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Energy-based and non-energy-based control strategies for modular multilevel converters with embedded energy storage

Hind BEKKOURI*, Abdelkrim BENCHAIIB*, Florent MOREL*, Pierre RAULT†, Juan-Carlos GONZALEZ-TORRES*, Florian ERRIGO*

*SuperGrid Institute, 23 rue Cyprian, 69100 Villeurbanne, France

†RTE (Réseau de Transport d'Électricité), Research and Development Department of RTE, 92073, Paris La Défense, France.

Corresponding author email: Hind.BEKKOURI@supergrid-institute.com

Keywords

«Modular Multilevel Converters (MMC)», «Energy storage», «Control strategy», «Modelling», «Grid-connected converter»

Abstract

This paper deals with a high voltage direct current (HVDC) system based on modular multilevel converter (MMC) with embedded energy storage capacity. The dynamic behavior of energy-based (EBC) and non-energy-based (NEBC) controls is analyzed and compared for balanced and unbalanced energy storage distribution. EMTP simulations results show an equivalent performance for both controls when energy storage is balanced. While the NEBC control highlights limitations for unbalanced energy storage management, the EBC shows satisfactory overall performance.

Introduction

The integration of power electronics (PE) induces a paradigm shift in the operation and control of electrical networks. This integration is mainly due to the connection of renewable energy sources and the multiplication of interconnections through the power network. High voltage direct current (HVDC) systems are considered as the best solution for interconnecting grids and far renewable energy sources thanks to their low transmission loss and high power-transmission capacity. In addition, voltage source converters (VSCs) based on modular multilevel converter (MMC) technologies highlight useful control flexibilities to participate positively to the overall stability enhancement. As a matter fact, the

replacement of synchronous machines, which provide stability to the power grid through their kinetic energy and inherently maintain the balance between electricity production and consumption leads to serious stability issues, especially in the event of a fault or disturbance. To deal with these stability issues, one solution is to add energy storage systems (ESSs) to the grid. ESSs are usually connected to the AC system through a power electronic converter but connection to an HVDC link [1] and integration in an MMC [2] can also be considered. This work is focused on the integration of ESSs in the sub-modules of the MMC to provide ancillary services needed for the AC power system. The ESSs are based on batteries or supercapacitors interfaced thanks to dc/dc converters.

Considering ESSs lifetime and discrepancies in aging, their distribution among the MMC submodules will become unbalanced at some point. Balanced and a sort of extreme unbalanced energy storage distributions can be implemented [3]. Unbalanced energy storage leads to uneven constraints for the converter devices which has been investigated in [4].

Two control philosophies of the MMC exist in the literature, namely non-energy-based (NEBC) [5] and energy-based (EBC) [6] controls. Both controls require modifications for additional ESS management and results have been shown in the literature but, to the best knowledge of authors, performances, and limitations of these control approaches for MMCs with embedded unbalanced energy storage have not been compared. This is the main contribution of this paper.

This paper is organized as follows. First, the MMC converter topology is described. Secondly,

the associated NEBC and EBC philosophies are discussed. Thereafter, physical and control layers modifications for ESS integration in the MMC are highlighted. Then, simulation results of three use cases, for balanced and unbalanced energy storage integration, are presented and analyzed. Finally, some concluding remarks end the paper.

MMC converter topology and modeling

Each phase of the half-bridge MMC outlined in Figure 1 can be divided into upper and lower parts, which are called arms [7][8].

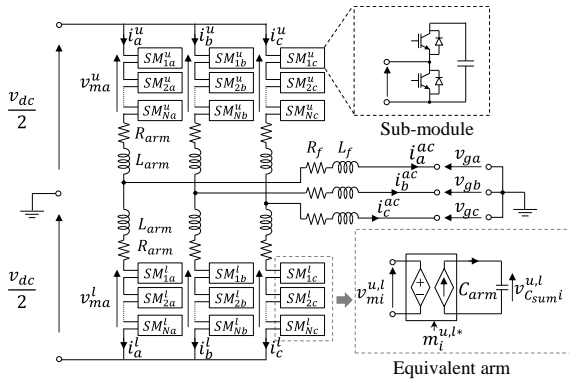


Figure 1: Three-phase MMC

In order to analyze the dynamic behavior of an MMC, it is necessary to solve a large number of simultaneous differential equations which can require enormous computational effort. Hence, some simplification techniques are needed. According to [9], for system-level simulations, each MMC arm can be represented with sufficient accuracy by an ideal DC/DC chopper associated with an equivalent capacitor. This model assumes that the voltages of all the sub-module capacitors $v_{C_i}^{u,l}$ are maintained within a close range by an appropriate voltage balancing control, i.e., $v_{C_1}^{u,l} = v_{C_2}^{u,l} = \dots = v_{C_N}^{u,l}$ in each arm, and that the capacitance of the sub-modules are sized identically. The assumptions above make it possible to grasp the general behavior of the hundreds of sub-modules by considering only the sum of all the capacitor voltages in each arm, i.e., $v_{C_{sum}i}^{u,l} = v_{C_1}^{u,l} + v_{C_2}^{u,l} + \dots + v_{C_N}^{u,l}$, which is applied on an equivalent capacitance given by $C_{arm} = C/N$, where C is the capacitance of a sub-module and N is the number of sub-modules in the arm. The arm average model (AAM) of the three-phase MMC is thus obtained as depicted in Figure 1 bottom right-hand side.

MMC control philosophies

Unlike classical VSC converters, the large number of SMs in HVDC-MMCs allows an almost continuous control of the valve voltage. MMC control differs then from classical VSCs and requires more controllers because the converter stores energy into the sub-module capacitors, which are not directly connected to the DC terminal [10]. Thus, the energy stored in the distributed submodules can be decoupled from the associated DC converter terminal voltage [11]. This brings a new degree of freedom but to take advantage of it, the regulation of this energy is an important requirement for the MMC control. In the following, NEBC and EBC of the MMC are described.

NEBC of MMC

For NEBC, since no MMC energy control is explicitly included, the regulation of the DC current essentially depends on the amount of transferred active power and DC voltage level of the MMC unit. This results in a coupling between the AC network response and the DC grid dynamics. The modulation index calculation is based on the measured DC voltage [6]. The associated control loops are shown in Figure 2.

EBC of MMC

For EBC, and unlike NEBC response, a variation of the DC voltage does not necessarily translate into energy variations for the sub-module capacitors.

This decoupling effect occurs since the energy in the arm is a function of the number of capacitors introduced (by the insertion index), and the DC voltage level. This double dependency has been mentioned in several studies as a beneficial feature capable of decoupling the AC network dynamics and the DC network dynamics [5]. The principles of EBC which were presented in [5] and [11], are shown with the control loops in Figure 3.

Energy storage system in the MMC

Compared to the MMC schematic presented above, some modifications at the physical layer as well as at the control layer have been done to integrate the energy storage systems in the MMC submodules.

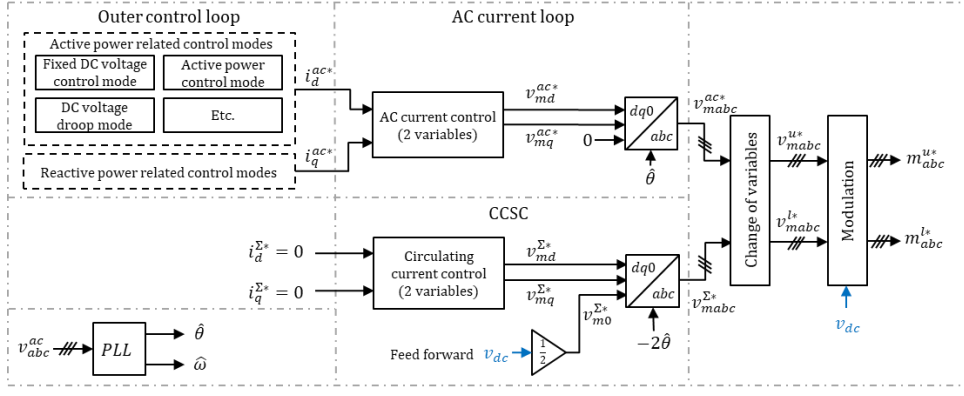


Figure 2: Considered non-energy-based control (NEBC) of MMC converter

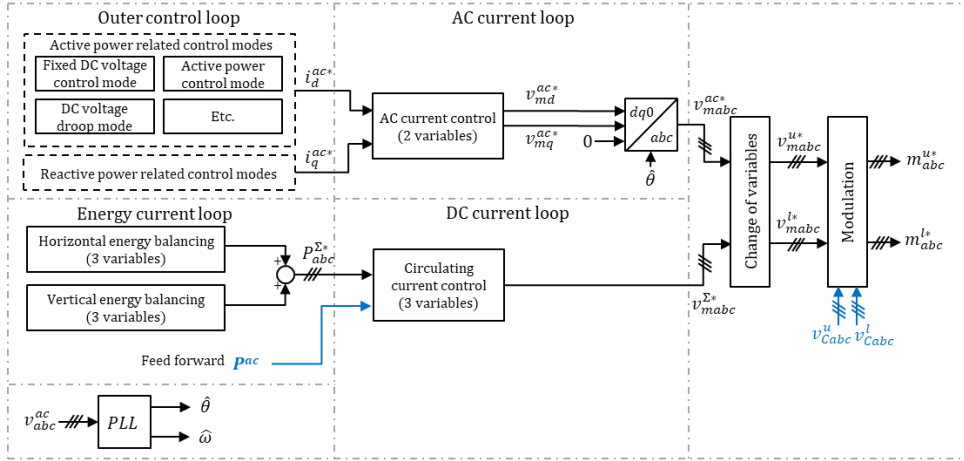


Figure 3: Considered energy-based control (EBC) of MMC converter

Modifications at the physical layer

For the considered MMC model, which is based on average arm models, a balanced distribution of the energy storage within one arm is considered, i.e., if the energy storage is integrated in one arm of the MMC, it is integrated in all the submodules of that arm. Figure 4 shows the topology of an MMC with embedded energy storage in all arms and the related arm model where equivalent energy storage system is added to the MMC equivalent arm model that has been presented in Figure 1.

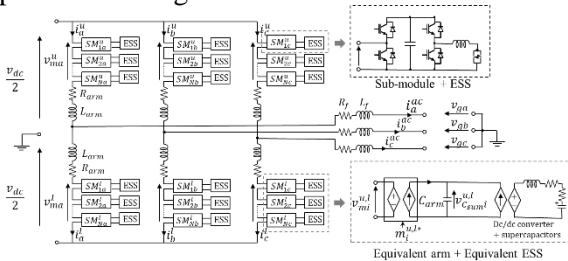


Figure 4: Three phase MMC with embedded energy storage in all arms

For the energy storage elements, several technologies could be considered, e.g., supercapacitor or battery. In this paper, the energy

storage elements are interfaced with the SM capacitor thanks to a dc/dc converter.

Since the focus of this study is on the MMC control, the ESS (energy storage elements and interface dc/dc converter) is reduced to a controllable current source as shown in Figure 5. The arm ESS power reference is filtered to account for the DC/DC converter dynamics.

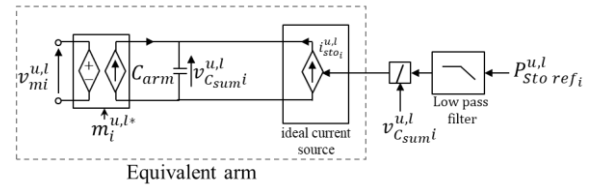


Figure 5: MMC equivalent arm connected to energy storage system represented as a controlled current source

Modifications in the control layer

For both controls, NEBC and EBC, the modifications concern mainly the outer control loop: a supplementary power reference $P_{Sto ref}^{u,l}$ is added to the AC power reference of the converter. The supplementary power reference can be injected either if the converter is on V_{dc} control or in P control mode, see Figure 6.

$P_{Sto\ ref}$ is also distributed among the MMC arms where the ESS is activated, Figure 5.

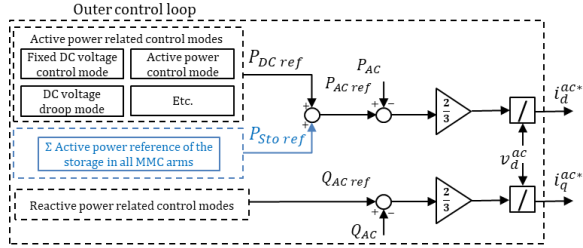


Figure 6: Outer control loop of NEBC and EBC of MMC with embedded energy storage

Case study

Benchmark description

Typically, symmetric monopole HVDC link is composed of two MMCs, one controlling the DC voltage while the second controls the active power. In this study, the energy storage is integrated in the MMC in P control. The energy storage power reference is equally shared among the arms with energy storage systems.

In simulations, the voltage controlled MMC, and the DC cable are replaced by a DC voltage source, as shown in Figure 7 to focus on the energy storage integration in the MMC. The AC grid is modeled by a Thevenin equivalent.

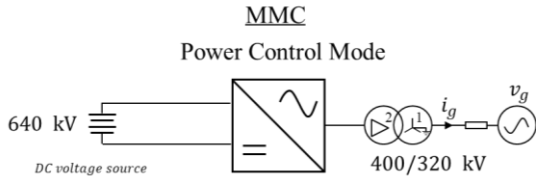


Figure 7: MMC converter connected to a DC source and an equivalent 3-ph AC source – Simulated model

The MMC with enhanced energy storage is simulated in EMTP. The simulation parameters used throughout this paper are detailed in Table I and Table II. In Table I, the electrostatic constant is defined as the total of energy stored in submodule capacitors divided by the rated power. The aim of these simulations is to address the performance of NEBC and EBC to handle balanced and unbalanced energy storage integration. In the following, three energy storage arrangements in the MMC are used, see Figure 8.

- Use case A: Energy storage elements are included in all the arms of the converter.
- Use case B: Energy storage elements are only included in phase B (in lower and upper arms of the leg B).
- Use case C: Energy storage elements are only included in the upper arm of phase A.

Table I: 1050 MVA MMC model parameters

Parameter	Value	Unit
Rated power S_n	1050	MVA
SM per arm N	400	-
SM capacitance C_{sm}	11.3	mF
Electrostatic constant H_c	33	ms
Arm inductance L_{arm}	46.6	mH
Arm resistance R_{arm}	0.4	Ω
AC filter inductance L_f	84.2	mH
AC filter resistance R_f	0.14	Ω

Table II: Grid parameters

Parameter	Value	Unit
DC grid voltage V_{dc}	640	kV
AC grid voltage V_{ac}	400	VLLrms
AC grid short circuit level	10000	MVA
AC grid frequency f	50	Hz

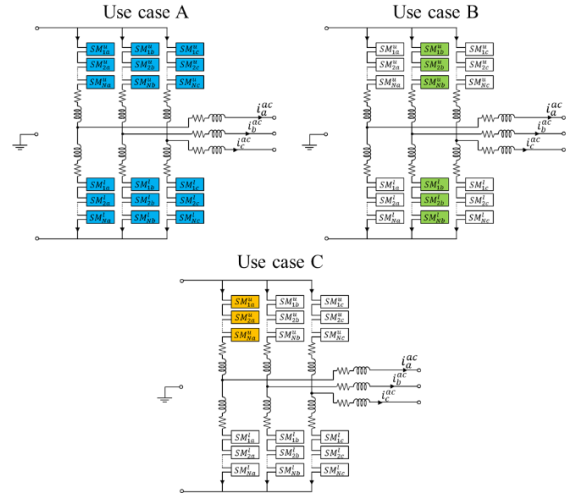


Figure 8: MMC with energy storage devices in all arms for use case A, only in one phase (leg B) for use case B and only in one arm for use case C

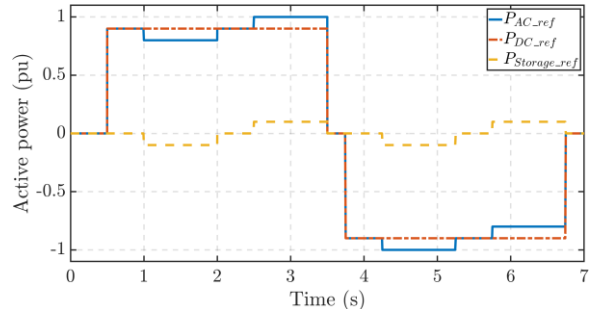


Figure 9: Power references for both use case simulations $P_{AC\ ref}$, $P_{DC\ ref}$ and $P_{Sto\ ref}$

In order to evaluate the performance of MMC control strategies with embedded energy storage, the ESS power and the HVDC link power reference profiles shown in Figure 9 are considered in all cases.

The energy storage power reference $P_{Sto ref}$ is defined in per-unit of the HVDC rated power. It corresponds to the total ESS power reference from the MMC. This power reference is equally shared between ESS arms according to the number of arms which have ESS embedded. Thus for use case A, the energy storage power reference for each arm of the MMC is $P_{Sto ref}/6$, for use case B, the energy storage power reference for the upper and lower arms of leg B is $P_{Sto ref}/2$ and 0 for the remaining arms, while for case C the power reference of upper arm phase A is equal to $P_{Sto ref}$ and 0 for the other arms. To cover the two operating modes of the MMC and consider the charge and discharge states of the energy storage system in both modes, the power references for all simulations are explained hereafter and given in Figure 9.

- A positive step of 0.9 pu for the HVDC link power reference $P_{DC ref}$ from $t = 0.5s$ to $3.5s$, during this phase the power $P_{Sto ref}$ goes up from 0 to 0.1 pu between $t = 1s$ and $2s$ and then goes down from 0 to -0.1 pu between $t = 2.5s$ and $3.5s$.
- A negative step of 0.9 pu for $P_{DC ref}$ from $t = 3.75s$ to $6.75s$, during this phase $P_{Sto ref}$ goes up from 0 to 0.1 pu between $t = 4.25s$ and $5.25s$ and then goes down from 0 to -0.1 pu between $t = 6.75s$ and $6.75s$.

In steady state, if losses are neglected, the AC power is equal to the ESS power reference plus the HVDC link power reference

Use case A: Energy storage elements are equally inserted in all the arms of the converter

Figure 10 shows the active and DC powers of the MMC. It is observed that for both controls (EBC and NEBC) the energy storage power P_{sto} is injected to the AC side via P_{AC} without modifying the power P_{DC} injected to the DC side. With EBC as for NEBC, the voltage ripples in the

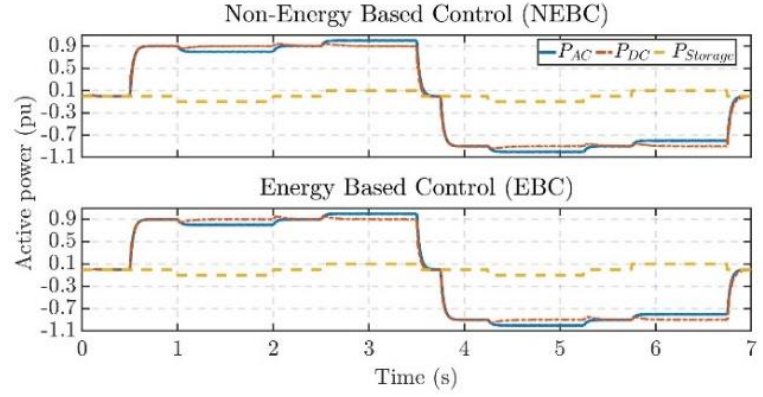


Figure 10: MMC active and DC powers: P_{AC} , P_{DC} and $P_{Sto ref}$

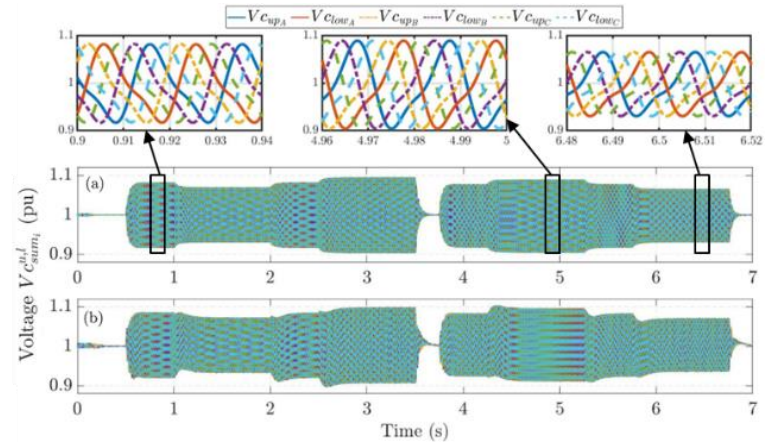


Figure 11: Voltage of the equivalent capacitor of the MMC arms $v_{c_{sum}^{u,l}}$ (a) – NEBC, (b) – EBC

capacitor of the MMC arms $v_{c_{sum}^{u,l}}$ are balanced, whereas their amplitude and shape are impacted by P_{sto} Figure 11.

For EBC, the transient in the voltage response is related to the tuning of the energy control loops.

Use case B: Energy storage elements are only inserted in one phase

In this use case, the storage system is unbalanced among the MMC arms, the ESS is available only in one phase of the MMC (leg B).

Applying the same power reference profile, for MMC with EBC, the energy storage power is injected into the AC grid without disturbing the DC side. As shown in Figure 12, both P_{ac} and P_{dc} follow their respective references. However, with NEBC, power oscillations at 100Hz are observed on the AC and DC powers when the energy storage power reference is not null. To understand the effect of the unbalanced integrated energy storage on the internal dynamics of the MMC with NEBC, the Circulating Current Suppressing Control (CCSC-dq) is disabled to observe the behavior of the differential currents in open loop.

The differential currents i_{diff_i} (also named circulating currents), defined in (1), comprise the DC currents, along with the additional AC currents that circulate within the converter as a result of the interaction between the arms.

$$i_{diff_i} = \frac{(i_i^u + i_i^l)}{2} \quad (1)$$

For the following, to highlight the undesirable phenomena at the AC side of the MMC, $P_{AC\ ref}$ is set to zero and $P_{Sto\ ref}$ is defined as previously. In this case, the energy storage power is injected to the DC side. Consequently, if active power is observed at the AC side, it is due to uncontrolled variables. As reference case, the previous case with balanced energy storage distribution is simulated with CCSC-dq disabled, which results are shown in Figure 13. As expected, when the CCSC-dq is disabled and ESS is evenly distributed, 100Hz oscillations are observed in the differential currents.

The aim of CCSC-dq integration in the NEBC structure is the elimination of the inner balancing currents i_{diff_i} in the MMC. In the absence of the CCSC-dq, i_{diff_i} are balanced and are composed of a DC component and an AC component at a double-fundamental-frequency i.e. 100Hz. With ESS, in Case A, the 100Hz oscillations are also balanced between the three-phases, and their magnitude varies according to the power from the ESS due to the change in the arm currents (Figure 13). Considering Case B, the differential currents i_{diff_i} are not balanced anymore. The phase B current is much larger when the power from the ESS is not null. This explains why the classical CCSC-dq is not working properly as it is designed to control balanced currents since it is based only on the positive sequence abc-dq transformation. To eliminate the AC component of the unbalanced differential currents, a solution based on the ideas presented in [12] is applied in the following. The control scheme consists of using a Proportional-Resonant (PR) controller per leg, as depicted in Figure 14. The PR control per phase allows to filter the oscillating component at a given frequency (in this case 100 Hz) per phase and it does not affect components at other

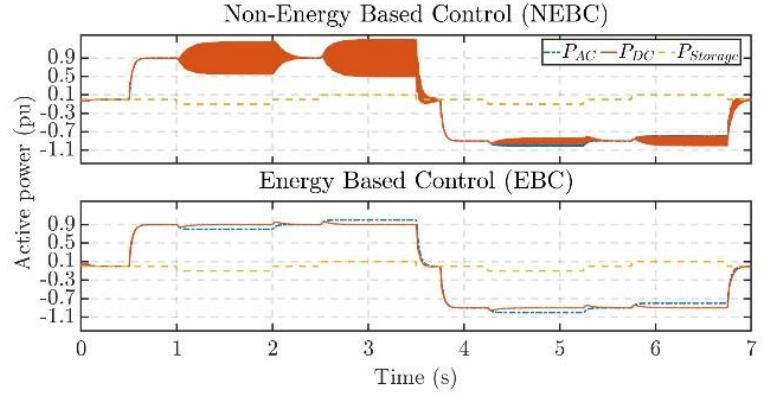


Figure 12: MMC Active power P_{AC} , P_{DC} and $P_{Sto\ ref}$

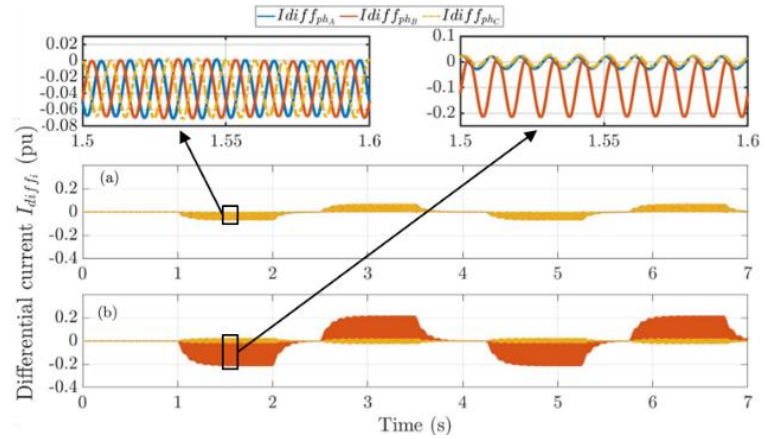


Figure 13: i_{diff_i} with NEBC and CCSC disabled (a) – Use case A, (b) – Use case

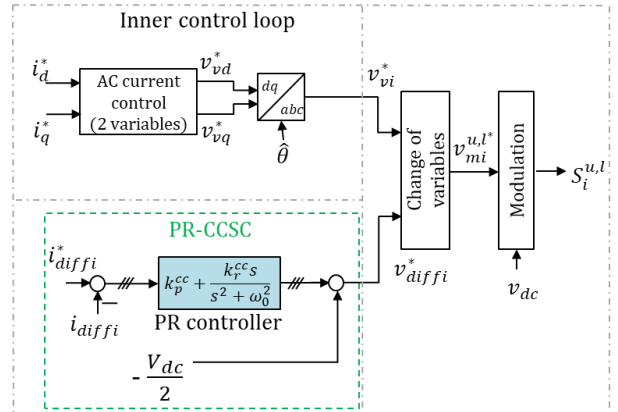


Figure 14: Inner control loop for NEBC using a PR-CSSC

frequencies such as the DC components. In this section, this control is named PR-CSSC. Regarding the PR control, k_p^{cc} and k_r^{cc} are the control gains, and ω_0 is the resonant frequency tuned at 100Hz to control the 100Hz oscillations. By comparison of Figure 13 and Figure 15, the effectiveness of the PR-CSSC is demonstrated as this controller allows in one hand to suppress the oscillating component at 100Hz and the DC component of the current in phase B can flow to the DC side. Although the differential currents are correctly controlled, when looking into the grid

instantaneous power P_{aci} shown in Figure 16, an oscillatory component at 100Hz can be observed.

Figure 17 represents MMC arm currents $i_i^{u,l}$ for an NEBC with PR-CCSC and an EBC. The currents of the two arms of phase B ($i_B^{u,l}$) for both controls have the same DC component, related to $P_{Sto ref}$. However, for PR-CCSC, these currents show an additional 100Hz oscillatory component (which leads to undesirable oscillations in the AC side). The differential current is necessary to balance the instantaneous power of the phases. When the 100Hz component of these currents is forced to zero, by means of additional 100Hz control component on the modulated voltage $v_{mi}^{u,l}$ (see Figure 1), 100Hz oscillations are created in the grid currents leading to AC power oscillations, see Figure 16. In [13], circulating current suppression for HVDC-MMC systems with asymmetric arm impedance shows similar phenomena. In [14], some strategies are proposed for balancing the energy among the different arms of the MMC while still using the DC voltage for computing the modulation indexes.

The addition of supplementary control loops to ensure the horizontal and vertical energy balancing of the legs and arms leads to very similar strategies to the EBC strategies.

It can be concluded that, in case of unbalanced energy storage, an EBC is somehow indispensable for the purpose of arm energy balance while allowing balanced grid currents.

Use case C: Energy storage elements are only inserted in one arm

To assess the balancing mechanism of the EBC in arm energy management, the energy storage integration in a single arm of the MMC, which presents the most constraining case for energy

balancing, is investigated. The simulated scenario is ESS integration in the upper arm of phase A. only. Power references are as described earlier and shown in Figure 9. Even with the ESS integration in only one arm, the AC active and DC power profiles in Figure 18 are identical to the ones in Figure 10 and Figure 12 for ESS in all the arms of the MMC and in one phase of the MMC, respectively. In other words, the EBC manages effectively to balance the energy among arms despite the most challenging case

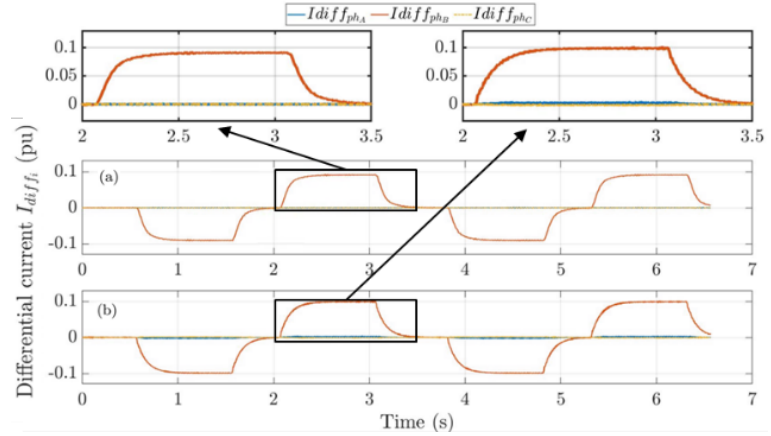


Figure 15: i_{diffi} in use case B (a) – EBC , (b) – NEBC with PR-CCSC

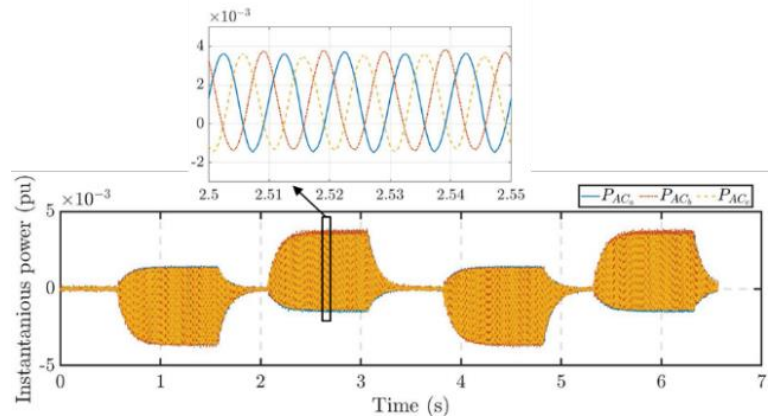


Figure 16: Instantaneous active power for NEBC with PR-CCSC

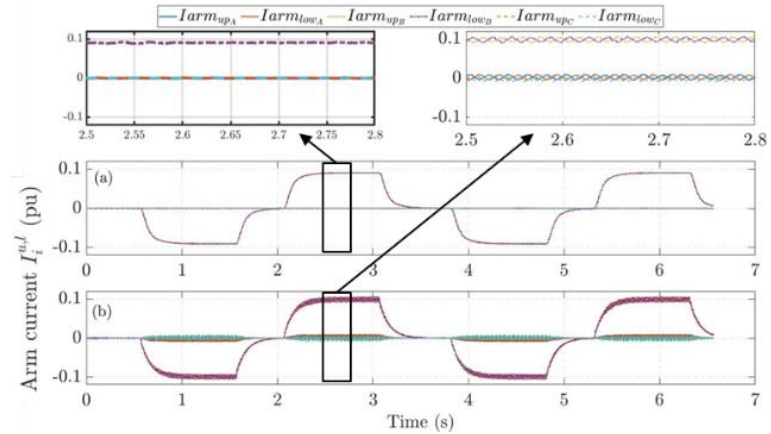


Figure 17: Arm current $i_i^{u,l}$ (a) – EBC, (b) – NEBC with PR-CSC

Figure 19 shows the voltage of the equivalent capacitor of the MMC arms $v_{C_{sum}i}^{u,l}$. The average values of these voltages are balanced as expected, but the ripples are different (in shape and in amplitude). This is also expected [4] since the currents and modulation index are different in each arm according to the energy storage power. Consequently, the voltage ripples for equivalent capacitors are not balanced among the upper and lower arms of leg A.

Highlights of Findings

Integrating energy storage within the MMC represents a challenge in terms of controlling and balancing energies in each arm. Differential currents i_{diff_i} serve as an indicator of this energy

distribution process. Depending on the adopted control strategies, such as EBC or NEBC, the management approach for these currents differs, potentially exerting significant influence on system controllability. These considerations motivate the selection of these currents as a key performance indicator (KPI), see Table III.

The impact of the energy storage integration on the MMC design would serve as an interesting KPI for comparing the three use cases for the MMC with EBC. The analysis in [15] covers deeply all key elements of this comparison, mainly the impact of energy storage distribution on the sizing elements of the MMC.

Conclusion

In this paper, MMC model with embedded ESS into its submodules was presented and simulated to assess NEBC and EBC strategy performance. Situations where the ESS is evenly or unevenly balanced between converter arms were investigated.

The comparisons are based on a power profile including combination of both HVDC link power and energy storage power. It has been observed that both NEBC and EBC are well suited for controlling MMC with balanced ESS within the arms. However, the NEBC has poor performance

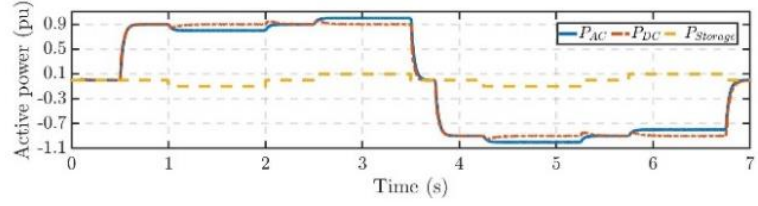


Figure 18: MMC Active power P_{AC} , P_{DC} and $P_{Storage}$

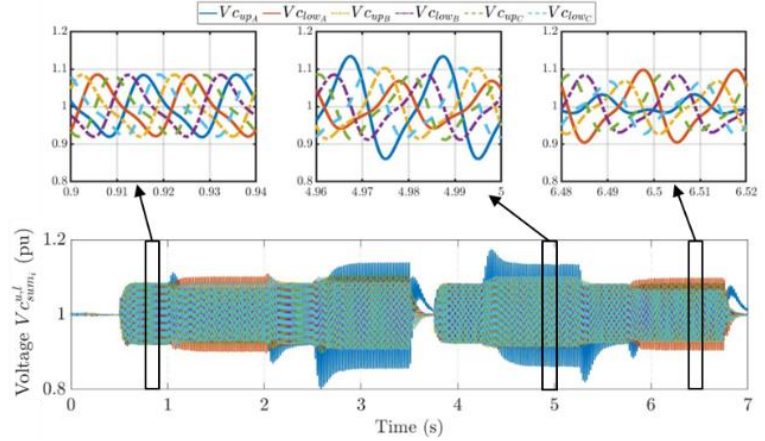


Figure 19: Voltage of the equivalent capacitor of the MMC arms $v_{C_{sum}i}^{u,l}$

when ESS are unbalanced among MMC arms. Both CCSC-dq and PR-CCSC leads to power oscillations on the AC and/or DC sides. In one case, the CCSC-dq is unable to suppress the 100Hz oscillations on the differential current leading to power oscillations, while in the other case, the PR-CCSC is controlling the circulating current to zero, but leading to unbalance the AC grid currents and power. In general, the NEBC is inefficient when the energies of ESS are not perfectly balanced among the MMC arms, which is always the case when considering ESS lifetime (due to uneven component ageing). The three use cases simulations have outlined the good performance of EBC for ESS integration into MMC arms for balanced and extremely unbalanced situations.

Table III: Summary of results based on the differential currents as a KPI

Use case	NEBC	EBC
A	Energy balance among the MMC arms is implicitly maintained, even though the primary focus of this control lies in achieving objectives such as output DC voltage or DC current or grid current regulation. However, this approach leads to less effective management of differential currents. See Figure 20.	Energy balance among the MMC arms results in a response where for all the legs, the upper and lower AC arm currents exhibit the same amplitude. These currents show a smoother response following variations in active power demand. See Figure 20.
B	Horizontal energy storage unbalance among the MMC legs results in unbalanced phase-shifted differential currents, oscillating at a frequency of 100Hz, rendering the use of the classical CCSC-dq inefficient. The implementation of CCSC-PR control results in the transfer of oscillations from the differential currents to the AC grid currents. See Figure 13.	Horizontal energy storage unbalance among the MMC legs leads to a response where for each leg, the upper and lower AC arm currents exhibit the same amplitude, resulting in differential currents displaying a DC offset. See Figure 21.
C	Given the unsatisfactory outcomes of employing CCSC-dq and CCSC-PR based NEBC in handling horizontal energy unbalance, it is nonsense to extend such control to this case.	Horizontal and vertical energy storage unbalances result in a response characterized by varying amplitudes in the upper and lower AC arm currents within each leg, leading to balanced phase-shifted AC components with different amplitudes observed in the differential currents. See Figure 22.

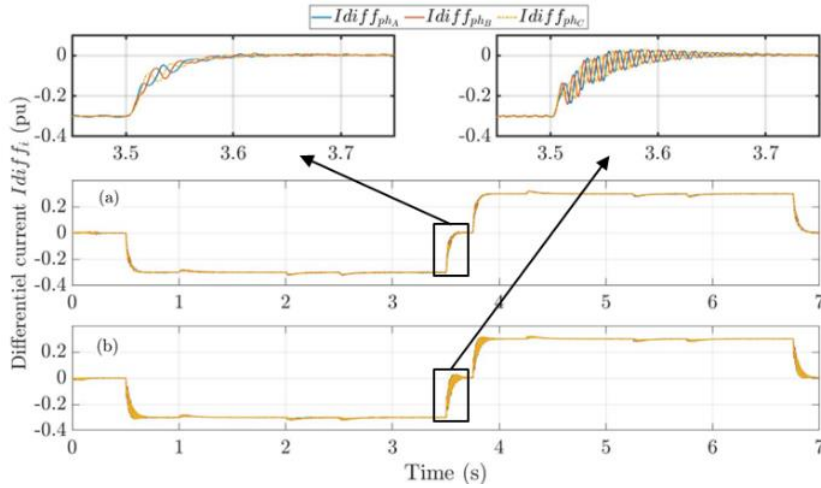


Figure 20: i_{diff_i} for use case A (a) – EBC, (b) – NEBC

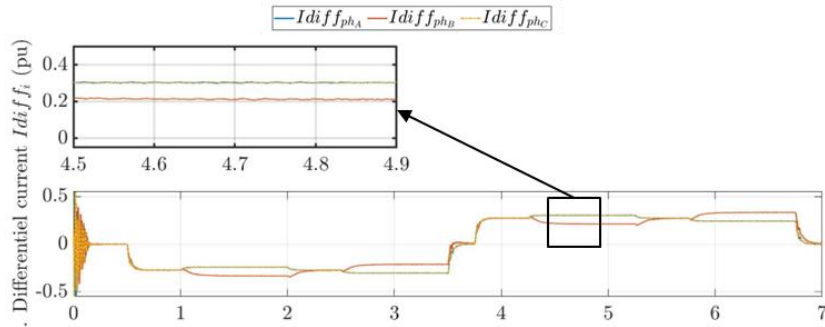


Figure 21: i_{diff_i} for use case B - EBC

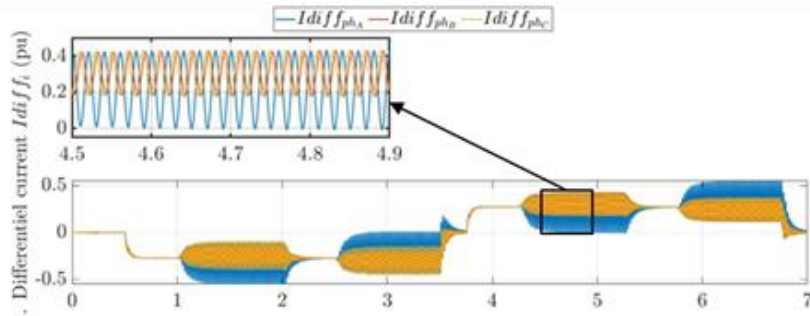


Figure 22: i_{diff_i} for use case C - EBC

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