Hybrid Full Bridge-Half Bridge MML Power Converter for HVDC Diode Rectifier Connection of Large Off-Shore Wind Farms

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***Abstract*---The connection of large off-shore wind farms using diode rectifier units presents important advantages due to the simplicity of the diode rectifier converter, its robustness and weight and loss reduction.**

Moreover, series connected diode rectifier units allow for increased reliability as the system is capable of reduced power operation in the case of the failure of one unit. However, a DR unit outage requires a reduced DC voltage, consequently, the use of full bridge MML power converters at the on-shore station. Such converters allow for reduced HVDC-link voltage operation when one diode rectifier unit is faulty and also help to improve transient response during faults.

However, the full bridge MML is more complex than its half bridge counterpart and has higher losses. In this paper a study has been carried out to ascertain the advantages and disadvantages of using a mixed full-bridge half-bridge MML power converter for the diode rectifier connection of off-shore wind farms, highlighting the operational limits of each type of MML converter under a reduced DC voltage.

***Index Terms*---HVDC transmission control, HVDC Diode Rectifiers, Wind power generation, Power system harmonics, MML Power Converters.**

I. Introduction

The use of Diode Rectifier (DR) stations for the connection of large offshore wind power plants (OWPPs) to HVDC links can lead to substantial CAPEX and OPEX reduction by increasing the efficiency and robustness of the overall system [1], [2], [3], [4], [5], [6]. Moreover, DRs represent a simple technical approach for the installation of distant off-shore HVDC stations.

Current development of XPLE cables allows for transmitting more than 1 GW which makes possible the connection of several wind power plants (WPPs) to the same HVDC link. Thus, several DR units will be series-connected at the off-shore platform and will share the DC voltage. For the on-shore station, both half-bridge (HB) or full-bridge (FB) modular multilevel converters (MMCs) can be used. HB-MMCs can only create monopolar voltages with their branches, therefore, the amplitude of the ac line-to-ground voltage has to be equal or lower than half of the dc voltage (considering a monopolar symmetrical configuration of the dc link). On the other hand, FB-MMCs are able to create bipolar voltages so the ac line-to-ground voltage can be up to twice the dc pole-to-ground voltage.

Only monopolar voltages have to be inserted by the MMC branches during normal operation, thus, HB-MMCs can be used. However, if some of the diode rectifier units are out of order, the dc voltage must be reduced proportionally in order to not jeopardize the healthy DR units. Moreover, since the DRs require a slightly higher off-shore ac voltage than the dc voltage to conduct, a reduction of the DC link voltage is required to continue the normal operation of the healthy DR units. As a result, the dc voltage will be lower than the amplitude of the on-shore phase-to-ground voltage and a FB-MMC will be needed.

However, FB-MMCs present higher losses than FB-MMCs. On the other hand, in contrast to FB-MMCs, HB-MMCs do not have dc-fault blocking capability [7], [8]. However, since the sum of the cell capacitor voltages within an MMC branch is equal to the pole-to-pole voltage, only half of the cells are requiered to be FB cells in order to block the pole-to-ground fault currents. Hence a trade-off solution consiting on a combination of FB and HB cells can be employed depending on the maximum reduction of the dc voltage [9].

The main aim of this work is to analyze the use of hybrid half-bridge and full bridge on-shore MML power converters for the connection of large off-shore wind farms using diode rectifiers, regarding losses and operational capability when one Diode Rectifier station is faulted. The minimum number of full-bridge cells required and the losses for different scenarios will be assessed. This study covers both the operation with symmetric and asymmetric pole voltage reduction in the event of a diode rectifier converter outage. Detailed EMT (PSCAD) simulations have been carried out to validate the control of the hybrid MMC and the theoretical results.

Therefore, this study can be used as the starting point to evaluate the impact of different on-shore MML power converter topologies regarding risk, capital and operational costs.

II. System Description

The system under study is shown in Fig. 1, where three off-shore wind power plants are connected to the HVDC cable via three 12-pulse Diode Rectifier stations. Each off-shore wind power plant comprises 27 Type-4 wind turbines rated at 5 MW

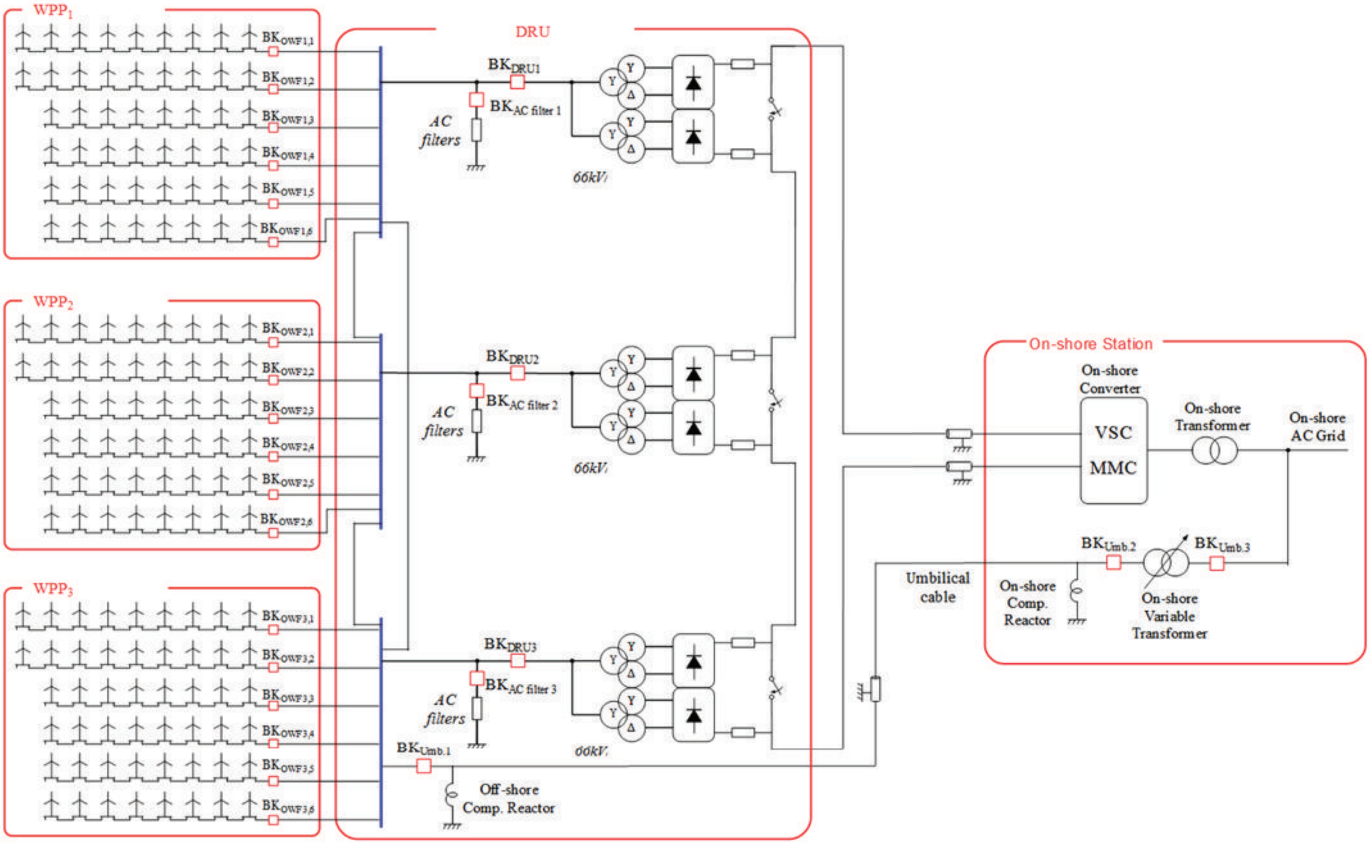

Fig. 1. Diagram of the HVDC Diode Rectifier connected Wind Power Plant

each one, totaling 400 GW aggregated power. A DC cable rated at ± 150 kV interconnects the off-shore station with the on-shore station. Each DR station also includes an ac filter and a dc disconnector to bypass the DR unit when out of service. The off-shore ac-grid has been modeled considering cables of a total capacitance of 0.03 pu.

The on-shore station interconnects the DC link with the on-shore ac grid by means of a hybrid MML converter and a transformer. The converter is connected as a symmetric monopole, so the on-shore MMC transformer does not require additional DC isolation. A zig-zag transformer located at the ac-side of the MMC is used as a grounding system for the DC link.

A. Off-shore ac-grid voltage and frequency control

Due to the use of the DR units at the off-shore station, the off-shore ac grid voltage and frequency have to be controlled by the wind turbines. The dc-link voltage of the wind turbines back-to-back converter is controlled by the machine-side converter [4], [10]. In this way, the grid side converter is free to independently control the active and reactive current references by means of traditional $d-q$ frame PI current controllers.

The off-shore grid dynamics in a synchronous frame rotating at ω_F and oriented on V_{Fd}, i.e., $V_{Fq} = 0$, can be written as:

$$\frac{d}{dt} V_{F_d} = \frac{1}{C_F} I_{F_d} - \frac{1}{C_F} I_{R_{acd}} \tag{1a}$$

$$\omega_F V_{F_d} = \frac{1}{C_F} I_{F_q} - \frac{1}{C_F} I_{R_{acq}} \tag{1b}$$

The overall WPP active current ($I_{F_d} = \sum_{i=1}^{n} I_{W_{id}}$) can be used to control the voltage magnitude of the offshore ac grid whereas the frequency can be controlled by means of the WPP reactive power current ($I_{F_q} = \sum_{i=1}^{n} I_{W_{iq}}$). Therefore, the wind turbine front-end converters act as grid-forming units.

The off-shore ac-grid voltage and frequency control loops are shown in Figs. 3 and 2 [3]. Figure 3 shows the active power and off-shore voltage control loop. When the diode rectifier is not conducting, voltage control is performed by the V_{Fd} loop. However, once the diode rectifier is conducting, I^*_{Wdi} will saturate, and then optimal power tracking will be performed by the individual wind turbine. Therefore, voltage control is only relevant during wind farm connection and during transients that lead to diode rectifier disconnection.

Figure 2 shows the frequency control loop, where the relationship between reactive power and frequency is used in order to keep a constant off-shore ac-grid frequency. A detailed description of the control strategy can be found in [3].

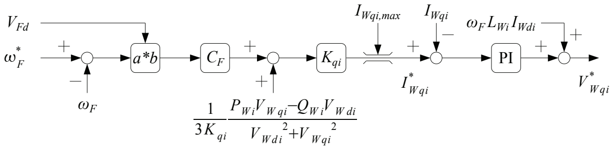

Fig. 2. Off-shore ac-grid frequency control.

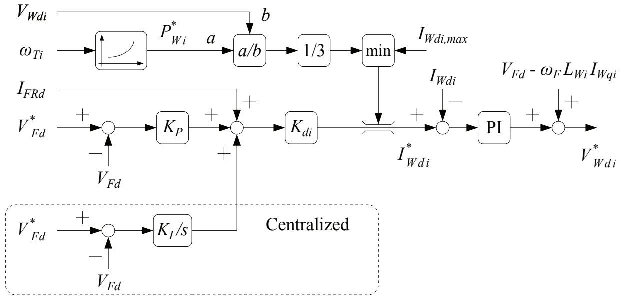

Fig. 3. Off-shore ac-grid voltage control.

III. MMC operation with reduced DC voltage

If one of the diode rectifier units is faulty, it will be by-passed by the corresponding dc-disconnector and the HVDC link will operate at a reduced voltage. Depending on the grounding system at the off-shore station and the control of the on-shore MMC, the dc voltage reduction will happen in one or both poles. Thus, the MMC can be required to operate not only with a monopolar symmetrical configuration of the HVDC link but also with an asymmetrical configuration. This voltage reduction will determine the minimum number of FB cells that are required.

A. Proportion of FB cells

The number of FB cells will depend on the dc voltage drop. To calculate the proportion of FB cells, the following positive and negative pole voltages are considered:

$$V_{dc+} = pV_{dc\_\max} \tag{2a}$$

$$V_{dc\_} = nV_{dc\_\max} \tag{2b}$$

where $V_{dc\_\max}$ is the nominal pole-to-ground voltage. The positive and negative dc pole-to-ground voltage reduction is taken into account by the indexes p and n respectively, where $0 \leq p \leq 1$ and $0 \leq n \leq 1$.

The amplitude of the ac voltage created by each arm is:

$$V_{ac} = mV_{ac\_\max} \tag{3}$$

where $V_{ac\_\max}$ is the maximum amplitude and m is the modulation index. The relationship between the maximum amplitude and the pole-to-ground voltage is:

$$V_{dc\_\max} = V_{ac\_\max} \tag{4}$$

The maximum positive dc voltage that must be inserted by each arm under normal operation, that is, rated dc pole voltages, is:

$$V_{u+} = 2V_{dc\_\max} \tag{5a}$$

$$V_{l+} = 2V_{dc\_\max} \tag{5b}$$

Similarly, the maximum negative voltage that must be inserted by each arm is:

$$V_{u-} = V_{ac} - V_{dc+} = (m-p)V_{dc\_\max} \tag{6a}$$

$$V_{l-} = V_{ac} - V_{dc+} = (m-n)V_{dc\_\max} \tag{6b}$$

The proportion of required FB cells to operate under reduced dc voltages is:

$$N_{FBu}(\%) = \frac{V_{u-}}{V_{u+}} = \frac{m-p}{2} \tag{7a}$$

$$N_{FBl}(\%) = \frac{V_{l-}}{V_{l+}} = \frac{m-n}{2} \tag{7b}$$

B. Operational limits of hybrid MMC under reduced DC voltage

HB cells can only insert positive voltages. Thus, positive and negative currents must flow through the cells in order to keep the average capacitor voltages at their rated value. Conversely, FB cells can also insert negative voltages, hence, this type of cells are able to control the capacitor voltages even if the arm current is only positive.

When the dc voltage drops below a certain value, the current through the MMC arms will be only positive and the cell capacitors will be only charged if HB cells are used. Thus, this value will set the operational limit of hybrid MMCs.

The dc power that flows through the upper and lower arms of a three-phase MMC is (P_{dc_u} and P_{dc_l} respectively):

$$P_{dc\_u} = \frac{V_{dc+}I_{dc}}{3} = \frac{nV_{dc\_\max}I_{dc}}{3} \tag{8a}$$

$$P_{dc\_l} = \frac{V_{dc-}I_{dc}}{3} = \frac{pV_{dc\_\max}I_{dc}}{3} \tag{8b}$$

where I_{dc} is the pole current.

The ac power that flows through the upper and lower MMC arms is (P_{ac_u} and P_{ac_l} respectively):

$$P_{ac\_u} = m\frac{V_{ac\_\max}I_{ac\_u}}{2} \tag{9a}$$

$$P_{ac\_l} = m\frac{V_{ac\_\max}I_{ac\_l}}{2} \tag{9b}$$

where I_{ac_u} and I_{ac_l} are the amplitudes of the ac upper and lower arm currents, respectively.

Neglecting losses, ac and dc powers must be the same.

$$\frac{pV_{dc\_\max}I_{dc}}{3} = m\frac{V_{ac\_\max}I_{ac\_u}}{2} \tag{10a}$$

$$\frac{nV_{dc\_\max}I_{dc}}{3} = m\frac{V_{ac\_\max}I_{ac\_l}}{2} \tag{10b}$$

Replacing (4) into (10):

$$\frac{pI_{dc}}{3} = m\frac{I_{ac\_u}}{2} \tag{11a}$$

$$\frac{nI_{dc}}{3} = m\frac{I_{ac\_l}}{2} \tag{11b}$$

From (11), the amplitudes of the upper and lower ac arm currents are:

$$I_{ac\_u} = \frac{2}{3m} p I_{dc} \tag{12a}$$

$$I_{ac\_l} = \frac{2}{3m} n I_{dc} \tag{12b}$$

Overall upper and lower arm currents are:

$$I_u = \frac{1}{3} I_{dc} + I_{ac\_u} \tag{13a}$$

$$I_l = \frac{1}{3} I_{dc} + I_{ac\_l} \tag{13b}$$

The voltage of HB cells can only be controlled if the arm current takes positive and negative values, that is, if the following conditions are met:

$$\frac{1}{3} I_{dc} < I_{ac\_u} \tag{14a}$$

$$\frac{1}{3} I_{dc} < I_{ac\_l} \tag{14b}$$

Replacing (12) into (14), the conditions for when only positive currents flow through the arms are obtained :

$$\frac{m}{2} > p \tag{15a}$$

$$\frac{m}{2} > n \tag{15b}$$

From the previous expressions, if the dc pole voltage reduction is larger than half the modulation index, then only unipolar currents will flow thought the HB cell capacitors and, hence, HB cells cannot be balanced in this situation. (Note that the previous analysis has been carried out when the converter operates with unity power factor).

IV. Results

The WPP described in Section II has been simulated in PSCAD and a hybrid MMC using HB and FB cells is used for the on-shore station. The parameters of the converter are shown in Table I. The hybrid MMC has been modeled using the method presented in [11]. In order to validate the theorical study, three scenarios have been considered: FB-MMC and asymmetrical operation of the HVDC link, hybrid-MMC and asymmetrical operation of the HVDC link, and hybrid-MMC and symmetrical configuration of the HVDC link.

A. FB-MMC and asymmetrical operation of the HVDC link

Fig. 4 shows the results for the operation of the FB-MMC with a reduced voltage only in the negative pole. The first trace shows the positive ($E+$) and negative ($E-$) pole voltages at the on-shore converter station terminals.

The second trace shows the currents though the upper (i_u) and lower (i_l) arms of one converter leg. The third trace is the circulating current, defined as $I_c = (i_u + i_l)/2$.

The fourth trace shows the maximum, minimum and average cell voltage of one of the negative branches (V_{cl}).

TABLE I
151-level MMC parameters.

Number of levels ($N+1$)	151
Arm inductance (L)	25 mH
SM capacitor voltage (V_c)	2 kV
Capacitance (C)	8.5 mF
Rated DC link voltage (U_{dc})	±150 kV
Rated active power	400 MW
Rated reactive power	±175 MVAr
On-shore Transformer	
Voltage	150/400 kV
Rated power	450 MVA
L_T	0.1 p.u.
R_T	0.01 p.u.

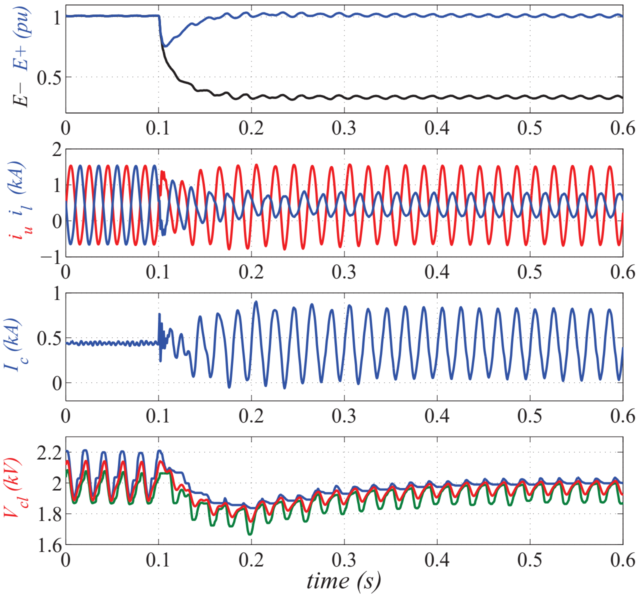

Fig. 4. Response with 100% full bridge cells

At $t = 0.1$ s one of the off-shore DR units is bypassed, thus the pole-to-pole voltage is reduced by one third. Given that only the negative pole voltage is reduced, $E-$ drops by two thirds, while the positive pole voltage is kept constant at its rated value. Therefore, the values of the indexes defined in (2) are $p = 1$ and $n = 1/3$. The negative pole voltage ($E-$) reduces from 1 pu to 0.33 pu in about 40 ms. According to (15), the current through the lower arm (i_l) is only positive, however, the cell voltages (V_{cl}) are kept at their rated value since FB cells are able to insert both positive and negative values, thus, the cell capacitors can be charged and discharged. A circulating current (I_c) among the three MMC legs is required for the arm energy control since the required upper and lower ac arm currents are different (see equation (12)). As explained previously, the main disadvantage of this configuration is its higher losses when compared to those of a half-bridge implementation.

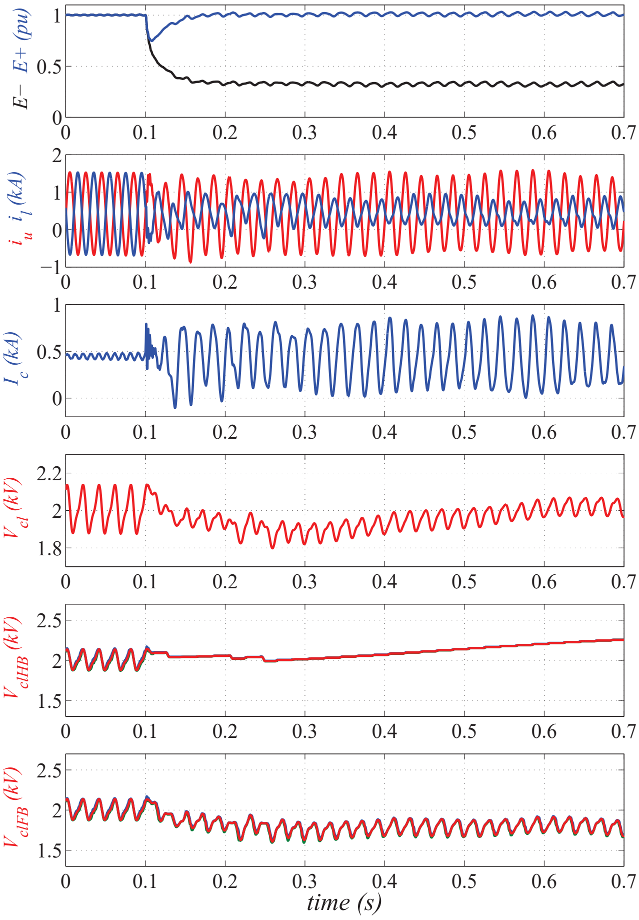

Fig. 5. Response with 35% full bridge cells and asymmetrical diode rectifier unit failure

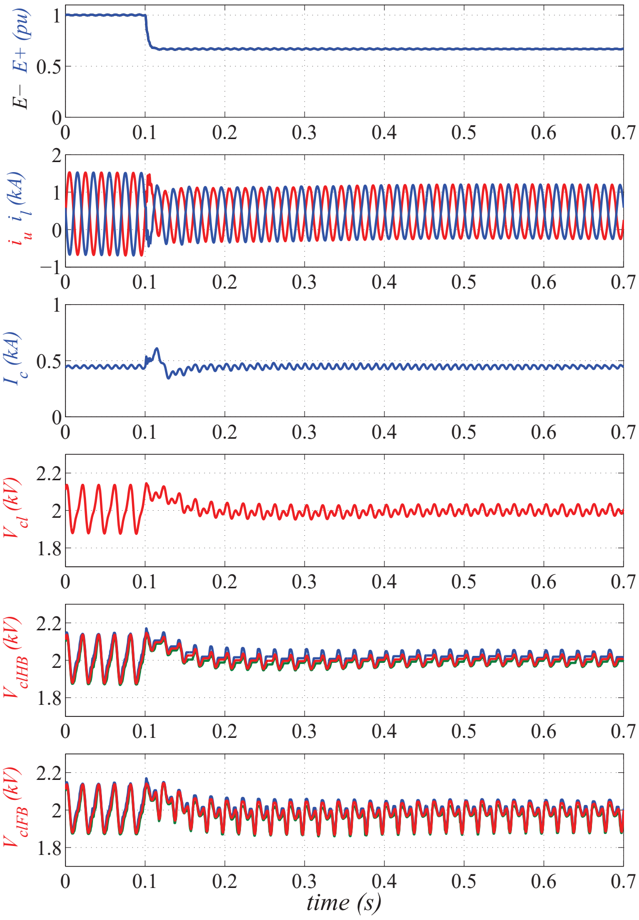

Fig. 6. Response with 17% full bridge cells and symmetrical HVDC voltage drop

B. Hybrid MMC and asymmetrical operation of the HVDC link

The results when a hybrid MMC is used are shown in Fig. 5. As in the previous case, at $t = 0.1$ s one of the off-shore DR units is bypassed, thus the negative pole voltage ($E-$) is reduced by two thirds, whereas the positive pole voltage ($E+$) is kept constant at its rated value. From (7b), the minimum proportion of FB cells in lower arms is 33.3%. At $t = 0.1$ s, negative pole voltage is reduced to 0.33 pu as a result of a DR unit becoming non-operational. According to (15), the current through the lower arm (i_l) is only positive. In this case, the arm energy control is able to keep the average capacitor voltages (V_{cl}) at their rated value. However, the HB cells can only be charged, hence, the average capacitor voltage of the HB cells (V_{clHB}) increases without control. On the other hand, the FB cells are discharged (V_{clFB}) by the branch energy control. Therefore, the operation of hybrid MMCs with such a dc voltage drop is not possible with only positive circulating currents (I_c).

C. Hybrid MMC and symmetrical operation of the HVDC link

Fig. 6 shows the results when a hybrid MMC is used, but the DR grounding is modified so voltage reduction takes place in both poles. At $t = 0.1$ s one of the off-shore DR units is bypassed but, as previously mentioned, voltage reduction in both poles is symmetrical. Note the symmetrical voltage reduction imply a change on the grounding arrangement of the DR units.

Therefore both pole voltages drop by one third ($p = 2/3$ and $n = 2/3$). From (7b), the minimum proportion of FB cells is 16.7% in both the upper and lower arms. At $t = 0.1$ s, pole voltages are reduced by 0.33 pu each, as a result of a DR unit becoming non-operational. According to (15), the current through the lower arm (i_l) takes both positive and negative values so the arm energy control is able to keep the average capacitor voltages (V_{cl}) at their rated value and the capacitor balancing control is able to keep balanced all capacitors within a branch (V_{clHB} and V_{clFB}). Now the circulating current (I_c) only presents a dc component since a symmetrical configuration of the HVDC link is used. Thus, the ac currents through the upper and lower arms are the same (see equation (12)).

V. Discussion and Conclusions

For operation with only one faulty 12-pulse diode rectifier converter (n-1 criteria), the on-shore MML power converter only requires 17% full bridge-cells, hence reducing normal operation converter conduction losses by more than 42% (i.e. almost half) with respect to the solution with 100% full bridges. In this case, the losses will be marginally larger than when using a half-bridge MML VSC station.

This solution requires that the voltage reduction is the same in both poles. Therefore, if either the top or the bottom Diode Rectifier stations are faulty, then the ground connection of the Diode Rectifier converters should be connected to the new resulting mid-voltage point.

The considered cost and loss reduction is achieved at the expense of losing the fault blocking capability offered by the full bridge MMC. However, pole-to-ground fault blocking capability can be achieved with only 50% full-bridge cells. Therefore, fault blocking capability can be kept while reducing MMC converter conduction losses by 25%. Moreover, in this latter case operation with two faulty diode rectifier units would also be possible.

Therefore, important capital and operational expense reduction can be achieved by considering that only one Diode Rectifier converter can be faulty at any given time and using a mixed half and full-bridge on-shore MML power converter.

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