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Florian Errigo, Juan Carlos Gonzalez-Torres, Abdelkrim Bennaib, Laurent Chédot, Ali Sari, et al.. Modular Multilevel Converter with Embedded Energy Storage for Power Oscillation Damping and Fast Frequency Response - A case study. 41. CIGRE International Symposium, Jun 2021, Ljubljana, Slovenia. hal-03669846

HAL Id: hal-03669846

<https://hal.science/hal-03669846>

Submitted on 17 May 2022

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Modular Multilevel Converter with Embedded Energy Storage for Power Oscillation Damping and Fast Frequency Response – A case study

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Abstract – The massive introduction of remote power electronics interfaced renewable generation units and high-voltage direct current (HVDC) interconnectors into the existing power system, with the aim of decommissioning a part of conventional centralized generation, has introduced new challenges to grid operators to maintain system stability. Since conventional balancing services rely on the availability of traditional synchronous generators and the kinetic energy stored in their rotating masses, new methods for providing ancillary services must be introduced. In this context, voltage source converters (VSCs), and particularly the modular multilevel converters (MMCs), have received a significant interest. An MMC stores energy in its distributed sub-modules and this energy can be controlled. This is a new degree of freedom that can be utilized to supply ancillary services. However, one of the major drawbacks is the limited amount of energy available, which is considerably smaller than a typical AC power plant. Nevertheless, the energy stored inside the MMC can be increased with the help of energy storage systems (ESSs). This paper examines the benefits on the transmission system of including additional energy storage in an HVDC link for ancillary services (fast frequency response (FFR) and power oscillation damping (POD)), and how this can be implemented using an MMC with large buffer storage. Firstly, the study investigates the energy requirements to provide these network services, using adequate control laws, through EMTP-RV simulations. Then, the energy storage function of the converter is designed and simulations are carried out to highlight that an MMC with an embedded energy storage can provide these services. The obtained results confirm that the combination of an MMC with an energy storage system and dedicated control laws can greatly increase the stability of hybrid AC/DC power systems. However, it highlights that an FFR function inside an MMC requires a higher quantity of stored energy to provide system benefits, in comparison to a POD action. This would impact more deeply the construction and the operating limits of the converter.

Keywords: High-voltage direct current (HVDC) transmission, hybrid AC/DC transmission grids, modular multilevel converters (MMCs), power converters, AC stability, ancillary services, fast frequency response, power oscillation damping, modular systems, energy storage, supercapacitors.



1 INTRODUCTION

In recent years, with the increasing deployment of offshore renewable energy sources and cross-border interconnections, as for trading mechanisms of the electricity, existing power systems are facing exponential growth and changes [1]. Most of them disrupt with the traditional way to operate the electrical transmission grid. This brings new challenges to transmission system operators (TSOs) to ensure the security of supply of the electrical energy. Thus, centralized traditional power plants, with synchronous generators directly connected to the grid, are foreseen to be replaced in favour of remote generation units, with a power electronics interface. Since these new generators are electrically decoupled from the grid, and so from conventional synchronous generators, they behave differently [2]. The existing dynamics of the grid are inevitably impacted. The traditional link between the speed (i.e. the kinetic energy stored) of conventional generators and the system frequency is reduced. This leads to an inherent decrease of system inertia. Consequently, less energy is available to limit the rate of change of frequency (ROCOF) and frequency nadir in case of severe changes in production or consumption.

In order to face these changes, the only alternative is a fundamental enhancement of the existing transmission systems. One of the most suitable solution to this problem is the use of high voltage direct current (HVDC) systems [1]. Although HVDC interconnectors have already been implemented in the world during the last century [3] and permit to transmit bulk power at high voltage, over long distances, with low losses, this technology has made remarkable advances during the last decades. This is due to the emergence of the Modular Multilevel Converter (MMC) [4]. This converter has drawn a considerable attention since it particularly offers a new degree of freedom with fast power control and independent active and reactive power injections.

From this perspective, the attractiveness of Voltage Source Converter (VSC)-HVDC links has risen. Particularly, if all their potential is fully exploited. HVDC links must not only be used for transmission purposes, but also to improve the AC stability of the networks, to which they are connected. It has been recognized that advanced functionalities of HVDC systems are essential for the efficient and secure operation of the grid [1], [5]. They usually take advantage of the possibility to modulate quickly and independently the DC and the AC active powers of an MMC to strengthen system stability margins [6]. Two of these functionalities are pivotal in a near future: power oscillation damping (POD) and fast frequency response (FFR). Those control actions contribute to damp power system oscillations and/or to support frequency stability. However, those methods are mainly characterized by the fact the energy has to come from somewhere else in the network, such as interconnected power systems, or by extracting a percentage of the intrinsic electrostatic energy stored in the capacitors of the converter. Nevertheless, this latter is insufficient to support the AC system [7].

As a solution to this problem, this paper investigates a concept that has rapidly gained popularity. It consists in integrating Energy Storage Systems (ESSs) inside an MMC to potentially support the grid [8]. The aim is to broaden the set of functions of the converter, by providing short-term ancillary services as, here, POD or FFR, without affecting significantly the design of the MMC [9].

For this purpose, this paper attempts to illustrate the benefits of such a solution on rotor angle and frequency stability. Furthermore, it tries to determine the impact of this new set of services on the design and the control of the MMC with its ESSs. Indeed, the energy and power requirements can highly vary to mitigate these disturbances on the AC system.

Based on it, this paper is organized as follows. Sections 2 and 3 recall the fundamental of an embedded VSC-HVDC link for the provision of ancillary services and the concept of an MMC with integrated ESSs. In Section 4, case studies are presented to highlight the positive impact of the association of an MMC with embedded ESSs and supplementary controllers for AC stability enhancement. In order to estimate power and energy requirements of the ESSs for supplying these network supports, EMTP-RV simulations are carried out before designing the energy storage function. Finally, the following section sheds light the feasibility of the solution through simulations of a point-to-point HVDC link while the last section draws conclusions.

2 ANCILLARY SERVICES SUPPORT BY VSC-HVDC LINKS

2.1. Potential applications

As reported in [5], advanced functionalities for ancillary services provision by HVDC links are essential for the secure and efficient operation of the grid. Indeed, the fast and independent control of active and reactive power injections of the HVDC stations can be used for the benefit of the AC system to which the stations are connected. Depending on the topological situation of the HVDC link (i.e. connecting two asynchronous grids or embedded into a single synchronous grid) the HVDC link is able to provide real-time operation services such as static and dynamic reactive power control, frequency control, power oscillation damping among others (an extensive list of functionalities can be found in [5]). In this article, the interest is focused on the dynamic active-power based services that can be provided through HVDC links interconnecting asynchronous grids, particularly the power oscillation damping and the frequency containment reserves delivery.

2.1.1. Frequency containment reserve delivery

When an HVDC link interconnects two asynchronous grids, balancing power can be distributed in order to support their frequency stability. The fast active power control of the HVDC system allows to share reserves in a faster way than the primary control of synchronous generators. This rapid service has received different names from operators [10]. In this article, the term Fast Frequency Response (FFR) is adopted. Different control schemes to implement FFR have shown to effectively reduce the frequency deviation and ROCOF during contingency events, especially in systems with relatively small capacity and higher penetration of non-synchronous energy sources [10]. Classical schemes for FFR implementation include: action proportional to the frequency deviation (droop control), action proportional to the derivative of the frequency (inertial response), or the triggered injection of a specified power profile [11].

2.1.2. Power oscillation damping (POD)

Inter-area oscillations (0.1 to 1.0 Hz) are inherent to interconnected power systems. These oscillations are considered as a key limiting factor when large amounts of power are transmitted through long AC lines. Indeed, unstable oscillations may lead to system collapse. Classically, electromechanical oscillations have been handled through the use of Power System Stabilizers (PSS) on the excitation system of synchronous generators. However, HVDC links and other power electronics devices, can also improve the damping of the interarea modes through the implementation of POD controllers. Different structures of POD controllers are reported in the literature. They differ mainly on the measured feedback (powers, voltages, frequency, etc.), the use or not of Wide Area Measurement systems, the modulation signals (active or reactive power references) and the control design techniques [12].

2.2. Studied active power modulation strategies for provision of ancillary services

To deliver frequency containment reserves and to damp power oscillations through active power modulation of the HVDC link, the considered strategies in this paper are presented in Figure 1. In order to provide support to the system frequency stability, the power characteristic ΔP_{FFR} , depicted in Figure 1(a), is injected to the grid through the HVDC link after the detection of the event (e.g. generator tripping) as proposed for example in [13], [14]. This power profile corresponds to the energy and power capacity of the HVDC link to provide FFR during a given time characterized by a response delay T_1 , a ramp up until full deployment at T_2 , a sustained response up to T_3 , and a ramp down to T_4 to gradually transfer the frequency containment to the generators governors.

Regarding the POD control, a structure that modifies the HVDC power reference by adding a term ΔP_{POD} , which is proportional to the difference of frequencies measured at two different buses in the same synchronous grid is used, as in [15], [16]. The selected buses must be electrically distant enough to have a high observability of the oscillation (e.g. one bus from each coherent area). So, the use of

remote (wide-area) signals is necessary to implement such POD control. In Figure 1(b), f_{Area1} represents the instantaneous frequency measured on a bus of Area 1, which oscillates against Area 2, where the frequency f_{Area2} is measured. Note that in steady-state the power modulation (ΔP_{POD}) is zero as the frequency measurements are taken in the same synchronous grid.

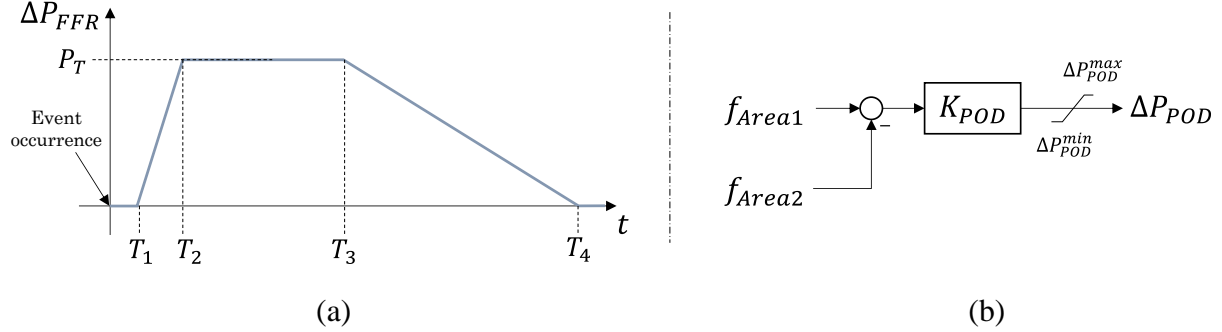


Figure 1 Studied supplementary active power-based modulation strategies to provide ancillary services to the grid using an HVDC link. (a) Characteristics of the fast frequency response (FFR) (b) Power oscillation damping (POD) control

It is evident that in order to provide the studied ancillary services, additional energy sources are necessary. In the case of two asynchronous grids (for example two transmission networks or an offshore windfarm and a transmission network) interconnected by HVDC systems, the power to provide these services to one grid, is necessarily extracted from the second grid. In the case of two interconnected transmission networks, the injection of the FFR to one grid will lead to a frequency deviation in the second one. Similarly, the power modulation necessary for oscillation damping in one grid will be extracted from the second grid leading to a potential excitation of its inter-area modes [17]. It is also known that by using the energy of the DC capacitors inside the MMC, the interactions between the asynchronous networks can be reduced only to a small extent. This is due to the fact that the energy stored in the capacitors is small compared to the energy needed to provide these auxiliary services, as explained in section 1.

As a result, the available energy to support the grids, in case of disturbance, must be increased. However, these ancillary services would require only a fraction of the total power of the converter and a relatively low amount of energy in regard with the traditional bulk storage services. Therefore, the proposed solution consists in embedding an energy storage system (ESS) inside the MMC. Thus, a converter with a dual purpose is feasible, that potentially provides an opportunity to reduce the additional footprint and cost for ESSs integration. Note that the sizing of such energy buffer can be based on the necessary energy to provide POD and FFR. As it has been observed, the proposed schemes in Figure 1 require only a finite amount of energy, since both actions have to tend to zero.

3 MMC WITH LARGE BUFFER STORAGE DESIGN AND OPERATION

3.1. Converter topology

The general configuration of an MMC with embedded ESSs is shown in Figure 2. It is based on a classical 3-phase MMC traditionally built-up with identical modular building blocks, the so-called submodules (SMs). Each phase i (with $i \in \{a, b, c\}$) contains an upper and lower arm (superscript u, l) which is composed of N series connected SMs and an inductor. A SM is usually a two level VSC with two IGBTs and two diodes in a half-bridge configuration and a capacitive storage. The inclusion of ESSs consists in connecting an energy storage element, here supercapacitors, to the capacitor of the submodules through a DC-DC converter to make an Energy Storage Submodule (ES-SM) as shown in Figure 2(c). In this paper, a modular interface converter with its own control method, illustrated in Figure 2(d) and (e), is considered [18]. It was demonstrated that this topology is well-suited for ancillary

services with low power and energy requirements, such as FFR. The proposed interface comprises a serial connection of N_{mod} subconverters. Each of them consists in a bidirectional converter, with high switching devices (i.e. typically above 10 kHz), between a supercapacitor stack and the ES-SM capacitor. This structure allows to share the high voltage at the ES-SM capacitor. This provides the opportunity to use fast switching devices as MOSFETs, with low voltage and current capabilities, which are more adapted for low power application. As a result, the size of the passive components can be drastically reduced and a better power density per ES-SM is achieved.

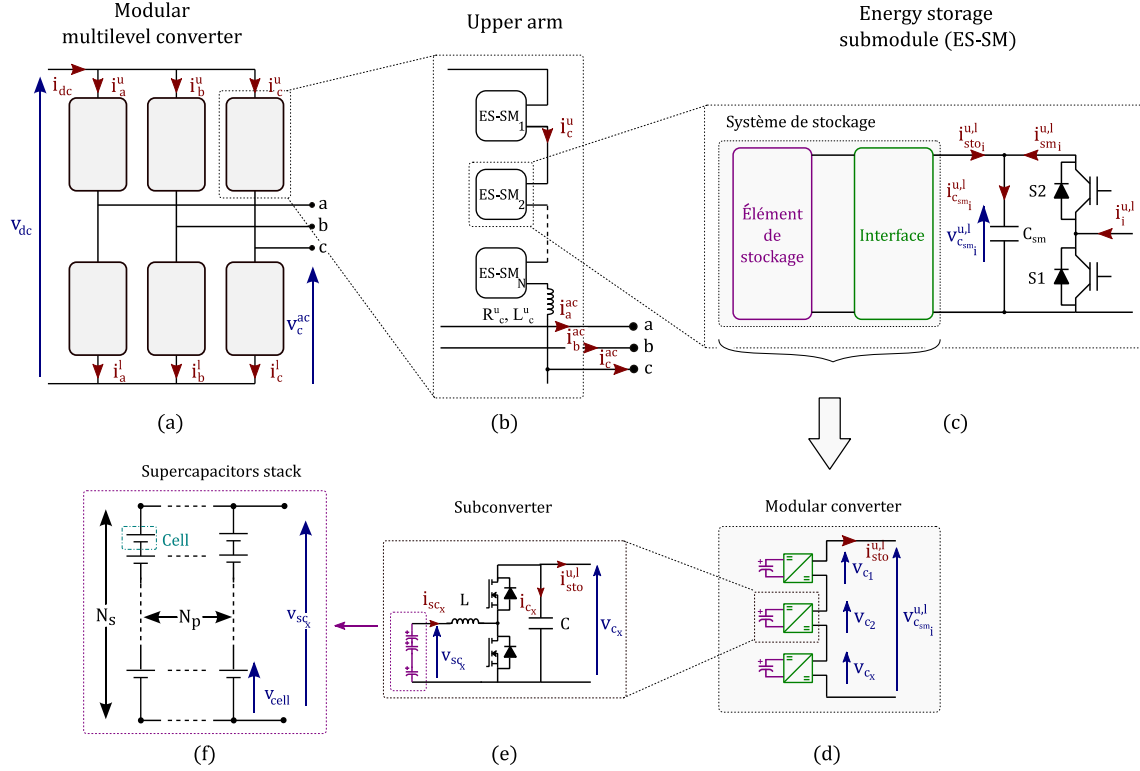


Figure 2 Topology of the proposed modular multilevel converter with integrated energy storage systems

During normal operation of an MMC, depending on the switching states, the SM capacitor is inserted or not in the arm voltage to transfer energy from/to the AC grid to/from DC grid. Since an MMC has a limited stored energy, it is usually controlled only to use its power conversion capability. Thus, the AC and DC powers are controlled to be equal (except internal power losses) in normal operation. By adding energy storage elements into SMs, a new energy source can exchange energy with the SM capacitor that results in a new degree of freedom in active power exchange between the MMC and the grids as illustrated in Figure 3. Since the converter can absorb/provide energy through its energy storage elements, the AC and DC power set points can be decoupled. This attractiveness is further increased because the converter is capable to extend its set of functionalities by providing ancillary services.

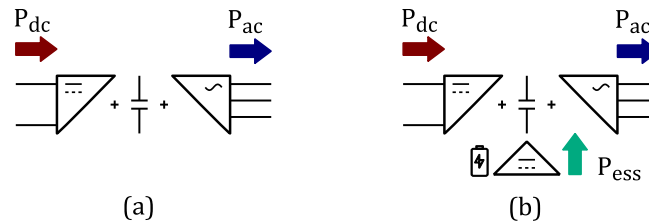


Figure 3 Simplified equivalent circuit of: (a) a classical MMC (b) an MMC with a large buffer storage

3.2. Control principle

The most common control method of an MMC is an energy based control with a $\Sigma\Delta$ approach, which is illustrated in dark in Figure 4 with a simplified schematic diagram [19]. The goal is to control the internal energy level W_{MMC} of an MMC. This is a new degree of freedom to govern the exchanged powers between AC and DC grids in comparison with classical VSC converters. Similarly, it ensures that the energy is distributed among the six arms of the MMC to provide stable operation. The control is divided into two parts with different time frames. A high level control has to determine the arm voltage references $v_i^{u,l*}$ depending on the desired powers. Those references are then converted to pulse signals for SM switches by a fast low-level control, which also guarantees the energy balance among the SM capacitors.

According to this approach, a control method, depicted in Figure 4, was proposed in [18] to consider the inclusion of ESSs into the overall control scheme of an MMC. As observed, it does not require notable changes to the traditional control of the MMC. The energy based control of the MMC remains unchanged since the management of the ESSs is decoupled of the MMC control. The ESS of each ES-SM is seen as a supplementary power source (i.e. external disturbance) from the ES-SM capacitor. This additional power tends to change the energy stored in submodule capacitors. To keep this energy constant, the natural behavior of the energy controller of the MMC is to adapt the power in the AC system. Thus, it tries to keep a stable ES-SM capacitor voltage to ensure correct operation of the converter. The extra power P_{ESS}^* , requested from the energy storage function, is distributed among the ESSs of each ES-SM. Then, it is translated into a current reference to a local controller to provide this additional power. More details are provided in [18] about this strategy.

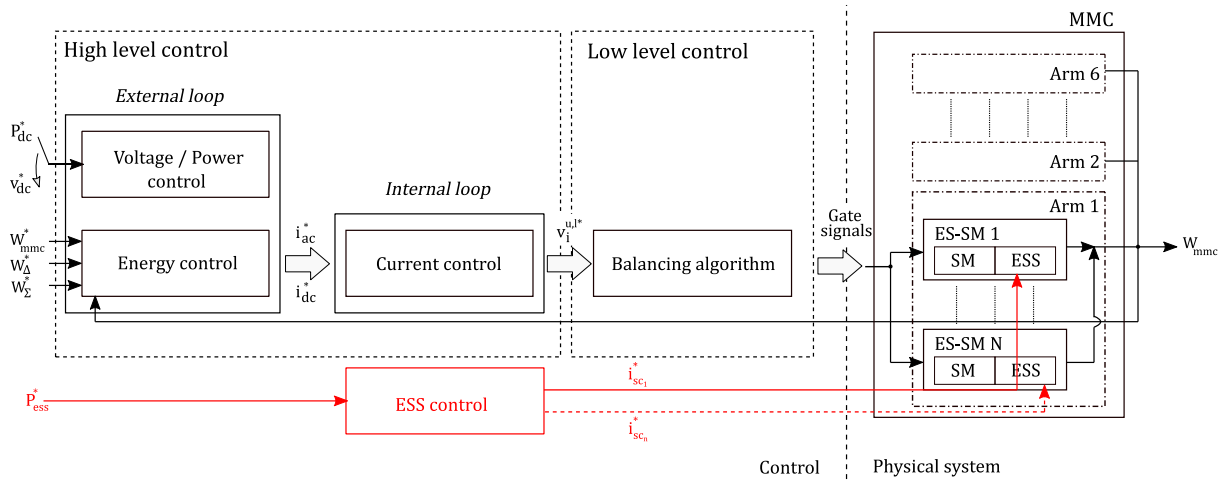


Figure 4 Schematic diagram of the proposed control of an MMC with embedded ESSs

4 ASSESSMENT OF THE INFLUENCE OF AN MMC-HVDC LINK WITH LARGE BUFFER STORAGE

4.1. Case study

In this section, a set of simulations are presented to highlight the positive impact of the association of an MMC with embedded ESSs and supplementary controllers for AC stability enhancement, presented in section 2. The electromagnetic transient software EMTP-RV is used to perform simulations. The goal is to estimate the power and energy requirements for these network supports and thus quantify the characteristics of the ESSs. Later in this section, a focus is made on the design on the ESS.

The power system presented in Figure 5 is implemented in EMTP-RV. It consists in two modified versions of the two-area four machines Klein-Rogers-Kundur's power system model [20] connected by a VSC-HVDC link. In this power network, all the generators are 900MVA synchronous machines with inertia constants of 6.5s. As for their controls, the generators are equipped with the automatic voltage

regulator (AVR) and PSS described in [20]. However, the PSS gain has been reduced to a half in order to observe weakly damped inter-area oscillations. Moreover, an IEEEG1 turbine-governor with a droop coefficient of 20% has been included for the primary frequency control. The HVDC stations are two 1 GW converters. Data are taken from [21]. With respect to the original case, the loads have been modified to allow a power exchange between asynchronous grids of 500MW (from MMC1 to MMC2). In addition, a third terminal, connected to an infinite source, is added to form a Multi-Terminal DC grid (MTDC) embedded in an AC network (Case A). The goal of this extra source of energy is to act as a firewall and to avoid disturbances to be transmitted from one power system to another. In this way, the third terminal evaluates the need of an additional source of energy to achieve ancillary services. Consequently, it is also used to compute the related power profiles for the ESSs in the case the energy source is directly embedded in one of the two converter stations (cf. Figure 5 Case B).

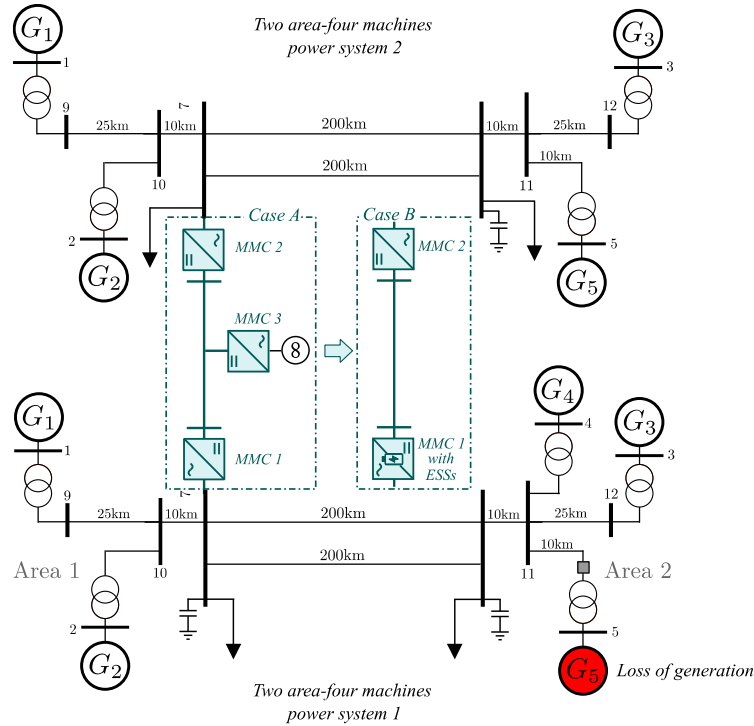


Figure 5 Case study – [Case A] Multi-terminal DC grid embedded in an AC network. The third terminal acts as an external power source [Case B] HVDC line embedded in an AC network. One of the two converter stations has an energy storage function

In this study, MMC1 and MMC2 are controlled in power with the sole difference the power set-points are of opposite sign, while MMC3 controls the DC link voltage of the MTDC grid. The contingency evaluated in this case study corresponds to a generator loss, G5 in red here, in power system 1. Four control strategies are implemented and compared for enhancing AC stability.

- **Case 1:** No actions are undertaken. Converter 1 provides no active power services.
- **Case 2:** The POD control, proposed in subsection 2.2, is implemented on MMC1 to damp the inter-area oscillation between Area 1 and Area 2 of power system 1. Note that the frequency at the Area 1, f_{area1} , corresponds to the frequency at bus 9. Similarly, the frequency at the Area 2, f_{area2} , stands for the frequency at the bus 12. The POD gain, K_{POD} , is arbitrarily set at 500 MW/Hz but taking into account the physical limit of the converter. Note that it has been shown that any positive value of K_{POD} is beneficial for the system contrary to PSS [15], [16].
- **Case 3:** The FFR characteristics, proposed in subsection 2.2, is implemented on MMC1 in order to mitigate the frequency drop in power system 1. Based on Figure 1, the characteristics of the proposed response are as follows: $T_1=0.2s$, $T_2=0.5s$, $T_3=6s$, $T_4=30s$ and $P_T=50$ MW [22].
- **Case 4:** Finally, both POD and FFR actions are implemented.

The simulation results are depicted in Figure 6 and Figure 7. In this paragraph, the role of the extra-power source is highlighted and only a POD function is discussed. In Figure 6 (left), the extra-power source is removed. The HVDC link is controlled in a way to damp power in the power system 1, where the loss of generation occurs. As observed, oscillations are well damped, in comparison with Figure 7 Case 1 where no ancillary services is provided. However, the frequency in power system 2 is disturbed. In contrast, in Figure 6 (right), the extra source of energy is introduced on the DC link. The HVDC link can now act as a firewall between both systems. Thus, the fault is imperceptible from the power system 2. This first case points out the need of an extra source of energy to increase the benefits of an embedded HVDC link for AC stability purposes.

Note that in Figure 7 Case 1, the HVDC system acts as a firewall and no active power services are provided. This means the converter only track a constant power set-point. It is noticed that the oscillations in power system 1 are poorly damped and the frequency nadir (i.e. the minimum frequency value) is significant, although the power system 2 is not disturbed. The potential risk of a low nadir is to activate protection schemes of the generators or AC lines, leading to their disconnection and an eventual cascaded failure.

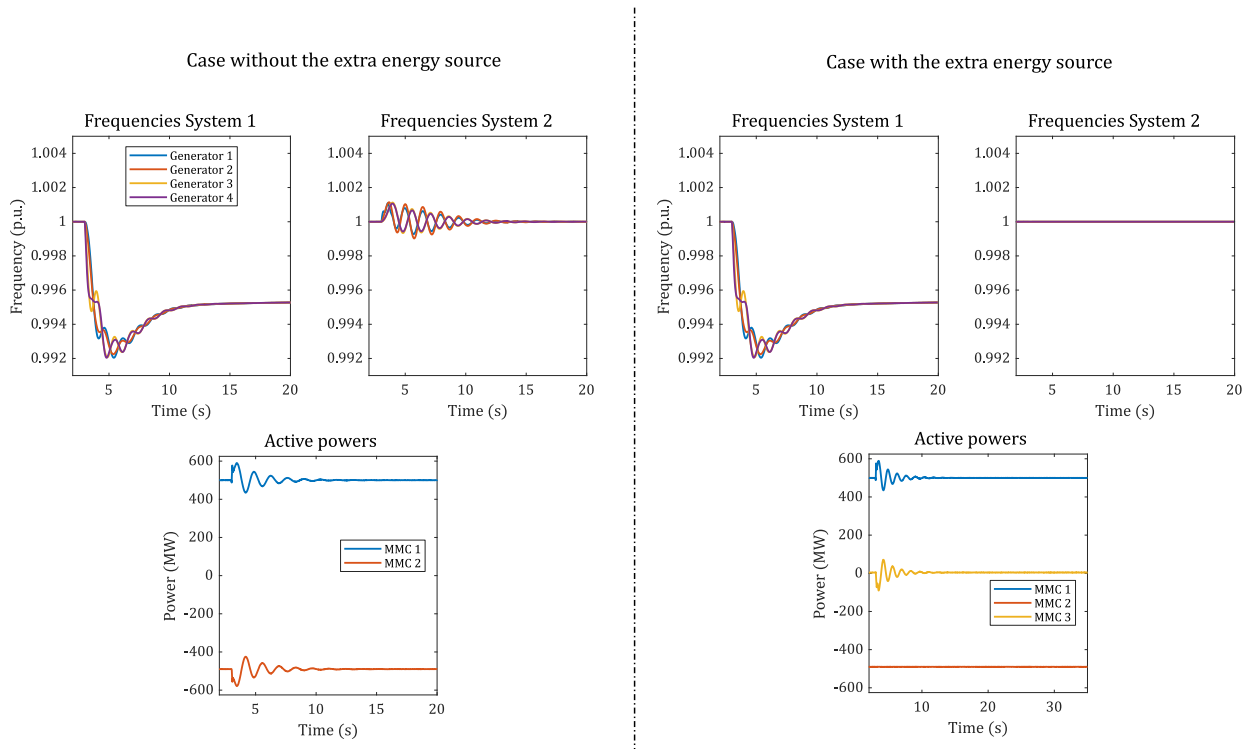


Figure 6 Simulation results of the modified Klein-Rogers-Kundur's power system. The HVDC link provides POD without (left) and with (right) an extra energy source added on the DC side.

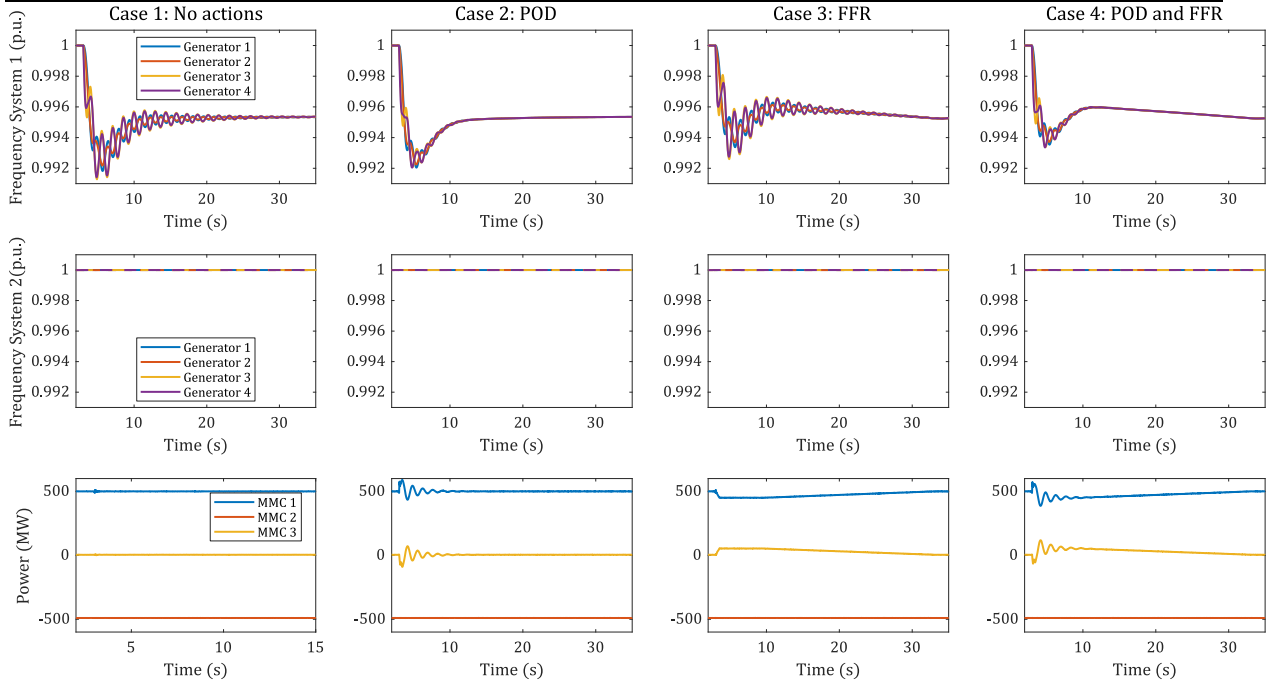


Figure 7 Simulation results of the modified Klein-Rogers-Kundur's power system. Different control strategies to enhance AC stability are applied. (Note that a positive power implies power injected into the DC grid)

As shown again, when a POD action is implemented (see Figure 7 Case 2), it is demonstrated that oscillations are well damped in power system 1 and power system 2 is not excited. Nonetheless, the frequency response is poorly improved which undoubtedly points out the need of injecting fast frequency reserves. As exposed in Figure 7 Case 3, the minimum value of frequency for each generator is improved (from 0.0991 to 0.0093 p.u) if FFR is delivered in the first hundred milliseconds, here 50 MW in 500 ms, after the fault. Finally, the response of the system is greatly enhanced if both actions (POD and FFR) are combined as shown in Figure 7 Case 4. To ascertain these remarks, Figure 8 shows the frequency of the center of inertia (COI), that describes the principal frequency dynamics of a power system, and the speed difference between generators 1 and 4 in power system 1 for each case described.

This indisputably proves that an HVDC link with embedded energy storage can enhance the AC system stability by providing power oscillation damping and/or fast power injections. In return, it must be well controlled to not adversely impact both power systems and extra energy has to be available to allow to increase transient stability margins [6]. Therefore, in the next section, the third terminal is substituted by an energy storage function included inside one of the two converter stations, as shown in Figure 5 (Case B). The aim is to demonstrate the feasibility to embed ESSs within the converter, but prior to that the design part must be addressed.

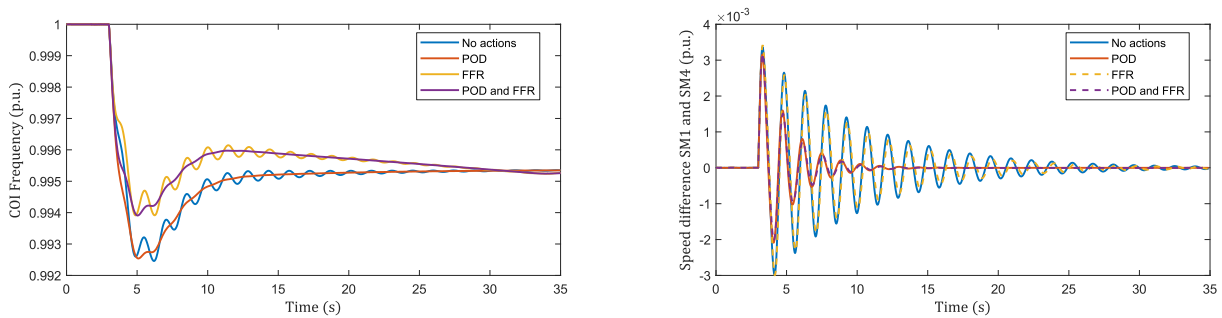


Figure 8 Frequency of the center of inertia in power system 1 (left) Speed difference between generators 1 and 4 in power system 1 (right)

4.2. Energy storage requirements

After quantifying the amount of energy and the power requested from the energy storage function of an MMC to achieve ancillary services, thanks to the simulations of section 4.1, this part aims to highlight the design of the solution. It can be easily noticed that a high amount of energy to store or an important percentage of the nominal power of the converter to supply would make this solution impractical. Indeed, it would significantly impact the design of an MMC. In that case, a separated energy storage system connected to the AC grid would be a more relevant solution.

Figure 9 shows the power profiles and the energy variation of the ESSs, for the three cases with a control action, studied in the paragraph 4.1. At the same time, Table 2 provides the order of magnitude of those metrics. As observed, the energy requirements for POD are negligible in regard to FFR. However, they remain greater than the total energy stored in a 1 GW MMC (30-40 kJ/MVA [21]), which only a small percentage can be really used for ancillary services [7]. It proves the need to use anyway energy storage elements. Finally, a POD function leads to important power transient during the first seconds. This peak current implies stronger constraints on the semiconductors of the converter. The risk is they cannot switch reliably, within their safety operating area (SOA), by operating possibly beyond their current limit threshold that may lead to a failure by overheating, and in the worst case to a thermal runaway. Therefore, the converter may require to be designed taking into account this overload capability. This is particularly the case if POD and FFR are combined.

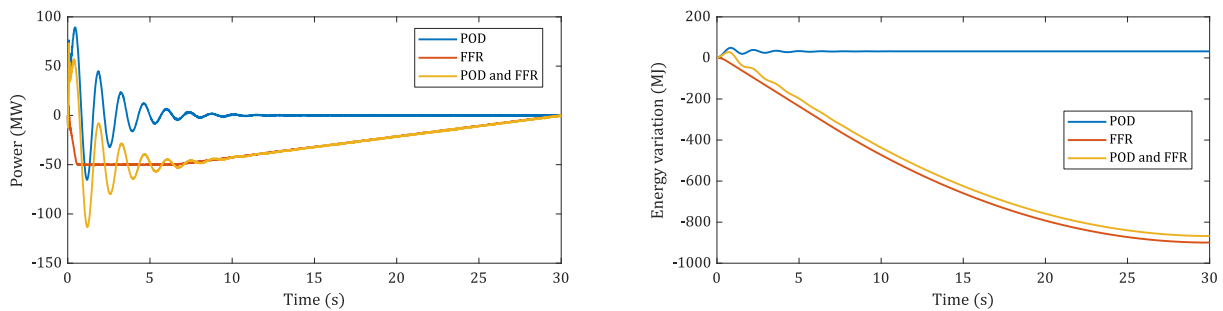


Figure 9 Energy storage function requirements with: (a) The power to supply (b) The energy variation

Measured values	POD	FFR	POD and FFR
Energy variation, ΔW [MJ]	49	900	895
Maximum power, $ P_{\max} $ [MW]	89	50	113
Maximum ramp rate $\frac{dP}{dt}$ [MW/s]	1960	820	1890

Table 1 Characteristics of the energy storage function of an MMC for the three proposed ancillary services

In the following study, it is assumed all the SMs of an MMC comprise an ESS, even if the modular structure of the converter allows to embed energy storage in a limited number of arms or in a limited number of SM in each arms [9], [23]. As shown in Figure 2(c), the presence of an interface converter between the ES-SM capacitor and the energy storage element is compulsory [8], [9], [18], [24]. This is mainly explained by the need to decouple the energy management of the energy storage element from the ES-SM capacitor, whose voltage variation is restricted to a small fraction of its total voltage. Furthermore, the insertion of a DC-DC converter also allows to optimize the connection of low voltage energy storage elements (here supercapacitors) to a high voltage SM capacitor. Similarly, it offers the possibility to filter the power fluctuations from the grid that should be buffered by the energy storage elements, and may significantly impact their performance.

Following the design methodology described in [18], this section details the characteristics of the proposed interface converter (see Figure 2 and paragraph 3.1), and its supercapacitor stack, required to achieve the specifications of the three ancillary services given in Table 1. The aim of this design methodology is to optimize the total volume of the ESS (i.e. similarly its cost). Indeed, the objective of the proposed solution, here, is to add an energy storage function within an MMC through all its ES-SMs without significantly impacting their design and dimensions. Results are shown in Table 2.

Parameters	POD	FFR	POD and FFR
Number of subconverters, N_{mod}	4	4	4
Supercapacitor cell capacitance (F) *	325	450	350
Number of cells in series in a stack, N_s	55	89	114
Number of branches in parallel in a stack, N_p	1	1	1
Maximum supercapacitor stack voltage (V)	148.5	240.3	307.8
Energy needed per stack (kJ)	5.1	93.8	90.5
Depth of discharge (%) of one stack	9	45	44
Inductor value (mH)	0.45	0.51	0.66
Volume (L)	15.7	25.3	28

Table 2 Main characteristics of the ESS of an ES-SM for the proposed ancillary services (*Maxwell Technologies were considered)

As observed for a POD, the depth of discharge (DoD) is less than 10%. Here, the DoD is considered as the ratio between the maximum voltage and the minimum allowable voltage of the supercapacitor stack to provide the requested energy for the expected service. For capacitive element, as supercapacitors, it is the reflection of the energy variation. In that case, this means most of the energy is not used and that the supercapacitor stack of each subconverter is oversized. This can be explained by the opposite characteristics of the application and the energy storage element.

First, the energy requirement for a POD function is relatively small, especially because all the SMs of MMC1 have an ESS. Consequently, low energy should be stored per ES-SM. Secondly, a supercapacitor stack is nothing more than a layout of low voltage cells in series and parallel as shown in Figure 2(f). Although an interface converter is present between the ES-SM capacitor and the supercapacitor stacks, the transformation ratio of the subconverters cannot be infinite due to current limitations for example. Note that a converter with a transformer, as a dual active bridge (DAB) could allow a high transformation ratio, but the structure of an ES-SM would be much more complex. Thus, the number of cells in series per supercapacitor stack cannot decrease as much as one wants. Finally, even if there is an interface converter, the voltage that the supercapacitor stack has to sustain remains relatively important. Since, a supercapacitor stack has a quadratic relation between the voltage at its terminals and its stored energy, a high number of cells in series leads to an excess of energy. This explains why the solution is oversized due to an important increase of the number of cells within a stack.

For FFR, more energy has to be stored. Thus, the voltage constraint is less predominant and the design of the solution more adapted. Note that the DoD is almost 50 % of the maximum stack voltage. This ratio is usually considered as good compromise, since 75 % of the total energy stored within a stack is employed at this operating point.

Adding a POD service in addition to a FFR function only needs a slight increase in terms of sizing as shown in Table 2. Therefore, if an FFR function is provided, it seems relevant to provide both ancillary services, POD and FFR. However, if a POD action is only required, solution to be investigated consists in equipping a small fraction of SMs in each arm with an ESS as proposed in [9] or only some arms equipped with ES-SM [23]. The energy that should be stored per ES-SM is thus increased and the voltage constraint is reduced. It thus offers the opportunity to optimize properly the operation range of the ESS and the design of the solution.

5 SIMULATION OF AN EMBEDDED HVDC LINK COMPRISING AN MMC WITH LARGE BUFFER STORAGE

5.1. MMC Modelling

The following section sheds to light the feasibility of the proposed solution through simulations. The point-to-point HVDC link, depicted in Figure 5, has been implemented under MATLAB/Simulink. The goal is to verify that the ESSs of the converter can track the reference defined by the simulation in the subsection 4.1. Furthermore, these simulations are also used to validate the design made in the subsection 4.2.

Both converters MMC1 and MMC2 were modelled with a so-called reduced average arm model [25]. This model is based on the assumption that the capacitances of all the ES-SMs are identical and kept at a same voltage. Consequently, it is possible to represent the behavior of the hundreds SMs of an arm by considering an ideal equivalent converter and an equivalent capacitor as shown in Figure 10. The voltage at its terminals $v_{c\Sigma}^{u,l}$ is the sum of all the N SM capacitor voltages. Finally, the arm voltage $v_i^{u,l}$ is proportional to the available voltage at this equivalent capacitor and to a modulation index $m_i^{u,l}$. It thus represents the fraction of SMs inserted in an arm at any time. As a reminder, one of the two stations has an energy storage function (see Figure 5). Following the same principle as in the previous paragraph, each equivalent capacitor of the six arms of the MMC with ESSs is also coupled to an equivalent interface converter with a supercapacitor stack. Similarly, the voltage at the terminals of this latter $v_{sc\Sigma}$ is the sum of all the supercapacitor stacks of the N_{mod} subconverters of the N ES-SM of an arm. Note that the control methodology described in subsection 3.2 and [18] was applied. Here, one MMC controls the power flow of on the HVDC link while the second converter manages the DC voltage.

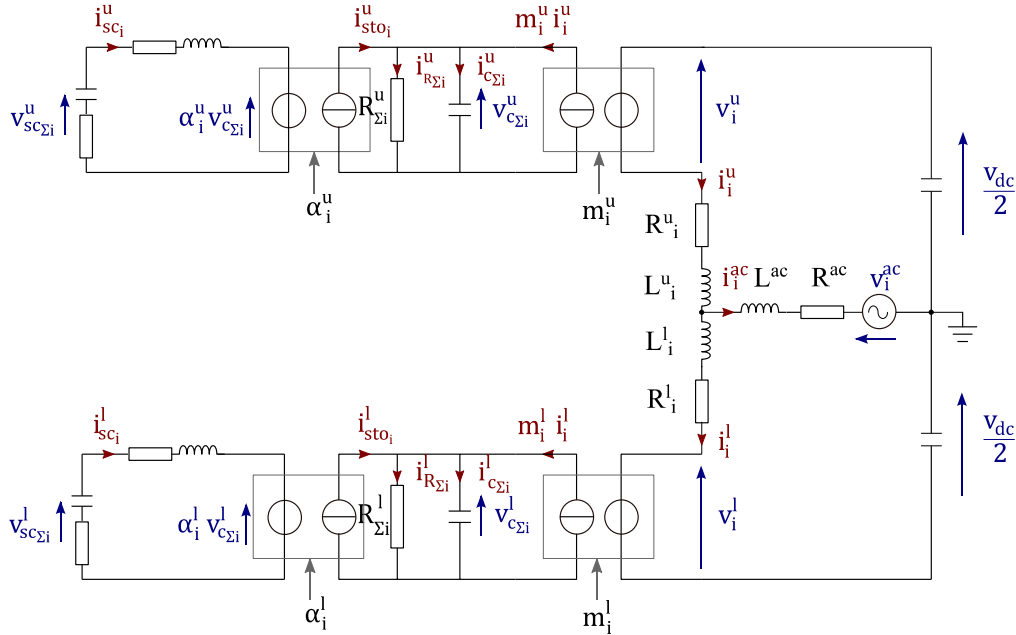


Figure 10 Arm average model of one phase of a three phase MMC with embedded ESSs

5.2. Results

The obtained simulation results are shown in Figure 11 and Figure 12. Figure 11 shows the DC and AC active powers of both converter stations. The dynamic on the AC side of the MMC 1 is identical as the active power reference P_{ac1}^* that comes from subsection 4.2. This proves that an MMC with embedded ESSs is able to provide the considered ancillary services. In addition, the DC power on the HVDC link and the active power of the MMC 2 remains constant. Thus, MMC 1 also acts as a firewall. It avoids the propagation of the fault into system 2 (see Figure 5) and simultaneously participates to improve AC stability of the whole power system.

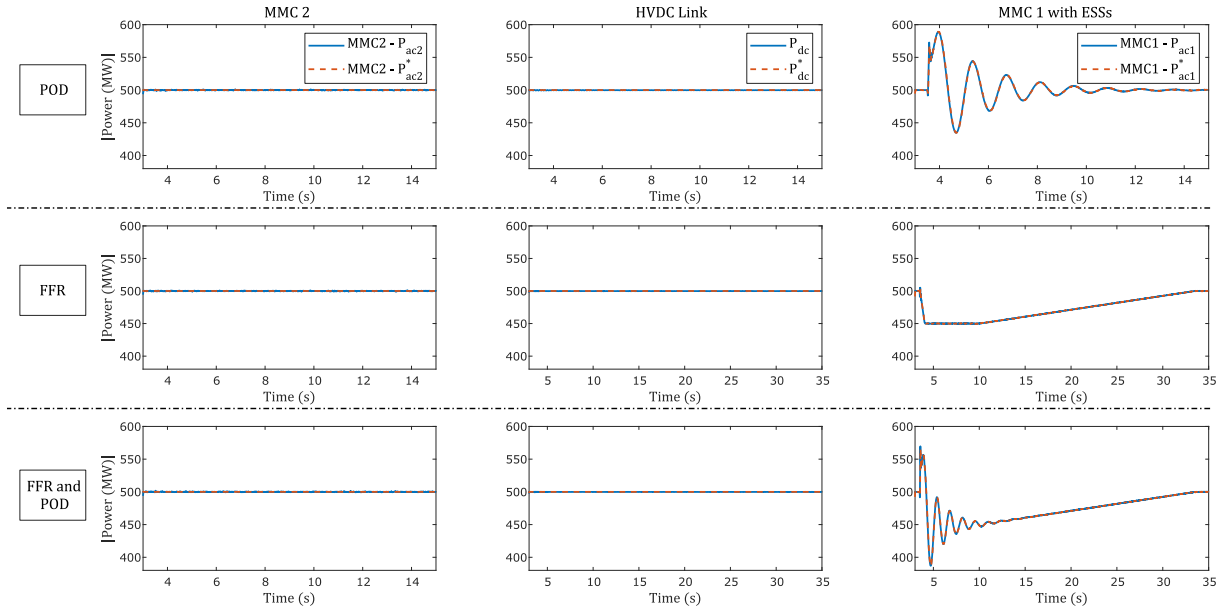


Figure 11 Simulation results of the point-to-point HVDC link with embedded ESS in one converter station to provide different ancillary services and acting as a firewall between power systems

In Figure 12, the behavior of the equivalent supercapacitor of one MMC arm is presented for each case study. Results are brought back to one supercapacitor assuming an identical behavior of all the ES-SMs. The internal supercapacitor stack voltage and the current that flows through it are displayed. By comparing the DoD in Figure 12 and values of Table 2, it can be noticed they are approximately the same. This implies that the design of the ESS is correct. Note that for this study, the ESS is considered as fully charged for providing the expected service. This means if a symmetric response is required, when a FFR service is supplied, the energy storage function of the MMC can provide the same power profile (see Figure 1) during half the time or half the power (P_T) during the same time with these sizing. Note that in the control strategy considered [18], a balancing method, to avoid dispersion among supercapacitor stacks, and a state of charge management, with a limited effect on the ES-SM capacitor, are proposed.

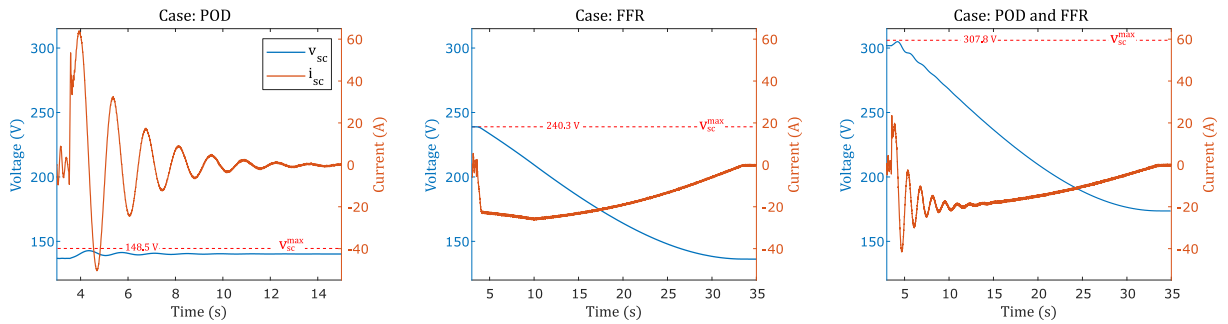


Figure 12 Simulation results of the point-to-point HVDC with embedded ESS in one converter station – Internal supercapacitor stack voltage and current for the three considered cases of ancillary services. Note that the red dashed line shown the maximum supercapacitor stack voltage for each design



6 CONCLUSION

In this paper, the concept of an MMC with embedded ESSs to provide ancillary services to the AC system has been investigated. It discusses both on the feasibility of such a solution and its impact for AC stability purposes. The paper focuses on a VSC-HVDC link that interconnects two AC asynchronous grids, whose one of the two converter station has an energy storage function.

First, a control method is presented to enhance system stability by benefiting of the fast power injections of classical MMC-VSC converters in an HVDC link. Then, its practicability is validated through EMTP-RV simulations. Thereby, the fast power control allows to use a traditional HVDC link to provide ancillary services, such as POD or FFR, but also to act as a firewall between two different networks in case of contingency. However, an additional source of energy is required in order to provide these services. From these simulations, requirements for each of them are determined.

Secondly, an appropriate ESS has been designed. Nonetheless, it can be remarked that the energy storage system is oversized for POD. This is due to the fact that low energy is required, but at the same time capacitive elements must be interfaced to a high voltage ES-SM capacitor. This participates to increase the number of series connected cells, and consequently the installed energy, even if there is an interface converter. Therefore, it is preferable to combine both FFR and POD approach to have a better solution or to decrease the number of SMs that includes an ESS in an MMC.

Finally, the feasibility of an MMC with embedded ESSs is also demonstrated through simulations. Furthermore, it was demonstrated the ESSs can easily follow the dynamics required by these services. The proposed concept can greatly broaden the set of solutions that TSOs can have at their disposal to ensure secure supply of the electrical energy.

ACKNOWLEDGMENT

This work was supported by a grant overseen by the French National Research Agency (ANR) as part of the “Investissements d’Avenir” Program ANE-ITE-002-01.

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