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Energy Control of Modular Multilevel Converter in MTDC Grids for Wind Power Integration

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Abstract—The role of Modular Multilevel Converters (MMCs) in HVDC grid greatly differs depending on whether it is an offshore or an onshore station. From the common point in their control schemes, an unexploited ability of the MMC—the controllability of the internally stored energy—is identified in both offshore and onshore applications. The virtual capacitor control, previously proposed by the authors, makes use of this degree of freedom to provide energy contribution to the DC grid. The impact of this control is demonstrated by time-domain simulations of a five-terminal HVDC grid.

I. INTRODUCTION

HVDC technology is particularly suitable for connecting offshore wind power plants to onshore mainland grids over long distances [1]. When the offshore wind power plants grow larger and farther from the onshore grid, interconnecting several HVDC terminals to form a meshed Multi-Terminal DC (MTDC) grid becomes an attractive option [2]. Such systems offer higher reliability and availability with smaller investment compared with individual point-to-point links because they can maintain wind power transfer even if a certain line is out of service [3].

The role of a converter in an MTDC grid greatly differs depending on whether it is an offshore or an onshore station. In particular, offshore stations must regulate the offshore AC grid voltage and frequency. This function is termed grid forming and is crucial to allowing the wind generators to connect and inject generated wind power as seamlessly as they would when directly connected to a classical AC grid [4].

Earlier studies involved offshore wind power plants connection using classical two-level VSC based HVDC transmission scheme [5], [6]. However, most of the VSC-HVDC converters commercially available today are based on the Modular Multilevel Converter (MMC) [7], depicted in Fig. 1. A fundamental difference in topology between the MMC and the conventional two- or three-level VSCs can be found in the location of energy storage [8]. Since the energy is stored in the sub-modules (SMs) of MMC, its proper operation relies on the control of this energy, which is not the case with the conventional VSCs, where the DC link capacitor voltage is imposed by the bus voltage [9], [10]. This difference in the operational principle and the control scheme makes the equivalent circuit model of

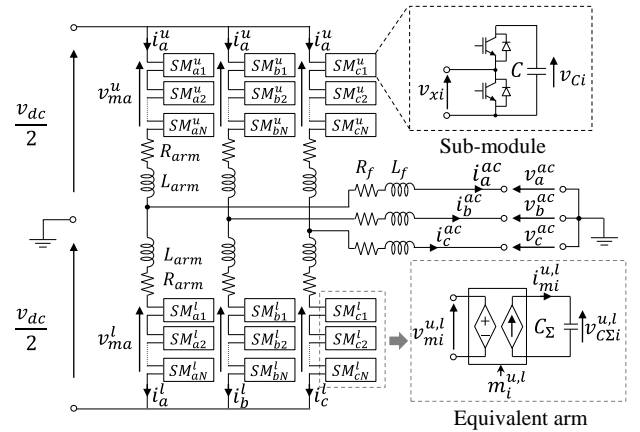


Fig. 1: Topology of three-phase MMC.

the MMC different from that of the conventional VSC [11]. However, very little attention has been paid to this feature of the MMC; thereby, the inherent capabilities of the MMC remain unexploited.

This paper analyzes the general control schemes for both offshore and onshore MMCs in order to identify the relevant degrees of freedom used to achieve desired functions. It is revealed that the internally stored energy is an available degree of freedom in both operations. Thus, the previously proposed Virtual Capacitor Control [12], which enables the MMC to improve the transient behavior of the MTDC grid by using the internal energy, can be applied to both the offshore and the onshore MMCs. The feasibility of the proposed solution is confirmed through simulations of a five-terminal MTDC grid model. The obtained results demonstrate the impact of the proposed control and highlight the novel opportunities of the energy contribution for offshore MMC stations.

II. MMC MODELLING AND FUNDAMENTAL CONTROL

In general, each arm of the MMC is composed of N series connected SMs, commonly designed as the half-bridge topology. For HVDC applications, the collective set of SMs for each arm needs to be several hundred to achieve the desired voltage rating [9]. The general behavior of an MMC arm can

be represented by its equivalent model (see Fig. 1) where it is assumed that the voltages of all the SM capacitors in each arm are balanced by a Balancing Control Algorithm (BCA) [13], so that they are collectively represented by an aggregated voltage $v_{C\Sigma i}^{u,l}$ applied to an equivalent capacitor $C_\Sigma = C/N$ [9]. The total energy stored in a single arm is thus

$$W_{\Sigma i}^{u,l} = \frac{1}{2} C_\Sigma \left(v_{C\Sigma i}^{u,l} \right)^2, \quad (1)$$

and the voltage applied on each arm, $v_{mi}^{u,l}$, can be expressed as

$$v_{mi}^{u,l} = m_i^{u,l} v_{C\Sigma i}^{u,l} \quad (2)$$

where $m_i^{u,l}$ is the modulation index which can take only in $[0, 1]$ in a half-bridge based MMC.

A. MMC Current Control

Unlike the conventional VSCs, the current control of the MMC comes down to the appropriate control of six arm voltages, which intuitively incurs more complex current control than conventional VSCs. By performing the well-known change of variables [8], the upper and lower arm voltages of a phase leg are transformed into controllable voltage quantities: an AC voltage v_m^{ac} and a DC voltage v_m^{dc} . The AC voltage governs the output current at the AC side Point of Common Coupling (PCC) whilst the DC voltage governs the common mode DC current in the phase leg. For three-phase MMC, the control of AC grid currents i_d^{ac} and i_q^{ac} is commonly achieved in dq rotating frame where an independent control of active and reactive power is possible. The control of the common mode DC currents is divided into the DC grid current i_{dc} control and the control of the circulating currents i_α^{cir} and i_β^{cir} . The DC side power exchange can be controlled by i_{dc} independent of the AC side. The circulating currents are confined to the converter legs and do not flow out of the MMC; hence, they have no impact on the connected grids nor the actual energy stored inside the MMC [14].

B. MMC Energy Balancing

For proper operation of the MMC, the energy stored in the six arms must be explicitly controlled in order not to damage the devices. It is noteworthy to state that such control is not required in the conventional VSCs where the energy stored in the DC link capacitors is imposed by the DC bus voltage. In literature, such control is split into three aspects: the total, horizontal and vertical energy balancing controls.

1) *Total energy balancing control*: When the losses in the MMC are neglected, the whole MMC can be considered as an energy buffer with total energy value W_{mmc} , whose dynamics is characterized by the difference between the DC power input and the AC power output

$$\frac{dW_{mmc}}{dt} = P_{dc} - P_{ac} = P_w. \quad (3)$$

where P_w is the mismatch between the DC power inflow and the AC power outflow. It is apparent that the internal energy of MMC can be controlled by temporarily imposing P_w .

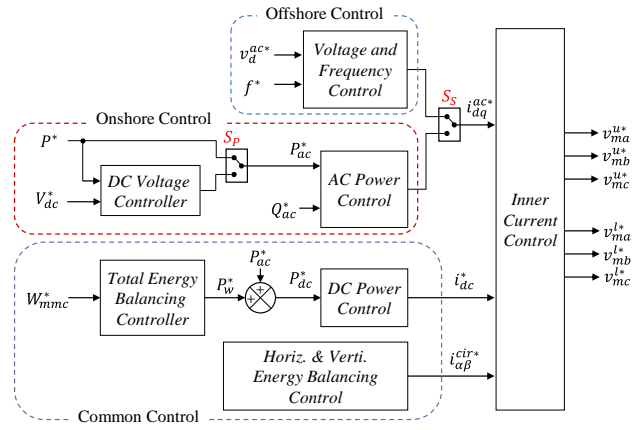


Fig. 2: Overview of outer control scheme for offshore and onshore MMC stations.

2) *Horizontal and Vertical energy balancing control*: To ensure the appropriate distribution of the energy among the converter arms, two supplemental controllers need to be implemented [10]. The horizontal energy balancing control is achieved by using the direct component of the circulating current to transfer energy from a leg with a higher energy level to lower ones. For the vertical energy balancing control, the fundamental frequency component of the circulating current is used to exchange energy between the upper and lower arms within a leg.

III. ONSHORE AND OFFSHORE MMC CONTROL

The different operational requirements between the onshore and offshore MMCs differentiate their overall control schemes. Fig. 2 illustrates the simplified generic control scheme for an MMC station. In this section, the operational requirements for both offshore and onshore applications are highlighted in order to identify the associated degrees of freedom.

In order to harvest the active power generated by the wind power plants, the offshore MMC stations are responsible for controlling the voltage magnitude and frequency of the offshore AC grid. The voltage and frequency controller is implemented, which adjusts the AC current references i_{dq}^{ac*} to the nested inner current controller according to the desired set-points of the voltage magnitude v_d^{ac*} and the frequency f^* [15].

On the other hand, it is usually the onshore stations that ensure the energy balance of the DC grid. When a power imbalance occurs, the stations participating in the voltage-droop control adjust their reference signal of the AC active power. The AC reactive power may be controlled in order to maintain the onshore AC grid voltage within the specified range. Both active and reactive power control are achieved by supplying appropriate values of i_{dq}^{ac*} to the current controller.

Therefore, i_{dq}^{ac*} (and thus P_{ac}) is used to realize different control functions depending on whether it is an offshore or an onshore station. Naturally, the control of the internal energy has to be accomplished by using the remaining available

controlled variable in (3), i.e. P_{dc} (and thus the DC grid current i_{dc}). Thus, the total energy balancing controller is nested to the DC power controller, which can be considered as a common feature shared by both onshore and offshore stations.

IV. VIRTUAL CAPACITOR CONTROL

It is a major concern for the MTDC grid operation to ensure that the DC voltage remains within an acceptable range. In fact, its rate of change in case of a sudden disturbance is determined by the electrostatic potential energy stored in the converters and the cables. However, according to the typical design specification of the MMC and the cables for HVDC applications, the amount of this energy is likely to be considerably smaller than the kinetic energy stored in the rotating mass of synchronous machines in bulk AC systems. Hence if a power disturbance of the same scale occurs, the rate of change of the DC voltage would be significantly greater than that of the frequency. As a solution to this problem, the authors previously proposed a novel control method, named Virtual Capacitor Control [12]. This control makes use of the internal energy of MMC to improve the DC voltage dynamics.

Under the virtual capacitor control, the reference signal for the total energy controller is dynamically calculated in conjunction with the variation of the DC voltage by the following formula

$$W_{mmc}^* = \frac{1}{2} k_{vc} C_{mmc} (v_{dc}^2 - v_{dc0}^2) + W_{mmc0}^* \quad (4)$$

where v_{dc0} is the set-point of the DC grid voltage and W_{mmc0}^* is the nominal level of the stored energy. A coefficient, named Virtual Capacitor Coefficient k_{vc} , is introduced as an adjustable parameter. Under this control, the MMC behaves as if there were a virtual capacitor C_{vc} on its DC side whose size is given by $C_{vc} = k_{vc} C_{mmc}$.

In practice, the emulation of the virtual capacitor dynamics only needs to change the reference signal for total energy balancing controller, which is available in both offshore and onshore converter control schemes, as explained at the end of Section III.

V. SIMULATION RESULTS

To demonstrate the impact of the contribution of offshore and onshore MMCs under the virtual capacitor control to improve the DC voltage profile, the five-terminal HVDC grid system, shown in Fig. 3, is implemented in EMTR-RV. The MTDC grid contains two offshore stations (OFSTs) and three onshore stations (ONSTs). For the sake of simplicity, all the stations are rated at 1000 MW. The wind power plants are modeled by the aggregated DFIG model of 250 MW [5]. All the onshore stations are in droop control mode with the identical droop gain of 15.625 MW/kV.

At $t = 1.0$, the power injected by ONST3 is instantly reduced to zero. Then, the dynamic response of the DC voltage as well as the power contribution of the stations are examined for four different cases summarized in Table I.

In Fig. 4, the obtained transient dynamics of the DC voltages are compared. To improve visibility, only the voltages

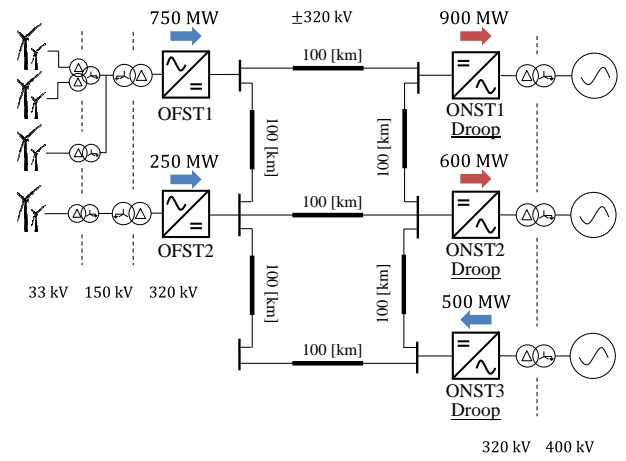


Fig. 3: Simulation setup: five terminal HVDC grid model.

TABLE I: Simulated cases.

Case	Description
1	No energy contribution is provided by the MMCs
2	Only the onshore MMC stations have $k_{vc} = 1$
3	All the MMC stations have $k_{vc} = 1$
4	All the MMC stations have $k_{vc} = 2$

measured at ONST1 are highlighted in solid lines whereas others are shown in dotted lines. As can be seen, the DC voltages in the four cases converge to the same level, i.e. 0.975 p.u.. However, their transient behavior, especially the rate of change, differ expressly. The voltage transient dynamics become visibly damped as the number of the energy contributing MMC stations increases, i.e., Case 2 and 3. Despite the same control arrangement, Case 4 shows the voltage dynamics noticeably better damped than Case 3. This implies the value of k_{vc} is an additional degree of freedom which can greatly affect the DC voltage transient dynamics.

In Fig. 5, AC active power of each stations are shown. In response to the abrupt change of the active power injection through ONST3, the droop embedded stations, i.e. ONST1 and 2, adjust their AC power withdrawal to compensate for

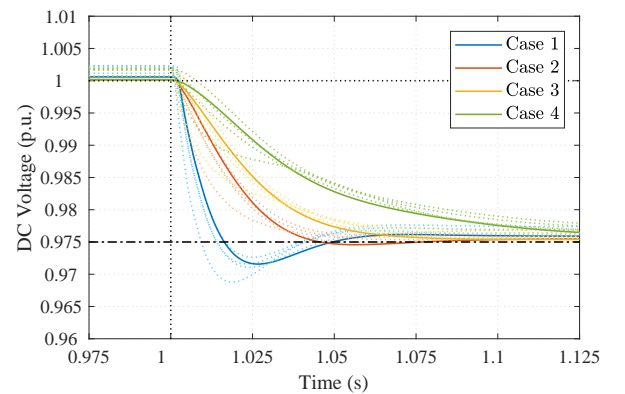


Fig. 4: Comparison of the simulation results: DC voltage.

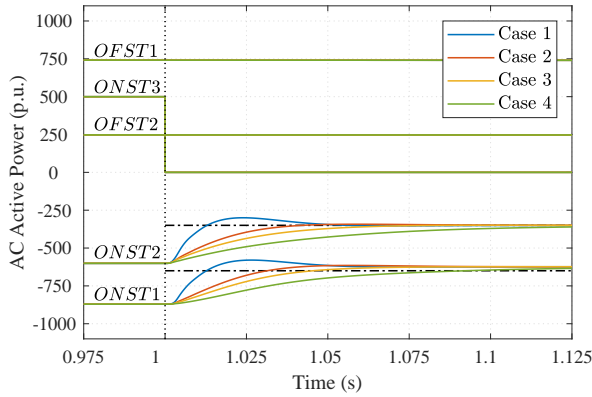


Fig. 5: Comparison of the simulation results: AC power.

the power deficit. It can be noticed that, although their power converges to the same steady-state level in the four cases, there are apparent differences in transient. Since the droop controller associates the AC power reference with the DC voltage, the DC voltage dynamics directly affects the AC power dynamics. As the DC voltage transient becomes more damped, the AC power variations become less steep, alleviating the stress on the connected AC grid. Meanwhile, no visible change of AC power is observed in the offshore stations, i.e. OFST1 and OFST2. This proves the capability of the offshore MMC stations under the virtual capacitor control to provide energy contribution without having any adverse effect on the offshore AC grids.

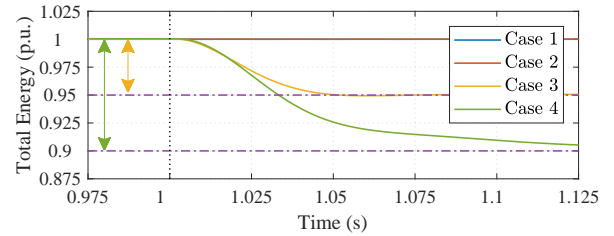
Fig. 6 shows the MMC total energy of OFST1 and ONST1. A clear relation between the studied cases can be observed. When the virtual capacitor control is activated, i.e. $k_{vc} > 0$, the MMC provide energy contribution at the expense of variations of the internal energy level. As seen, the deviation becomes larger as the value of k_{vc} increases. This means that the degree of energy contribution can be readily adjusted by simply changing this coefficient, which can be wisely chosen for different MMCs by taking into account their relative ratings.

VI. CONCLUSIONS

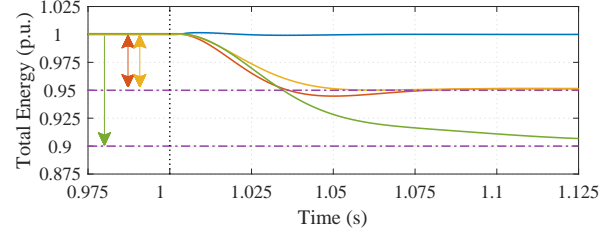
A comparison between the offshore and onshore control designs have been made to identify the associated degrees of freedom. It has been revealed that there are common parts in the outer control design for both applications, and the reference signal to the total energy W_{mmc}^* is a degree of freedom available for both. The virtual capacitor control makes use of this degree of freedom to provide energy contribution to the DC grid. Through this control, the offshore MMC stations evacuating wind power can provide energy contribution without disrupting the offshore AC grids. The impact and applicability of the proposed control have been demonstrated by simulations of a five-terminal HVDC grid on EMTP-RV.

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(a) OFST1



(b) ONST1 and 2

Fig. 6: Comparison of the simulation results: Total energy.

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