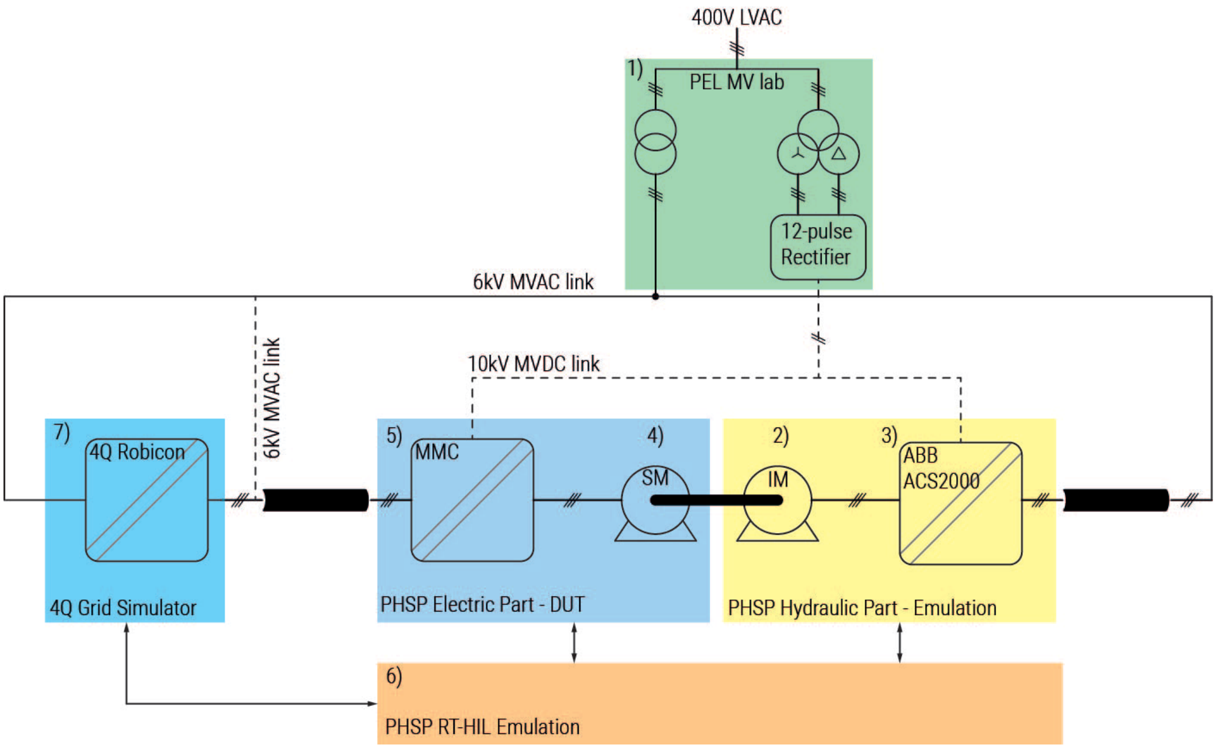
Real-Time Hardware-in-the-Loop Emulation Platform for Pumped Hydro Storage Power Plants



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Summary

Considering recent decisions to phase out nuclear energy generation, a large energy void is getting created that has to be filled or compensated with other sources, ideally renewable technologies. Hydro power plants are an important element of the Swiss energy landscape, contributing with around 60% to the annual energy production. While the Energy Strategy 2050 foresees only a minor increase of 3% in hydro generation capacity, with the support of power electronics technology, there is a large potential to improve the energy efficiency of the existing installations, increase their operational flexibility and improve ancillary service offering on the energy market.

At the moment, Doubly Fed Induction Generator (DFIG) is the predominant variable speed solution, since the power converter, which is connected to the rotor has to be sized only for around 1/3 or less of the total generator rated power. On the other hand, improvements in power electronics allow for higher power converter to be realized and Converter Fed Synchronous Machines (CFSM) are considered as the future solution, as demonstrated with recent KWO update of Grimsel-2 PHSP, and installation of 100MW rated multilevel converter from ABB.

A large number of pumped hydro storage power plants (PHSPs) are coming to the end of their lifetime and majority of present hydro installations requires some kind of improvements through retrofitting to extend and improve its operational flexibility in order to offer faster response times and increased support to the power system.

For those reasons, the objectives of this project were related to PHSP variable speed drives with Synchronous Generators and development of highly flexible medium voltage PHSP emulation platform, where performance and impact of novel power electronics converter topologies can be quantified. Power electronics technologies today allow for realization of variable speed pumped hydro plants in excess of 100MW per single unit, and new converter topologies, such as Modular Multilevel Converter (MMC) make it possible to significantly reduce burden on the installation, due to ability to easily adapt design to different voltage and power levels encountered in typical installations. These new conversion technologies, further supported by advanced tools, such as Real-Time Hardware-In-the-Loop systems, allow for fast and effective verification of relevant operating regimes and modes encountered in hydro applications, in a safe and cost effective manner.

Résumé

En prenant en compte la volonté récente de sortir du nucléaire, le déficit en énergie doit être compenser par d'autres sources, idéalement par des sources d'énergie renouvelables. Les centrales hydroélectriques sont des éléments importants du paysage énergétique suisse, contribuant à la hauteur de 60% de la production d'énergie annuelle. Alors que la stratégie énergétique suisse 2050 ne prévoit qu'une augmentation minime de 3% de la capacité de production de l'hydroélectrique, grâce aux technologies d'électronique de puissance, il y a un potentiel élevé d'améliorer l'efficacité énergétique des installations existantes, d'augmenter leur flexibilité opérationnelle et de faire progresser l'offre de services auxiliaires sur le marché de l'énergie.

Pour l'instant, la machine asynchrone à double alimentation est l'acteur principal des machines à vitesse variable, puisque le convertisseur de puissance, connecté au rotor, peut être dimensionné pour un tiers voire moins de la puissance nominale du générateur. D'autre part, les améliorations en électronique de puissance permettent de réaliser des convertisseurs d'une puissance plus importance et les machines synchrones alimentées par convertisseur sont présagées comme future solution, comme prouvé par la récente révision par KWO de Grimsel-2, installation de pompage-turbinage, et l'installation de 100MW de convertisseurs multi-niveaux ABB.

Une majorité de centrales de pompage-turbinage arrivent en fin de vie et la majorité des installations hydroélectriques actuelles demandent quelques améliorations au travers de retrofitting pour étendre et améliorer leur flexibilité opérationnelle dans le but d'offrir un temps de réponse plus rapide et fournir un meilleur support du réseau électrique.

Pour ces raisons, les objectifs de ce projet sont liés au drive de machine à vitesse variable avec générateur synchrone dans les installations de pompage-turbinage et le développement d'une plateforme d'émulation flexible en moyenne tension, où les performances et l'impact des topologies d'électronique de puissance novatrices peuvent être quantifiée. Les technologies d'électronique de puissance modernes permettent la réalisation de centrales de pompage-turbinage à vitesse variable au delà de 100MW par unité, et de nouvelles topologies de convertisseur, telles que les convertisseurs multi-niveaux (MMC) donnent la possibilité de réduire les contraintes sur l'installation, grâce à leur capacité à s'adapter à différents niveaux de tension et de puissance, comme retrouvé dans les installations typiques. Ces nouvelles technologies de conversion, d'autant plus soutenues par des outils avancés, tels que les systèmes temps réel 'hardware-in-the-loop', qui permettent une vérification rapide et efficace des régimes d'opération et modes d'exploitation des installations hydroélectriques, de façon sûre et rentable.

Contents

List of abbreviations

PHSP	Pumped Hydro Storage Power Plant
CFSM	Converter Fed Synchronous Machine
DFIM	Doubly Fed Induction Machine
RT	Real-Time
HIL	Hardware-In-the-Loop
MMC	Modular Multilevel Converter
PEL	Power Electronics Laboratory at EPFL
SM	Synchronous Machine
SFOE	Swiss Federal Office of Energy
WP	Work Package

1 Introduction

1.1 Background information and current situation

Considering recent decisions to phase out nuclear energy generation, a large energy void is getting created that has to be filled or compensated with other sources, ideally renewable technologies. Hydro power plants are an important element of the Swiss energy landscape, contributing with around 60% to the annual energy production. While the Energy Strategy 2050 foresees only a minor increase of 3% in hydro generation capacity, with the support of power electronics technology, there is a large potential to improve the energy efficiency of the existing installations, increase their operational flexibility and improve ancillary service offering on the energy market.

At the moment, Doubly Fed Induction Generator (DFIG) is the predominant variable speed solution, since the power converter, which is connected to the rotor has to be rated only for around 1/3 of the total generator power. On the other hand, improvements in power electronics allow for higher power converter to be realized and Converter Fed Synchronous Machines (CFSM) are considered as the future solution, as demonstrated with recent KWO update of Grimsel 2 PHSP, and installation of 100MW rated multilevel converter from ABB. Simplified schemes of both variable speed drive configurations are shown in Fig.1.

A large number of these PHSP installations are coming to the end of their lifetime, and according to data obtained from GE, 34.9GW of PHSP generators in Europe would have to be refurbished in upcoming years. The maximum power deliverable by a PHSP with power electronics based speed regulation can be extended by a 30%, compared to a conventional PHSP unit. Thus, converting 100 MW of conventional PHSP into variable speed PHSP will provide around 30 MW regulations while in pumping mode. This essentially means that operation with variable speed allow for PHSP operators to extend their operating speed range, and thus power range, especially in the pumping mode. While conventional fixed speed PHSP can be operated at its rated speed (power), ability to adjust pumping power through power converter, greatly enhances flexibility of PHSP in its respond to power demands from utilities. It also means that if the 34.9 GW of conventional generators older than 30 years are converted into variable speed, around 10.47 GW of additional frequency regulation capability in pumping mode are obtainable. These improvements are possible, since application of frequency converters, and especially in case of CFSM installations largely decouple machine's operating frequency from the network operating frequency, allowing for independent regulation action in the ancillary service market. Yet, retrofit projects are subject to various limitations (hydraulic efficiency, grid connection, available installation area, cost…) and careful quantification of potential benefits must be provided.

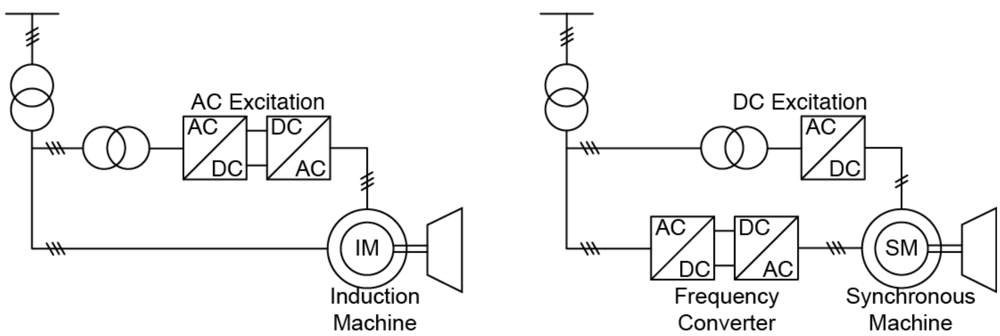


Fig.1: Variable speed drive configurations for the PHSPs: left) Doubly Fed Induction Generator (DFIG), right) Converter Fed Synchronous Machines (CFSM)

Nevertheless, thanks to advancement in power electronics, it is possible today to build medium voltage power electronics converters in excess of 100MW. Thus, the objectives of this project were related to PHSP CFSM variable speed applications and novel power electronics converter topologies which promise to maximize the operational performance, beyond those presently reported.

1.2 Purpose of the project

Main objectives of the project were related to the establishment of medium voltage research platform for pumped hydro storage pump applications, that would allow for various investigations on role and impact of power electronics technologies in hydro applications. SFOE project has served the role of seed project and led to new contracts and research activities, as explained at the end of report.

Simplified layout is demonstrated in Fig.2, where several elements are already installed in the power electronics laboratory while the works on the custom develop power electronics converters are still on-going. Commercially available equipment includes: 1) MV supplies, 2) Induction Machine (0.5MVA, 6kV), 3) ABB Medium Voltage Converter ACS 2000 (4Q, 1MVA, 6kV) and 4) Synchronous Machine (0.5MVA, 6kV). Efforts of the power electronics laboratory are mainly directed to finalize developments of: 5) Modular Multilevel Converter (0.5MVA, 6kV), 6) RT-HIL system allowing to simulate relevant hydro application scenarios and 7) High Performance Medium Voltage Grid Emulator (1MVA, 6kV). While the tremendous progress has been achieved regarding research platform, there is still significant work ahead considering complexity of installation, medium voltages involved and various safety considerations. Next sections provide summary of project results, as well as future plans and activities in this domain.

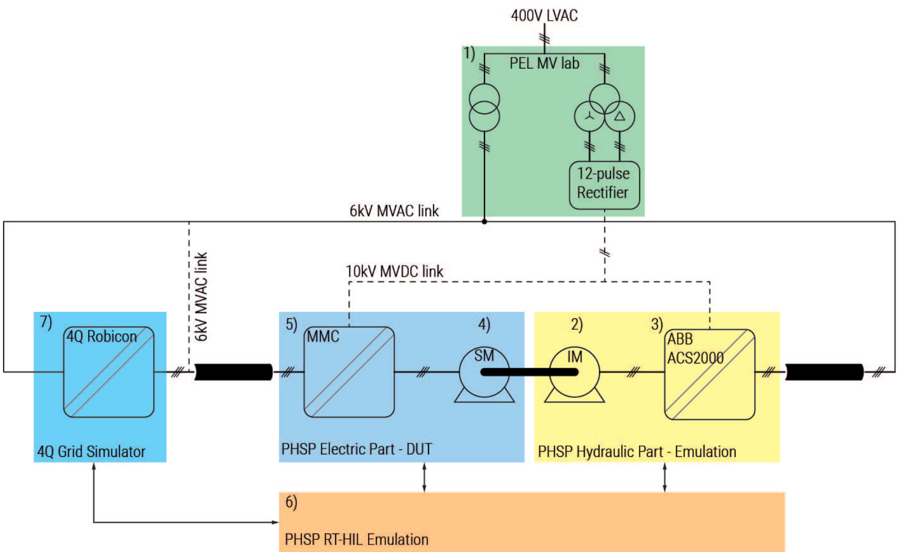


Figure 2: Principal setup of the Real-Time Hardware-In-The-Loop platform for hydro applications.

1.3 Objectives

The main objectives of the work are related to development of the Real-Time Hardware-In-the-Loop (RT-HIL) platform that would enable various investigations in two domains:

1) Real time simulations of hydro installation relevant operating modes or scenarios

2) Performances of various power electronics technologies in hydro applications and impact on both on the utility grid and motor/generator.

2 Description of the facility

Related to principal layout shown in Fig.2, the equipment currently installed in the Medium Voltage Power Electronics Laboratory is shown in Fig.3. Electrical machines are mechanically coupled and electrically wired to their supplies. However due to long delays with finalization of electrical installation of the laboratory, commissioning of the test setup could not have been finalized. This is mainly due to fact that facility is to be operated at medium voltage of 6kV, which require various protection and safety equipment (SIEMENS commercial products) to be tested and finalized in the laboratory, prior to the actual use of the setup.

Majority of project efforts, for those reasons, were directed towards the realization of Modular Multilevel Converter prototype and 4Q Grid Emulator, as described in next sections. Thanks to the new EU H2020 project, additional funds have been raised to finalize and activate complete test setup.

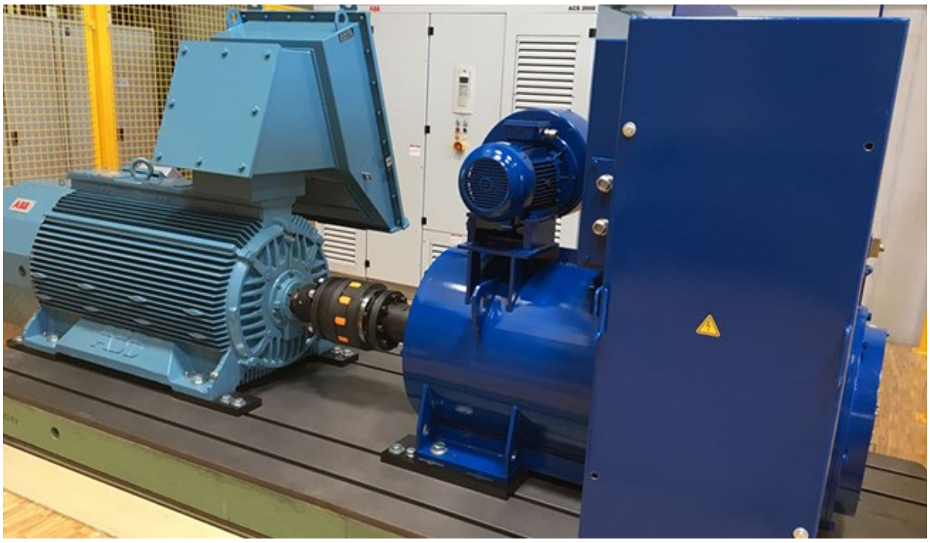


Figure 3: 0.5MW, 6kV rated Induction and Synchronous machines. ABB medium voltage drive ACS 2000 is visible behind.

3 Procedures and methodology

The results of research and implementation work obtained within the past 24 months are briefly summarized here. For the sake of clarity, presentation is grouped into several subsections.

3.1 Investigation of CFSM perspective with Modular Multilevel Converters

To achieve very high power levels implied by the PHSP application, independently of current semiconductor technology limitations, a topology with better scalability is required. For those reasons, Modular Multilevel Converter is a promising alternative to monolithic converters currently used for DFIM applications. In scenarios where two AC systems are to be interconnected (fixed network frequency on one side and variable machine frequency on the other side), there are two possible topologies – indirect (I-MMC) and direct (D-MMC), depicted in Fig. 4.

Indirect, or back-to-back MMC is well established in point-to-point HVDC bulk energy transmission. Direct MMC found its use in static frequency converters (SFC) for railway interties, as an interface between three-phase 50Hz public grid and single-phase 16,7Hz railway supply; a reference to a recent ABB's 2x40MW unit in Geneva can be found easily online. In these established applications, MMC is interfacing two grids of fixed frequencies, while in case of PHSP, electric machine side of the installation operates at variable frequency, which introduces its own challenges.

The building block of an MMC is a submodule, comprising standard switching elements (IGBT or IGCT) either in basic half-bridge (HB) or full-bridge (FB) configuration, or some of the alternative ones, and a capacitor bank. Converter arms are realized as strings of these submodules, making very high voltage levels achievable with available semiconductor technologies. Since each submodule is controlled independently, output voltage is of multilevel waveform. This is beneficial in terms of lower stress on machine windings insulation, enabling retrofit with older machines without additional dv/dt filtering.

In monolithic back-to-back VSCs, a central DC bus capacitor bank stores the total converter energy. For high power converters, in case of faults, it is very challenging to handle high short-circuit currents and consequential mechanical stresses provided by such a source. In an MMC, energy storage is evenly distributed in submodules, making fault management easier. High availability of the converter in case of submodule failure is achieved through redundancy, by stacking additional submodules in converter arms. Operation can be continued after electrical bypass of failed submodule, which is replaced during scheduled periodic maintenance, e.g. yearly.

Both of these topologies have been extensively studied in the project for their role and impact in hydro applications. Simulation models have been developed, enabling us to simulate various operating modes, while the research platform is being finalized.

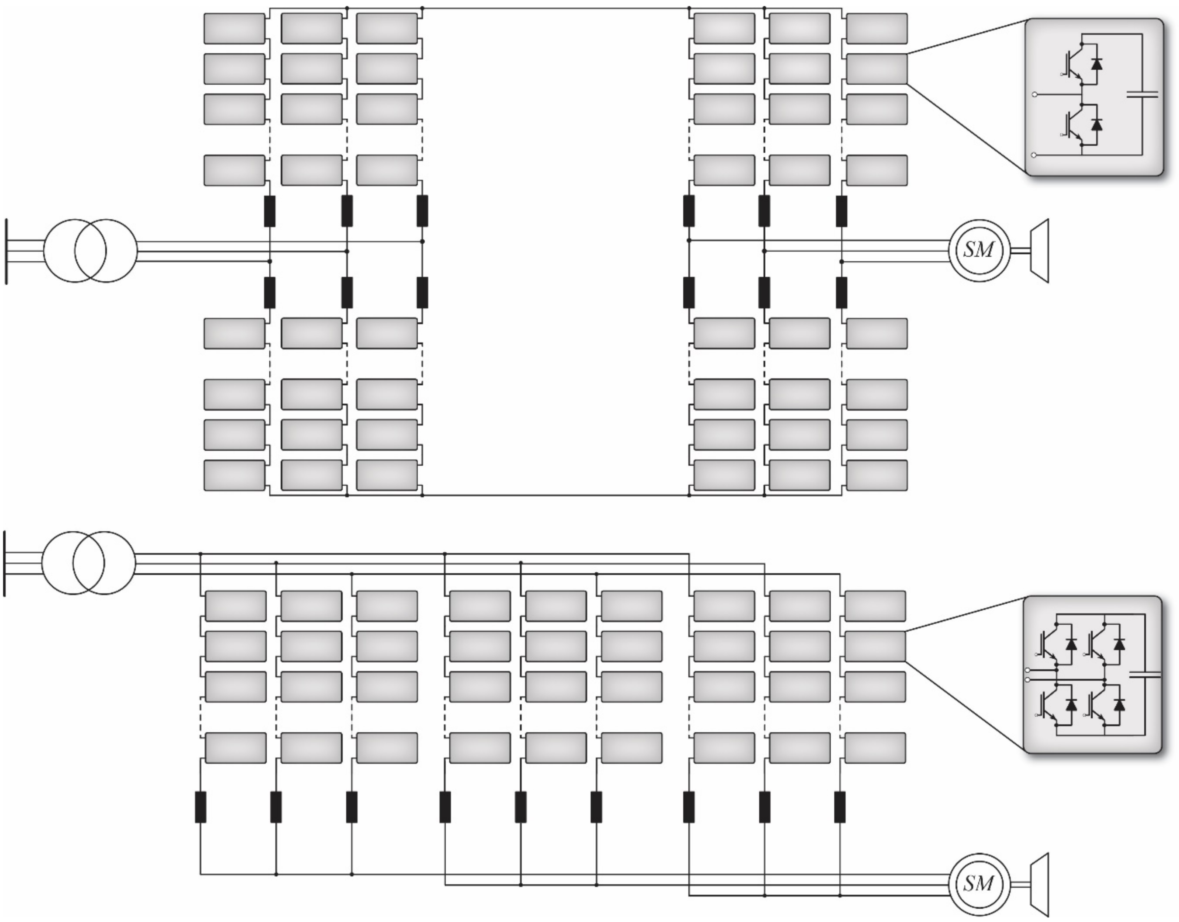


Figure 4: Indirect MMC (up) and direct MMC (down) topologies suitable for hydro applications.

3.2 Insulation coordination for converter fed machines

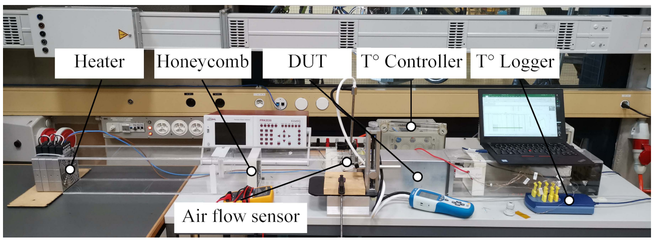
Direct connection of power converter to electrical machines causes increased stresses for the insulation system, compared to regular electrical machines connected to the network. In case of limited number of levels, high dv/dt values can be putting extra stress to machine windings' insulation. PHSPs that are candidates for conversion from fixed- to variable-speed pumping are based on older SMs designed for grid voltage waveforms. The insulation of these machines, subjected to high dv/dt stresses of VSC output, would age significantly faster and deteriorate. This limitation introduces the need for filtering, which directly translates to additional space, losses and financial requirements, with first two being critical in limited cavern spaces. For those reasons understanding influence of converter voltage waveforms on the machine winding system is of paramount information.

A measurement campaign has been organized, in the framework of on-going CTI (Innosuisse) project with GE Renewable Hydro from Birr, to verify their existing machine design models against measurements on the SM available in the Power Electronics Laboratory and equipped with multiple accessible measurement points on the stator winding. Results have been transferred to GE, and are not discussed here for the confidentiality reasons.

3.3 MMC research prototype development

Development of the 0.5MW MMC prototype has made great progress forward and various subassemblies are in the phase of performance testing before their production. Basic building block is the MMC submodule shown in Fig. 5a) that is already heavily tested in the custom-made thermal test setup shown in Fig.5b). Electrical operation under increased ambient conditions, full power operation and relevant cooling conditions have been already verified, and production of multiple modules will commence soon.

a)



b)

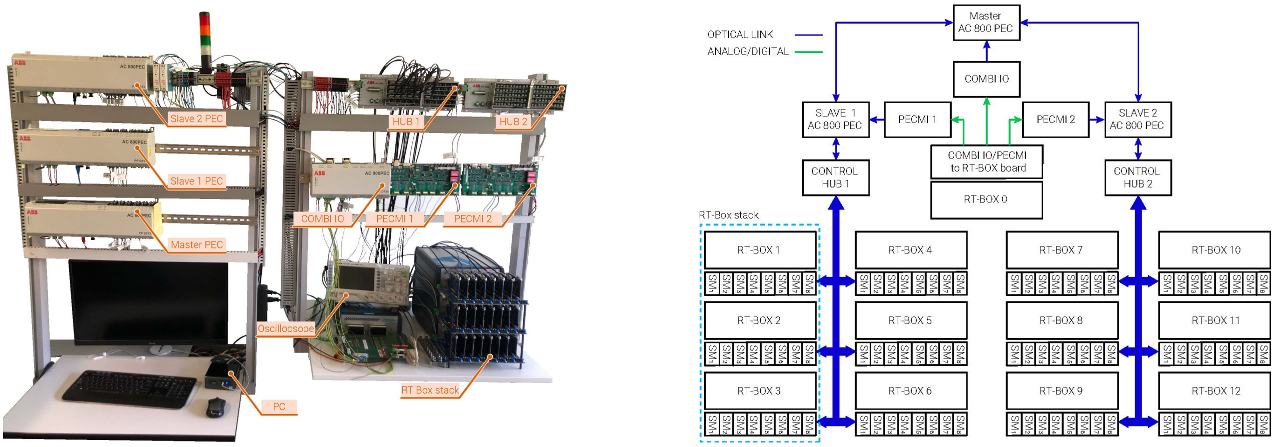
Figure 5: a) MMC Submodule for the implementation of the MMC prototype; b) Thermal setup used for power tests

Main mechanical elements of the MMC prototype are finished and shown in Fig. 6. Left part of the cabined hosts six coupled branch inductors, which are provided by Schaffner, while the right hand side is ready for installation of 96 MMC submodules from Fig.5a. Inside the shown cabinet, there are actually two MMCs (each with 48 submodules in total), which would allow for I-MMC configuration and experiments on the available SM machine of the PHSP platform. To develop and verify MMC control algorithms in parallel with the development of the MMC hardware, dedicated MMC RT-HIL test setup is designed and partially tested already. Considering complexity of MMC, namely due to large number of submodules that need to be controlled and coordinated, there is a need to have a research tool capable of providing safe and reliable test environment.

This is achieved by adaptation of the electronic control circuitry from the MMC submodule into a new board which is then connected to PLEXIM's RT-Box FPGA based RT-HIL system. Complete MMC hardware is then modelled on the multiple of RT-Box units and models are executed in the real time, allowing for tests of MMC control algorithms. Current test setup is shown in Fig.7a, while the complete scheme of the system to be implemented in shown in Fig. 7b). MMC control hardware consists of Master and Slave PEC800 controllers from ABB, and various interface boards for grid voltage and current measurements, Combi IO digital interface module, fiber-optic hub for connection to individual submodules and DSP controllers within the submodules.

To efficiently continue working on these activites, recently an Innosuisse project with PLEXIM as implementation partner has been approved recently, and will start in 2020. There are many unknowns on the large scale RT-HIL capabilities of the RT-Box, and project will address those.

Figure 6: Cabinets of the MMC 0.5MVA prototype

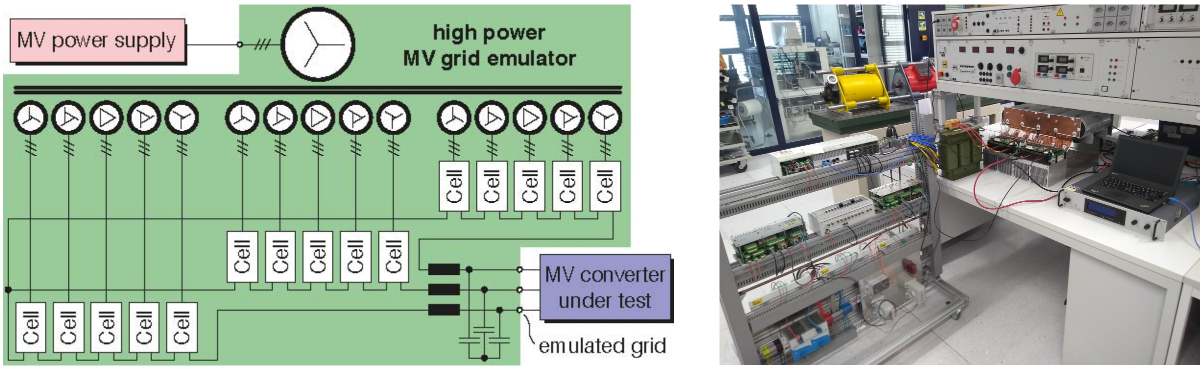


a) b)

Figure 7: RT-HIL system based on ABB PEC800 controller: a) reduced system currently in testing; b) complete system layout.

3.4 Medium voltage grid emulator

Another important element of the RT-HIL PHSP research platform is the MV grid emulator. This element is needed in order to provide relevant supply voltage to the platform and most importantly to be able to emulate various grid conditions defined in different grid codes. Overall scheme of the grid emulator topology is shown in Fig.8a), and is based on the multi-winding transformer with single primary and 15 secondary windings which is used to supply multiple power converter stages, with their outputs connected in series. Currently, single power stage is developed and is undergoing testing in the lab, before multiple of them will be produced.



a) b)

Figure 8: 1 MVA, 6kV grid emulator: a) overall scheme based on the multi-winding transformer and 15 Power Electronics Building Blocks (PEBBs); b) PEBB during control and co,munication testing.

4 Results and discussion

Activities started two years ago have produced various learnings related to the role and impact of power electronics in hydro applications. Increased interest in the relevant communities (power electronics, hydraulic machinery) can be observed and more importantly there are announcement form industrial vendors about new project beings signed for commercial installations.

Working jointly with GE Renewable Hydro from Birr, have provided us opportunity to support them, but also learn form them on the topic of insulation coordination of medium voltage machines fed from power electronics converters. While GE has delivered equipment into many DFIM hydro installations, they are entering into CFSM area as well. Even though not fully finalized PHSP research platform was already used to support GE needs when it comes to this topic.

Strong contacts with ABB Switzerland, gave us opportunity to understand better business directions and technical challenges associated with MMC based solutions for hydro applications. It is important to mention that ABB will deliver MMC based solution into Austrian hydro installation supported by GE SM in incoming 2-3 years. This will be world’s first ever installation of these technologies in hydro plant. This gives even more reasons to finalize PHSP research platform and provide support for future projects and operating modes that these installations can encounter.

Various delays encountered in the project are not of technical nature, but rather logistics associated with commissioning of new medium voltage laboratory, which is subject to various protections, and safety measures that had to be put in place. While the EPFL has been extremely supportive, these tasks simply require time and coordination of multiple subcontractors. It is believed that electrical installation will be fully functional by the end of 2019.

5 Conclusions

SFOE project funding has been considered as very important initial or seed funding towards the realization of highly flexible PHSP research platform. This is particularly valid considering importance of hydro in Swiss energy landscape, and many retrofitting projects that are on-going. Further developments of the PHSP research platform will continue through new projects, as described in section 7, and further acquisition of equipment as described in Section 6. Our ties with key players in Switzerland, namely ABB and GE, have been strengthened and will lead to closer joint activities in the future. At the same awareness of existence of such a facility is now brought to international level.

6 Outlook and next steps

The availability of PHSP research platform will be of direct importance of recently approved large EU H202 project "*Hydropower Extending Power System Flexibility – X-FLEX*", with EPFL as leading house (Prof. Avellan, Prof. Paolone and Prof. Dujic), budget of around 18M EUR and 19 partners in the project. Project has been officially launched from September 2019, and research platform initiated by SFOE seed funding will be finalize, extended with new equipment and used to support investigations related to real demonstrator installations.

Overall project goals are to demonstrate various technologies that can improve flexibility of hydro applications, and power electronics technologies are definitely of high importance. Fundings are available for 4 years, both for personnel as well equipment. Main extension of the platform will be realized by acquisition of 6kV, 0.5MVA DFIM and appropriate rotor-side converter, to achieve drop in replacement solution for the existing SM. Finally, various operational scenarios will be deployed on the Speedgoat RT-HIL system, for the demonstrator sites outlined in the X-FLEX project.

7 National and international cooperation

As already mentioned, X-FLEX project consortium has 19 partners, providing us opportunity to extend our network significantly outside the Switzerland. Some of the partners are: Andritz Hydro (Austria), GE Hydro (France), Voith Hydro (Germany), CNET (Portugal), EDP (Portugal), EDF (France), INESC (Portugal), Supergrid Institute (France), IHA (UK).

New contacts are established in Switzerland as well, with:

- Power Vision Engineering, a leader in hydro simulation solutions based on SIMSEN. We are currently investigating how to deploy their "Hydro-Clone" on Speedgoat RT-HIL system.

- HES-SO Sion and Prof. Munch related to simulation of turbines, as this is relevant for our work and it provides forbidden regions of operations

- ALPIQ, considering that their Z'Mutt installation is among the first user case that will be further investigated on the PHSP research platform.

We hope to build substantial visibility of RT-HIL PHSP platform in incoming years, allowing us to serve the needs of industrial partners, as well as our research needs. SFOE project has been of great help to launch these activites.