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Increasing DC system stability thanks to energy control in MMC based DC-DC converters

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Abstract

DC voltage regulation of DC networks is essential to the operation of the system. Recently a new control method called virtual capacitor control has been proposed for the Modular Multilevel Converter (MMC) to increase the inertia of HVDC systems. In the development of future DC grids, DC-DC converters will be needed. Most of DC-DC converters proposed in the literature for HVDC are based on the MMC, thus some of the features of this converter can be extended for DC-DC converters. In this paper, the virtual capacitor control is proposed for the Front-to-Front MMC. The proposed control approach is validated in transient simulations, analysing the impact on the interconnection of two DC systems. The simulation results show that the variation of the voltage of a DC network after a power disturbance can be decreased with the proposed control and at the same time the DC-DC converter offers a decoupling to the second DC network which is not affected by the perturbation. Moreover, the results show how the virtual capacitor concept can be extended to MMCs that are not directly connected to the DC network where the service is provided.

1 Introduction

High Voltage Direct Current (HVDC) grids have been recognized as a potential solution for the upgrade of the existing transmission electrical system [1]. Most of works on HVDC multiterminal systems consider a common rated voltage and line configuration (bipole, symmetric monopole...) for the whole system. However, DC-DC converters enable the interconnection of systems with different characteristics, and thus they can offer relevant degrees of freedom to optimise DC systems. An example is busbar-like systems with backbones or high-power corridors where there is a main route and several additional connections which exchange a fraction of the total power [2]. If DC-DC converters would be considered in such grid architectures, the characteristics of the additional lines could be different from those of the main route, potentially optimising the system. Another example is related to hubs or energy islands where several offshore wind farms (OWF) are connected to a hub which is connected to shore through export cables [3]. Considering DC-DC converters for such projects would allow to have connections to OWFs with different characteristics than connections to shore. Also, one of the available options to build HVDC multiterminal systems is to reuse the existing HVDC links to create new interconnections between different markets with a reduced cost when compared to a new infrastructure [4]. As link characteristics have been defined specifically to each project, the HVDC links to connect usually have different characteristics. In consequence, different voltage levels, line configurations, and potentially converter technologies are found. The interconnection of such different systems requires then interface elements: DC-DC converters.

Regarding DC-DC converters for HVDC applications, several topologies have been proposed in the literature [5–7]. The main trend on the different proposals is to use stacks of sub-

modules (SMs) following the conversion principles of the Modular Multilevel Converter (MMC) [6,8–11]. The Front-to-Front MMC (F2F-MMC) is chosen for the rest of this paper because of its similarities with the MMC and because, compared with the rest of proposals on the literature, it can be considered as a benchmark topology given the possibility of its implementation with existing technologies.

DC-DC converters not only enable the interconnection of HVDC networks with different characteristics but can also provide different functionalities like power flow control, firewall to prevent the propagation of faults between DC systems [12] and contribution to the regulation of the DC voltage [13].

This paper is focused on this last topic. Indeed, the regulation of the DC voltage is key for maintaining the stability of the system and, when a DC-DC converter is used to interconnect different DC systems, a control scheme has to be proposed to share the responsibility of the DC voltage control between several converters (as in multi-terminal DC systems). Different options for the role of DC-DC converters to control DC voltage have been proposed in the literature [14–16]. In any case, the voltage is maintained constant if there is an equilibrium between the power generated and consumed. DC-DC converters must be then involved to some extent in controlling the energy balance of the system. Any disturbance on the power balance creates a voltage deviation from the nominal value. The rate of variation of the DC voltage depends on the power unbalance magnitude and the inertia of the DC system.

The inertia of a DC system is related to the ratio between the energy stored in the system capacitances and the rated power. The typical values of the stored energy in the lines and converters on a DC system is relatively low. For example, this

value in is the range of 40 ms for an HVDC MMC [17], which is considerably smaller than the typical values on AC systems (2s- 6s) [18] where synchronous generators are used. Then, to increase the inertia of the DC networks to be more robust against power disturbances, advanced control methods have been proposed in literature [19].

The virtual capacitor concept for the MMC was proposed in [19]. In this control approach, the internal control of the converter energy is modified to increase artificially the equivalent capacitor observed by the DC system. Thus, with an appropriate control of the internal energy of the converter, the line capacitance is virtually increased, then the inertia of the system is also increased. The concept is interesting since it increases the robustness of the DC system by only control means, i.e., no additional equipment is required.

As the F2F-MMC stores energy in submodules, the virtual capacitor concept can be also applied to this DC-DC converter. This idea is explored in this paper with the aim of reducing the variations of the voltage of a DC network after a power disturbance without disturbing the second DC network (using the firewall capability of the F2F-MMC). The virtual capacitor concept is also extended to MMCs that are not directly connected to the DC network where the service is provided. The concept is tested in a case study analysing its impact in the interconnection of two P2P HVDC links. Different control variants are considered and compared with the classical control scheme where the virtual capacitor concept is not implemented.

The paper is organised as follow: in Section 2 the F2F-MMC topology is presented, briefly explaining the control principles of the MMC and how they are applied to the F2F-MMC. Section 3 presents the DC voltage regulation and virtual capacitor concept, first recalling what is known for the MMC and then proposing the concept to the F2F-MMC. Finally, Section 4 presents a case study involving the interconnection of two HVDC links and the simulation results for the proposed control method. Conclusions are given in section 5.

2 Front-to-Front MMC

The Front-to-Front MMC (F2F-MMC) is a DC-DC converter formed by two MMCs interconnected on the AC side through an AC transformer as shown in Fig. 1.

Each MMC is formed by 6 arms. Each arm is an assembly of an inductor (arm inductance) and a stack of SMs. The typical type of SMs are Half-Bridge (HB) SMs. The control of the semiconductors of each SM allows to generate at the SM terminals a voltage equal to the voltage on the SM capacitor or zero. In the first case, the SM is said “inserted” and in the second case “bypassed”. By controlling the insertion and bypass of the SMs, a controlled voltage waveform is obtained on the terminals of each stack.

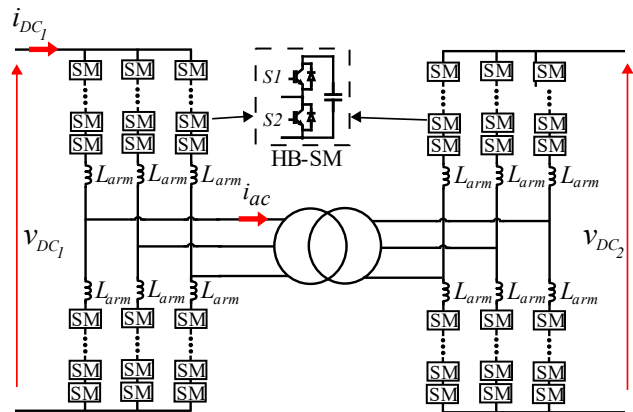


Fig. 1 Front-to-Front MMC

2.1 MMC Control overview

The number of SMs is considerably high in an HVDC application. Thus, the coordination of bypass and insertion of all the SMs can be difficult. To simplify the control, the converter controller is separated into two control stages: high-level control and low-level control (Fig. 2). The low-level control is responsible of generating the control orders for each SM and balancing the voltage on all the SMs in the same arm. It receives as input the voltage to be generated on the terminals of each stack. This voltage reference is calculated by the high-level control. The low-level control is not detailed in this paper, details can be found in [20–22]. In this paper it is assumed that the low-level control guarantees a good balancing in all the SM capacitor voltages and generate stack voltages as defined by high-level control.

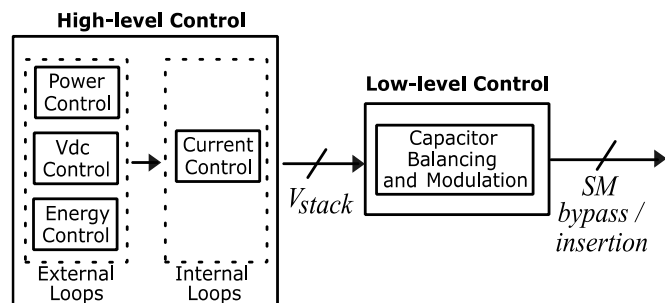


Fig. 2. High and low-level control

Concerning the high-level control, a typical scheme for the control of one MMC is shown in Fig. 3. The details can be found in [19,23]. In this energy-based control scheme, the control is divided in external and internal control loops. The internal control loops are responsible of controlling the converter currents. They are the AC current, the DC current, and the circulating current between converter legs.

The external control loops give the references to the current controllers. They are related to the control of the active and reactive power, the DC voltage, and the internal energy of the converter.

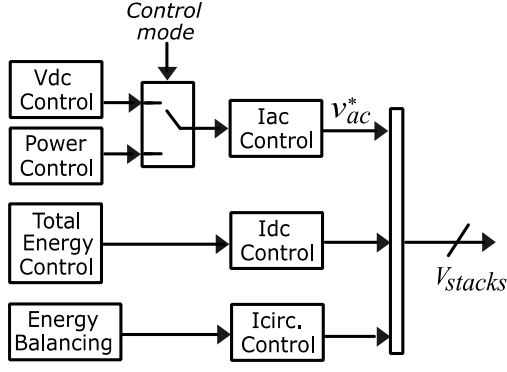


Fig 3. High level control of one MMC

2.2 MMC Energy Control

The control of the internal energy is essential in the operation of the MMC. It is related to the control of the voltage on the SMs. While the low-level control guarantees a balancing on the voltages of all the SMs, the energy controllers control the sum of the voltages on all the SMs in each arm.

The energy stored in one converter stack is given by (1). $V_{C\Sigma}$ is the sum of the voltages of all the SM capacitors in the arm, and C_{arm} is the equivalent capacitance of one arm given by (2), where C_{SM} is the capacitance of one SM, and N_{SM} is the number of SMs in one arm.

$$W_{arm} = \frac{1}{2} C_{arm} V_{C\Sigma}^2 \quad (1)$$

$$C_{arm} = \frac{C_{SM}}{N_{SM}} \quad (2)$$

The total energy stored in the MMC is given by (3), where C_{eq} is an equivalent capacitance given by (4), assuming that the six arms in the converter have the same equivalent capacitance and sum of SM capacitor voltages.

$$W_{MMC} = \frac{1}{2} C_{eq} V_{C\Sigma}^2 \quad (3)$$

$$C_{eq} = 6 C_{arm} \quad (4)$$

The control of the MMC energy can be divided in the control of the total energy (3), and the balancing of this energy in the different arms (1). The energy balancing controller gives the reference to the converter circulating currents. For the total energy control, the dynamics is given by (5).

$$\frac{dW_{MMC}}{dt} = P_{DC} - P_{AC} \quad (5)$$

From (5), it is seen that the energy dynamics on the MMC can be controlled by means of the power exchanged with the AC or DC sides. Typically, it is done with P_{DC} , thus by the DC current.

2.3 F2F-MMC Control

The same scheme of the MMC can be applied to control the F2F-MMC. However, some points should be taken into consideration to adapt the MMC control to this topology.

First, in the F2F-MMC, the AC current is common to both MMCs. Thus, the control of the AC current can be complex if

both MMCs try to control the same current, some techniques have been however reported in literature [24]. A simpler method is to control the AC current with only one MMC while the second MMC fixes the AC voltage on the transformer. This method is used in this paper.

Secondly, in the MMC, the AC current is typically used to control the power transfer between networks, while the DC current is used to control the converter energy. For the control of the F2F-MMC this paper proposes to use the AC power (so the AC current) to control the energy of the second MMC in the structure, while the DC power transfer between both networks is controlled by the DC current of the second MMC.

With these assumptions, the F2F-MMC control scheme is given in Fig. 4. The sub-indexes F1 and F2 refer to the quantities on the MMC F1 and MMC F2 respectively. For the AC current there is not a subindex because the AC current is common to both MMCs.

It is assumed that the MMC F1 controls the AC current, while MMC F2 fixes the AC voltage. Each MMC controls its DC current. The energy of MMC F1 is controlled by P_{DC1} (i_{DC1}) while the energy of MMC F2 is controlled by P_{AC} (i_{AC}), thus the energy controller of MMC F2 give the reference to the AC current to be controlled by MMC F1. The DC power transfer between DC networks is controlled by means of the DC current on MMC F2 (i_{DC2}). The other control loops, such as energy balancing on each MMC are done as usual on each MMC by means of the circulating currents.

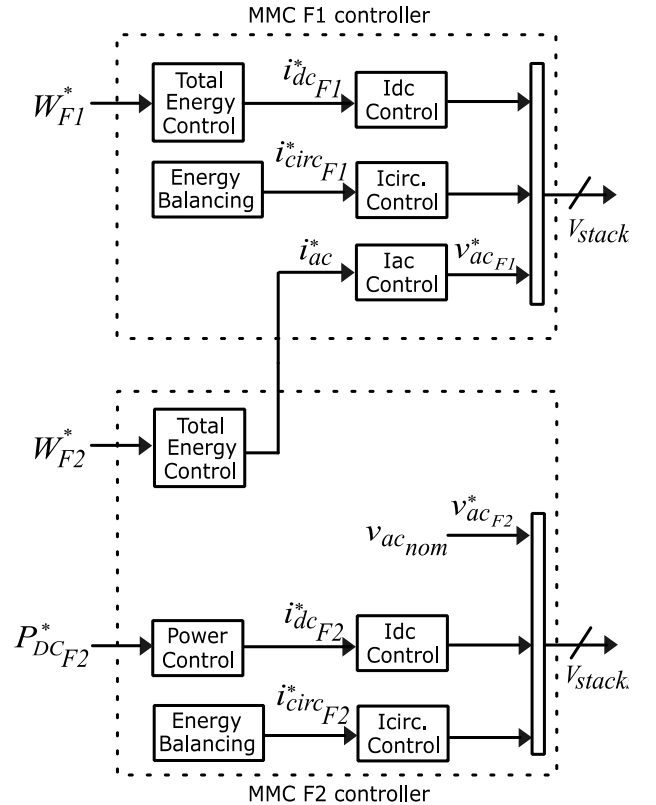


Fig. 4 F2F-MMC Control

3 DC voltage control and virtual capacitor

3.1 Reminder of virtual capacitor concept for the MMC

The control of the DC voltage on a DC network consists in regulating the voltage on the equivalent capacitor of the system as shown in Fig. 5. In this figure it is observed that the energy stored in the network equivalent capacitance C_{dc} depends on the DC power P_l of the network and the DC power P_{DC} being delivered/absorbed by the converter as presented in (6).

$$\frac{1}{2} C_{dc} \frac{dv_{dc}^2}{dt} = P_l - P_{DC} \quad (6)$$

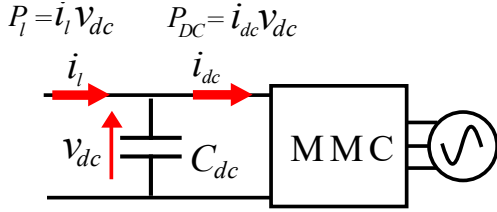


Fig. 5 DC voltage equivalent circuit for control design

For an MMC, as it has been seen in (5) the DC power is related with the AC power and the dynamics of the converter energy. Thus, when the DC voltage is controlled by an MMC, Eq. (6) gives (7) by replacing the DC power on the converter from (5).

$$\frac{1}{2} C_{dc} \frac{dv_{dc}^2}{dt} + \frac{dW_{MMC}}{dt} = P_l - P_{AC} \quad (7)$$

The concept of virtual capacitor consists in choosing the dynamics of the MMC energy in a way that the capacitance seen by the DC network is increased. According to [19], the MMC energy reference can be given in function of the difference of the DC voltage v_{dc} with respect to the nominal value $v_{dc,nom}$ as shown in (8), where $W_{MMC,nom}$ is the nominal value of the MMC energy and k_{vc} is a control constant denominated *virtual capacitor coefficient*.

$$W_{MMC}^* = \frac{1}{2} C_{eq} k_{vc} (v_{dc}^2 - v_{dc,nom}^2) + W_{MMC,nom} \quad (8)$$

If the control loop of the MMC energy is faster than the control loop of the DC voltage, it can be assumed that the MMC energy perfectly follows its reference, i.e., $W_{MMC} \approx W_{MMC}^*$. Then, deriving (8) and replacing in (7), considering that $W_{MMC,nom}$ and $v_{dc,nom}$ are constants, gives (9).

$$\frac{1}{2} (C_{dc} + C_{eq} k_{vc}) \frac{dv_{dc}^2}{dt} = P_l - P_{AC} \quad (9)$$

In (9) it is observed how the capacitor of the DC system is increased from C_{dc} to $C_{dc} + C_{eq} k_{vc}$ only by means of the control of the MMC. The system capacitance is increased by virtual capacitance of C_{vc} given by (10).

$$C_{vc} = C_{eq} k_{vc} \quad (10)$$

This concept can be extended to all the converters in the DC network. Indeed, in (6) the power coming from the DC network is the sum of the power being injected by all the other converters connected to the system as shown in (11).

$$P_l = \sum P_{DC,converters} \quad (11)$$

For all the MMCs on the network the same energy control strategy can be implemented, thus assuming a low voltage drop on the network and only MMCs are connected to the dc system, Eq. (11) becomes (12), where $C_{vc,i}$ and $P_{AC,i}$ are respectively the *virtual capacitance* and the AC power of an i^{th} MMC in the network.

$$P_l = \sum \left(\frac{1}{2} C_{vc,i} \frac{dv_{dc}^2}{dt} + P_{AC,i} \right) \quad (12)$$

Therefore, the different MMCs in the network can participate to increase the stability of the DC network by applying the virtual capacitor concept.

For a network made by N MMCs as shown in Fig. 6 where the DC voltage is controlled by MMC1, the DC voltage dynamics (9) becomes (13) when applying the virtual capacitor concept to the different converters in the network. In (13), $C_{vc,1}$ and $P_{AC,1}$ are the *virtual capacitance* and the AC power of the station controlling the voltage (MMC1). The variables with subindex i represent the same quantities but for the rest of MMCs in the system.

$$\frac{1}{2} (C_{dc} + C_{vc,1} + \sum C_{vc,i}) \frac{dv_{dc}^2}{dt} = \sum P_{AC,i} - P_{AC,1} \quad (13)$$

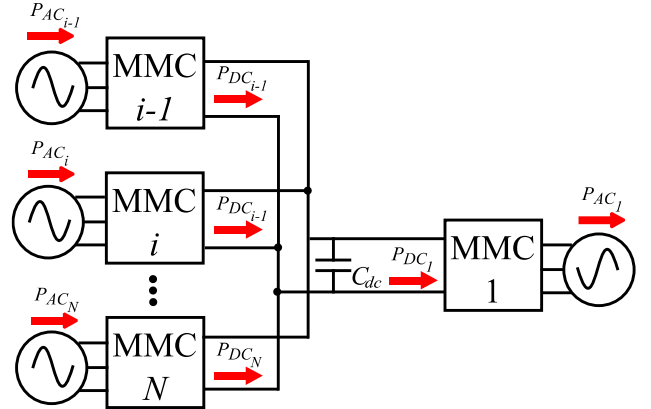


Fig. 6 Network example to show the different powers

3.2 Virtual capacitor on the F2F-MMC

The virtual capacitor concept can be also applied to modular multilevel DC-DC converters.

In the case of the F2F-MMC, there are two MMCs. Assuming the power directions of Fig. 7, the dynamics of energy of each MMC is given by (14) and (15).

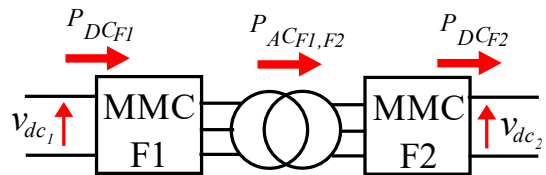


Fig. 7 F2F-MMC power directions

$$\frac{dW_{F1}}{dt} = P_{DC_{F1}} - P_{AC_{F1,F2}} \quad (14)$$

$$\frac{dW_{F2}}{dt} = P_{AC_{F1,F2}} - P_{DC_{F2}} \quad (15)$$

The energy of both MMCs on the F2F-MMC can be controlled to follow the DC voltage of either of both DC sides. In the rest of the paper, it is assumed that the virtual capacitor is applied to the first DC side. Then, when applying (8) with respect to the DC voltage v_{dc1} , Eq. (16) and (17) are obtained, where $C_{eq_{F1}}$ and $C_{eq_{F2}}$ represent the equivalent capacitances of both MMCs in the F2F-MMC, and $k_{vc_{F1}}$ and $k_{vc_{F2}}$ their virtual capacitor coefficients.

$$\frac{1}{2} C_{eq_{F1}} k_{vc_{F1}} (v_{dc}^2 - v_{dc_{nom}}^2) = P_{DC_{F1}} - P_{AC_{F1,F2}} \quad (16)$$

$$\frac{1}{2} C_{eq_{F2}} k_{vc_{F2}} (v_{dc}^2 - v_{dc_{nom}}^2) = P_{AC_{F1,F2}} - P_{DC_{F2}} \quad (17)$$

It is seen in (16) that MMC F1 follows the virtual capacitor concept as proposed originally for the MMC. However, in (17), the energy of the MMC F2 is controlled following the DC voltage at the terminals of the MMC F1. Thus, in this case the MMC F2 provides the virtual capacitance to a DC network to which it is not directly connected.

Adding (16) and (17) and solving for $P_{DC_{F1}}$ gives (18), where the $C_{kv_{F1}} = C_{eq_{F1}} k_{vc_{F1}}$ and $C_{kv_{F2}} = C_{eq_{F2}} k_{vc_{F2}}$ are the virtual capacitances of both MMCs in the F2F-MMC.

$$P_{DC_{F1}} = \frac{1}{2} (C_{kv_{F1}} + C_{kv_{F2}}) (v_{dc}^2 - v_{dc_{nom}}^2) + P_{DC_{F2}} \quad (18)$$

Considering the example network of Fig. 6 adding a F2F-MMC as presented in Fig. 8 and following (9), (11) and (13), Eq. (19) is obtained. This equation represents the dynamics of the DC voltage on the network. It is seen how the capacitance of the network has been increased with the F2F-MMC virtual capacitance control.

$$\frac{1}{2} (C_{dc} + C_{vc1} + C_{kv_{F1}} + C_{kv_{F2}} + \sum C_{vc_i}) \frac{dv_{dc}^2}{dt} = \sum P_{AC_i} - P_{DC_{F2}} - P_{AC1} \quad (19)$$

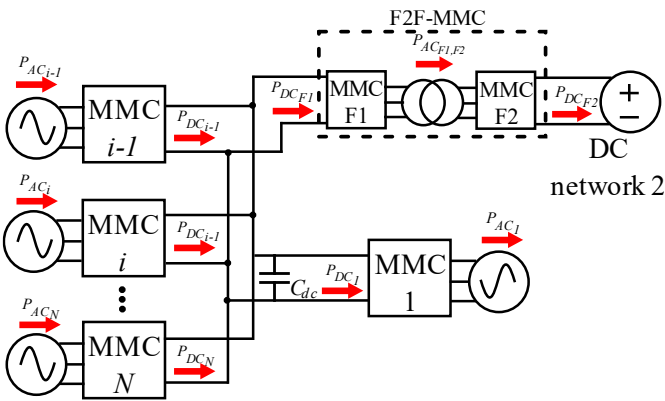


Fig. 8 Network example of Fig. 6 but including an F2F-MMC

The increase with $C_{kv_{F1}}$ is evident, because it is given by the MMC F1 on the F2F-MMC which is connected to the DC network where the increase of inertia is observed. However, (19) shows how the inertia of the DC system can be increased even with an MMC that is not connected directly to that network (in this case MMC F2 on the F2F-MMC). The contribution of this MMC is $C_{kv_{F2}}$.

3.3 Increase of energy range available in the F2F-MMC

To provide the virtual capacitor control on the MMC, the limits on the variation of the energy in the converter should be considered [19]. Indeed, the converter energy cannot be decreased below certain limit because the converter control is lost. There is also an upper limit given by the number of SMs and the maximal voltage that they can accept. These limits have been studied in [25] for the MMC.

Considering the lower limit, the constraint is related to the need for the MMC to generate AC voltages corresponding to the AC network voltage. Thus, the voltage on the SMs cannot go below a certain value where synthesizing the AC network voltage is no longer possible. In the F2F-MMC the AC voltage is a degree of freedom. Thus, this lower limit can be modified.

Indeed, in the F2F-MMC, the AC voltage magnitude is controlled internally as explained in Section 2 (see Fig. 4 where the voltage is fixed by MMC F2). Then, to increase the range of energy variation, it is proposed to decrease the AC voltage according to the variation of the DC voltage on the side where the virtual capacitor is provided. Thus, for the case where the service is provided to support v_{dc1} , the AC voltage is modified as presented in (20), where $v_{AC_{F2F_{nom}}}$ is the nominal value of the AC voltage and k_{vac} is a gain that determines how much the AC voltage is varied according to the DC voltage variation.

$$v_{AC_{F2F}} = v_{AC_{F2F_{nom}}} - k_{vac} (v_{dc1_{nom}} - v_{dc1}) \quad (20)$$

The control action proposed in (20) is useful when the DC voltage disturbance is an undervoltage, for an overvoltage the action on (20) cannot be applied since the F2F-MMC is not capable of increasing the AC voltage beyond a maximal value given by the number of SMs and their voltage limits. It should be also noted that this AC voltage reduction may reduce the transferred power $P_{AC_{F1,F2}}$ due to current limitations in switches.

3.4 Control scheme of the F2F-MMC providing virtual capacitor control

Fig. 9 presents the complete control scheme proposed for the F2F-MMC including the virtual capacitor concept to support v_{dc1} , and including the dynamic variation of the AC voltage. Comparing with the previous control (Fig. 4), the added control actions are highlighted in red.

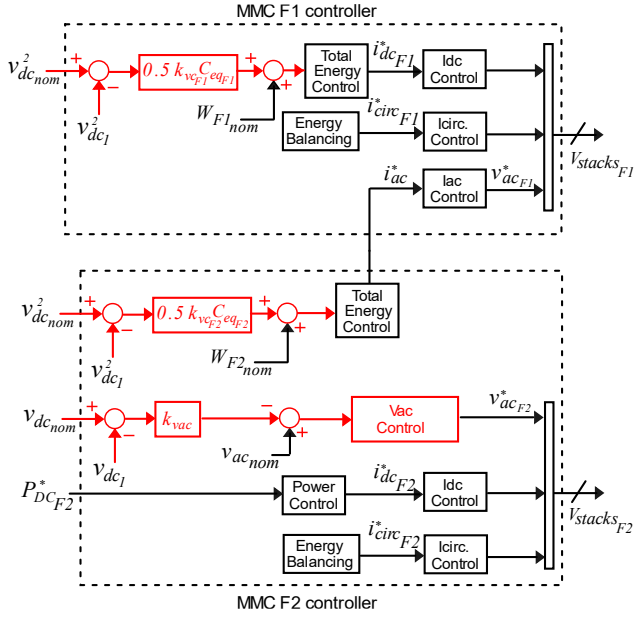


Fig. 9. F2F-MMC control including virtual capacitor control

4 Case study and validation of the concept

4.1 Case study

To test the validity of the proposed control and its impact in a DC system, a case study is proposed. It consists of the interconnection of two P2P HVDC links with an F2F-MMC as shown in Fig. 10. The considered HVDC links are symmetrical monopoles. MMCs are used as AC-DC converters to interface the AC systems which are modelled as ideal sources with a 15% reactance. The converter stations are modelled with a reduced order average model where each SM stack is replaced by a controlled voltage source and the SM capacitors are replaced with the equivalent arm capacitance and a current source [26]. For the cables, wide band models are used based in the models provided by Bestpaths project [27]. The parameters are based on 320 kV XLPE cable parameters which give an equivalent capacitance of 0.176 $\mu\text{F}/\text{km}$.

The control of each link follows a master-slave strategy, i.e., a MMC controls the DC voltage while the rest of the stations are controlled in power. Stations MMC2 and MMC4 are the stations controlling the DC voltages on each DC network. The DC voltage control used on these stations follows the principles presented in [19] for the tuning of the DC voltage controllers.

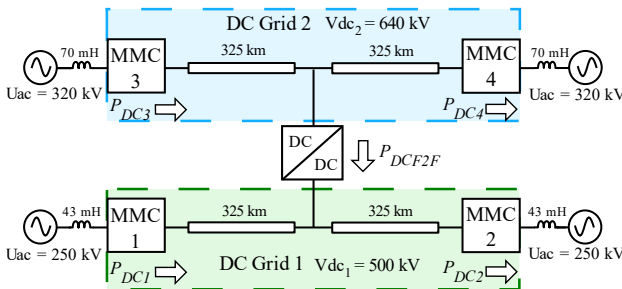


Fig. 10. Case study

As this study is focused on the impact of the virtual capacitor implemented in a DC-DC converter, only the F2F-MMC employs this control strategy. The rest of the AC-DC stations have their virtual capacitor coefficient set to zero.

The parameters for the converter stations are presented in Table 1. The F2F-MMC operates at medium frequency to decrease the size of passive elements. The value of 150 Hz has been selected because it provides a good trade-off between increase of switching losses and reduction of passive elements and because we consider that at this frequency the high-power high-voltage transformer is still feasible [13]. Observe that because of this frequency, the energy stored in the MMCs on the F2F-MMC is a third of the total energy on each MMC at 50 Hz.

Table 1 Converter parameters for case study simulation

Parameter	MMCs		F2F-MMC	
	1 – 2	3 – 4	MMC F1	MMC F2
DC power P_{DCnom}	700 MW	700 MW	700 MW	700 MW
DC voltage v_{dcnom}	500 kV	640 kV	500 kV	640 kV
AC voltage U_{acnom}	250 kV	320 kV	260 kV	333 kV
AC frequency	50 Hz	50 Hz	150 Hz	150 Hz
SMs per arm N_{SM}	313	400	313	400
SM capacitance C_{SM}	11 mF	9 mF	3.7 mF	3 mF
Equivalent capacitance C_{eq}	0.22 mF	0.14 mF	0.07 mF	0.045 mF
Converter energy W_{nom}	28 MJ	28 MJ	8.8 MJ	9.2 MJ
Arm inductance L_{arm}	43 mH	70 mH	9 mH	15 mH

For the control tuning, the response time of the DC voltage control loop on the MMC stations is set to 100 ms, while the total energy loops to 50 ms. On the F2F-MMC the control energy loops are set to have a time response of 15 ms. The difference on the response time between the MMCs and the DC-DC converter are related to the increase of the operating frequency, which allows to have faster responses in the internal filters used to filter out the operating frequency on the energy measurements. In the control of the F2F-MMC the AC voltage is fixed to the nominal value but giving a margin for control purposes.

For simulations, the considered virtual capacitor coefficients are summarised in Table 2. Scenario 0 can be understood as a test case with no virtual capacitor enabled in the DC-DC converter. Scenarios 1 and 2 corresponds to the contribution to

voltage stability of DC grid 1 thanks to the energy stored in MMC F1 and MMC F2 respectively. In Scenario 3, both MMC F1 and MMC F2 support voltage stability of DC grid 1. In the three last scenarios, the AC voltage in the F2F DCDC is reduced when the voltage in DC grid 1 is reduced.

Table 2 Test Scenarios

	k_{vcF1}	k_{vcF2}	k_{vac}
Scenario 0	0	0	0
Scenario 1	6	0	4
Scenario 2	0	6	4
Scenario 3	6	6	4

In all the scenarios the system behaviour is analysed after a disturbance of power on MMC1. The considered disturbance is a blocking of MMC1, causing an abrupt loss of power. The power flow on the system before the disturbance is 200 MW on MMC1, 700 MW on MMC3 and 200 MW on the F2F-MMC. The MMC2 and MMC4 adapt their power to keep controlled the DC voltages.

4.2 Simulation results

Fig. 11 presents the simulation results for the scenario without virtual capacitor (Scenario 0).

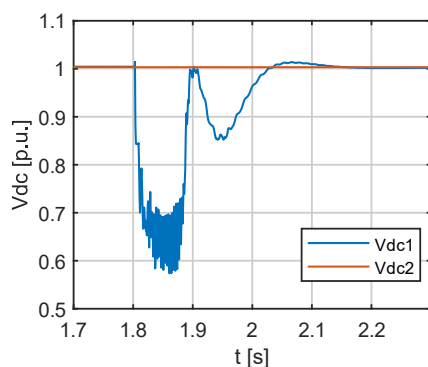


Fig. 11. Vdc on both networks for scenario 0

The figure shows the DC voltage on both networks. After the perturbation, the voltage drops below the minimal value required on MMC2 to work properly. The control of MMC2 reaches the saturation limits and thus the voltage is disturbed.

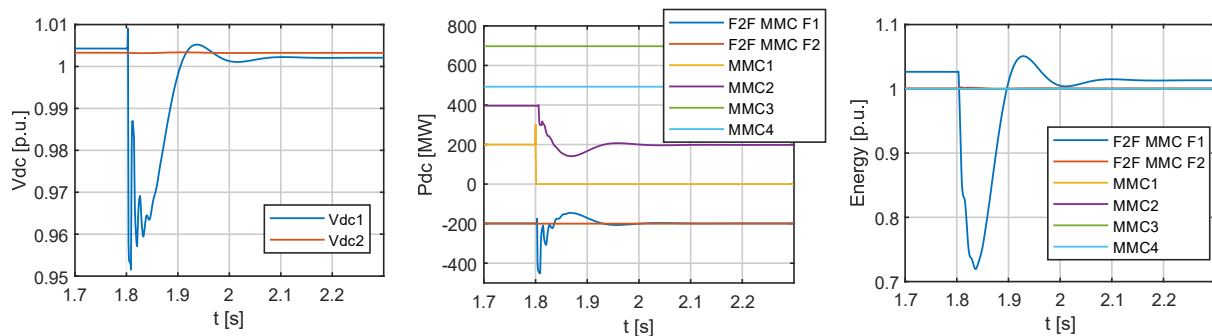


Fig. 12 Simulation results for Scenario 1

Once the voltage comes back to an admissible value, the controller on MMC2 tracks back the voltage to the nominal value. From this result it is concluded that the case study is very sensible to DC power disturbances without the virtual capacitor control.

The results for the Scenario 1 are presented on Fig. 12. The DC voltages are shown as well as the total energy on each MMC and the DC power on each converter. For the F2F-MMC, the individual quantities on MMC F1 and MMC F2 are presented. It is seen that thanks to the virtual capacitor control on MMC F1, the voltage drop on network 1 has decreased to around 5% (in Scenario 0 it was of more than 30%).

From Fig. 12 it is also seen how the network 2 is not affected by the disturbance on network 1. The F2F-MMC decouples both networks, acting then as a firewall. Considering the converter energies, it is seen how the energy on MMC F1 is decreased during the transient to support the network 1.

The simulation results for the scenario 2 are shown on Fig. 13. The results are similar to the previous case but in this case, it is observed that the energy on MMC F1 is kept constant, and the virtual capacitor functionality is provided only by MMC F2. This result shows how an MMC that is not directly connected to the network 1 can provide the service. Moreover, the network 2 is not disturbed, only a small variation on the voltage is observed but not on the power flow.

Fig. 14 shows the simulation results for Scenario 3. This time both MMCs on the F2F-MMC provide the virtual capacitor functionality. In this case the voltage drop is only 3%. It is seen how the energies on both MMCs on the F2F-MMC follow the voltage on network 1 without affecting the power flow on network 2; only small variations on the voltage are observed.

For all the cases where the virtual capacitor is provided, it is seen how the energy is decreased. The reached values can be below the limits for a typical MMC. However, thanks to the modification on the internal AC voltage on the F2F-MMC, the control is not lost (modulation indexes do not reach saturation limits). Fig. 15 presents the AC voltage and current on MMC F2 for the different cases. It is seen how the voltage is decreased but at the expense of a higher AC current to maintain the same power.

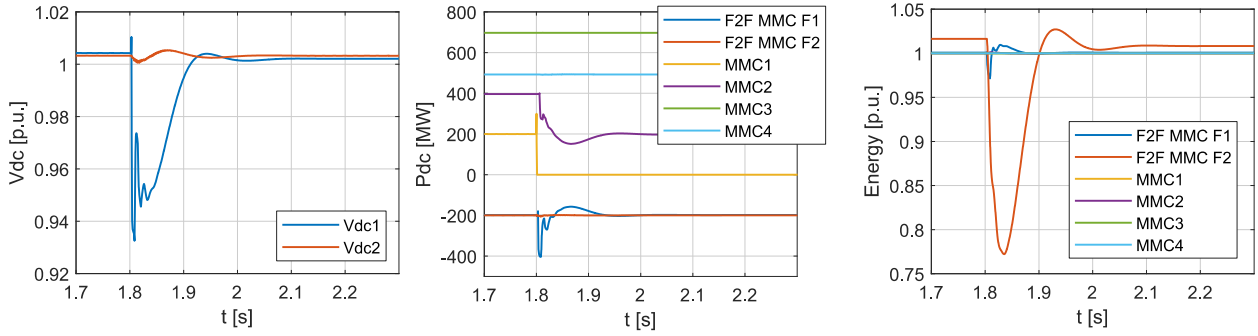


Fig. 13 Simulation results for Scenario 2

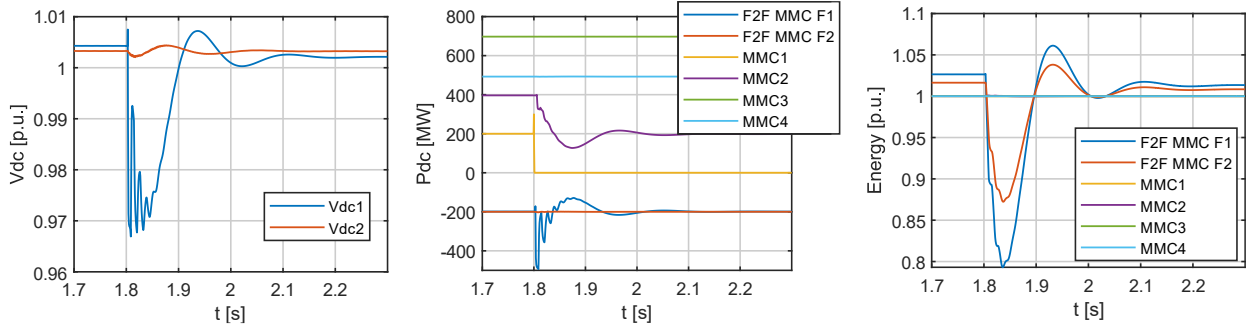


Fig. 14 Simulation results for Scenario 3

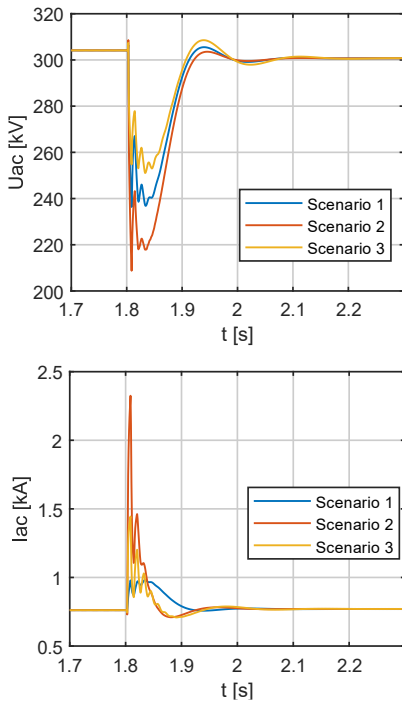


Fig. 15. AC voltage and current on the F2F-MMC for the Scenarios 1, 2 and 3.

5 Conclusion

In this work, the virtual capacitor control has been proposed for the F2F-MMC. It has been shown how the energy on both MMCs on the topology can be used to increase virtually the equivalent capacitor of a DC network, thus increasing the inertia.

In the proposed control, both MMCs provide the service to one side of the DC-DC converter, although other alternatives could be explored. It has been also demonstrated how an MMC that is not directly connected to a DC network can also provide an increase of the equivalent capacitance of this network.

The control has been validated in a case study where a F2F MMC interconnects two HVDC networks. In this example it has been shown how the network has difficulties to operate without the virtual capacitor control against disturbances on the DC power. The proposed control decreases considerably the DC voltage variation after an abrupt blocking of an MMC station in the network. Different scenarios were studied according to the possibilities of providing the virtual capacitor by only one or both MMCs in the F2F-MMC. It has been seen how the three studied options can effectively provide the service. The scenario where both MMCs are controlled following the virtual capacitor control has presented the best results. Which can be explained by the higher available energy to support the DC network.

Finally, the degree of freedom of the AC voltage inside the converter has been used to increase the available energy variation on the converter. Thus, the virtual capacitor coefficients can be increased. However, there is an impact on the internal AC currents. Therefore, an appropriate tuning method for the virtual capacitor coefficients on both MMCs, and how to modulate the internal AC voltage has to be studied with more detail.

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