Autonomous Control Based on Capacitor Energy Storage of Converter for DC Distribution System

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ABSTRACT The converter valve is the core equipment of the DC distribution systems. This paper proposes an autonomous control strategy for grid-connected and islanded operation of hybrid topology modular multilevel converter (MMC). The overall control structure is designed, including the outer loop for autonomous control and the inner current loop. Firstly, for the outer loop, it is proposed to use the equivalent capacitance storage energy of MMC power module to simulate the inertia of synchronous generator rotor to achieve the purpose of buffer power fluctuation. So, the outer loop provides system inertia. Second, the inner loop is designed for current tracking control and suppresses transient fault current effectively. It is proposed that the current inner loop reference value can be directly calculated through the grid-connected impedance matrix and voltage across it. And the small signal model of autonomous control for a hybrid MMC is established. Then the influence of the proposed control structure and control parameters on the impedance characteristics of the system is analyzed in detail. Finally, a hybrid MMC simulation model for DC distribution system is built based on PSCAD, simulating island operation, grid-connected operation mode and transient faults respectively for verifying the proposed strategies.

INDEX TERMS Autonomous control, hybrid MMC, full-half bridge, DC distribution.

I. INTRODUCTION
The DC distribution system has been rapidly developed in the past two years after the VSC-HVDC (Voltage Source Converter Based High Voltage Direct Current) transmission technology. It has the advantages of facilitating the access of DC power equipment and new energy power generation systems, as well as high controllability and flexibility. It has become one of the new academic and engineering research hotspots. A lot of theoretical research and some demonstration engineering constructions have been performed. For example, there is a four-level AC/DC hybrid power distribution system proposed by the CPES Center of Virginia Tech University [1]. And a 10kV DC network started in 2014 by the University of Aachen, in Germany and so on [2]. In China, the AC/DC hybrid micro grid demonstration project of Zhejiang Shangyu was put into operation in Aug. 2017, and the “Smart Energy Demonstration Project” in Zhuhai is being planned, etc. [3]. The core units of DC distribution network include distributed generation, energy storage system, DC transformer and converter. It can provide grid-connected interface for new energy, increase access ratio of wind power and photovoltaic power, and supply power to DC load. Its voltage level has not yet been clearly defined. For this, CIGRE established SC6.31 “DC Distribution Feasibility Study” in Jul. 2015 to research and promote medium-voltage DC distribution network technology. It is preliminarily considered that the voltage level range of distribution is reasonable between 1.5 and 100 kV [4], [5]. The voltage level covers a wide range and can support the access of DC microgrid to form a wide-area DC distribution system. So, its control technology is relatively complex, and its operation mode is more flexible and diverse. Usually, the hierarchical control structures are adopted, at least including two layers, top and bottom. The top layer includes the optimal scheduling, output and load forecasting of the distributed generation system in the network, and network loss optimization. The bottom layer control is mainly the converter control technology, which realizes the tracking control of the power, voltage amplitude and frequency of the network node, also including the conversion...
between isolated and grid-connected operation. The bottom layer control corresponds to the function of converter control in VSC-HVDC system, but its control function is more complicated.

Autonomous control synchronizes with the grid without phase-locked loop (PLL), such as virtual synchronous generator (VSG), droop control and virtual impedance etc., highlighting the autonomous operation characteristics of converters, and is especially suitable for the design of DC distribution network converter control structure. It includes the advantages of grid forming operation, smooth switching between islands and grid-connected operations, and improving AC system stability etc. The VSG control, droop control, virtual impedance control and other ones to achieve the grid forming operation can be classified as autonomous control. In [6], [7], the response characteristics of converter droop control and virtual inertia control strategy are compared under power step and grid frequency variation conditions. It illustrates that virtual inertia method is suitable for implementing autonomous operation of the converter and there are smaller overshoot and slower frequency change rate during system dynamic processes. At present, most of the literatures are also based on VSG algorithm and its improved strategy. Papers [8]–[10] design the active power control loop of the converter to simulate the active-frequency inertia of the synchronous generator. It does not depend on the PLL in steady-state operation. However, its current inner loop is designed based on the AC side LC output filter of the two-level converter. For the modular multi-level converter (MMC) station, the reactor is directly connected to the grid, and this kind of current inner loop control structure cannot be directly applied. In [11], transfer function of converter grid-connected system based on VSG control strategy is established, and the voltage feedforward link is designed to effectively reduce the grid-connected harmonics. In [12], based on the VSG control structure, a cooperation control strategy based on center of inertia (COI) is proposed for multi-terminal DC networks, which can suppress power oscillation. In [13], the control modes of converters need to switch frequently between island and grid-connected. The droop control and VSG strategy are combined to dynamically improve power tracking characteristics with little overshoot, and without control structure converting. In [14], [15], the mechanism of dynamic coupling between active and reactive power control loop of the converter based on VSG strategy is analyzed. During the pre-synchronization of the converter to the grid, dynamic decoupling of active power and reactive power is realized. In [16], energy storage characteristics of the capacitor in the converter are utilized to design the DC voltage outer loop and simulate the inertia of the generator. The same idea is also used in [17], which provide inertia by using DC-side capacitor energy storage, and at the same time, the PLL is used to realize the self-synchronization function of the converter connected to the grid. But it may affect system stability when the converter is connected to a weak AC system.

The above literatures provide a detailed analysis of the VSG outer control loop, but less for the inner current loop. For this, in papers [18] the active current and synchronous phase command is calculated by the VSG control loop. In paper [19] the synchronous phase command is generated by the inner current loop. Direct control of the current is realized. But they are used for wind turbine converter and supplying to passive loads. For grid-connected applications, PLL may be needed. Further, in [20]–[22], the virtual impedance control link is designed, connected in series behind the outer VSG control loop. The current through the virtual impedance can be calculated by the converter output voltage and the grid voltage directly, being as the current inner loop command signal. But in this kind of control structure additional active and reactive power decoupling control needs to be added, especially for weak AC systems. The power angle is considered as coupling term and the decoupling control amount is superimposed in the modulation signal [23]. But the decoupling performance is affected by the voltage crossing virtual impedance. And a method based on voltage compensation of reactive power control loop is proposed to improve decoupling performance [24]. In [25], [26], the control structure of AC voltage and current inner loop is used to achieve direct current control. And it is connected with outer control loop based on VSG strategy. It is a multi-loop control structure, which is relatively complicated. In [27], without current references, voltage compensation components are calculated by output current and virtual impedance, and in [28] peak current control method is proposed. They can limit the transient fault current, but cannot achieve steady-state current tracking control.

In summary, the existing research results mainly use the VSG control strategy to realize autonomous operation of the converter. They provide detailed analysis and simulation verification for the inertia simulation of the synchronous machine and the design of the current inner loop. However, most of the existing research results are based on two-level converters. For larger DC distribution networks, the voltage level is usually high (≥10 kV and above), so the MMC topology is usually adopted. The full-half-bridge hybrid topology MMC can eliminate transient DC faults and is suitable for DC distribution network applications. It is quite different from the two-level converter [29]. There is relatively little research on the grid autonomous control of MMC, especially for hybrid topologies. In this paper, the DC distribution system based on hybrid topology MMC is introduced in the second part. Then for the third part, a VSG control structure based on MMC capacitor energy storage is proposed, and the impedance characteristics of this control structure are analyzed. It can maintain autonomous synchronization with the power grid and shows that the low frequency characteristics of the system is mainly affected by the outer capacitor energy storage control loop (autonomous control loop). Finally, the transient and steady-state simulations of the converter are carried out. Compared with traditional control methods, it shows that the proposed autonomous control method can provide transient inertia support and improve system stability.
II. HYBRID MMC-BASED DC DISTRIBUTION NETWORK

The typical two-terminal DC distribution network structure is shown in Fig. 1. It includes AC power, wind power, DC microgrid and AC load, form a 5-terminal network structure. There are 5 ports T1-T5, with T1 and T3 being full-half bridge hybrid MMC. The system has the following engineering significance: (1) It is beneficial to the distributed generation of photovoltaics and wind turbines connecting with grid; (2) In the DC side fault, the T1 and T3 converters can clear transient DC system faults which improves system stability; (3) The architecture can supply power to the DC load, or it can supply power to the AC load through the inverter.

![FIGURE 1. Configuration of DC distribution.](image)

The hybrid MMC topology for T1 and T2 is shown in Fig. 2 (Another hybrid topology composed of thyristor-based converter valve and MMC is not considered in this paper [30], and this type of topology is usually used in DC transmission systems with higher voltage levels.). Its six MMC bridges are composed of a certain proportion of half-bridge units and full-bridge units. The full-bridge power unit can achieve permanent DC fault isolation and transient DC fault ride-through. DC breakers and DC fuses can be used as backup protection. Because of the low average switching frequency of the full-half bridge hybrid topology, the converter valve loss is about equivalent to the converter valve of the half-bridge topology.

In the figure, \(U_{ij}(j=a,b,c)\) is the three-phase AC voltage of valve side, and \(I_{ij}\) is the three-phase AC current, and \(V_{dc}\) is the DC side voltage, and \(I_{dc}\) is the DC current, and \(L_0\) is the bridge arm reactance. Each bridge is composed of \(N_h\) half bridge power units and \(N_f\) full bridge ones connected in series. Since the full-bridge power units can output a negative voltage, the ratio of the full-bridge unit mainly affects its DC fault-clearing capability. The ratio of full and half bridge units in one phase can be selected as 50%.

III. AUTONOMOUS CONTROL OF HYBRID TOPOLOGY MMC

A. VIRTUAL INERTIA PART OF AUTONOMOUS CONTROL

For converters in DC distribution networks, droop control and VSG control can achieve their grid forming operation. In this paper, the VSG control idea is adopted to simulate the synchronous generator inertia with the MMC sub-module capacitor energy storage. But it is different form VSG control and not completely equivalent to the generator control characteristics. The inner current loop control is reserved to avoid the low frequency oscillations in the traditional AC system. As shown in Fig. 3, \(P_S\) is the AC side input power of the converter, and \(P_E\) is the output power, which corresponds to the mechanical shaft input power \(P_M\) and the electromagnetic power \(P_{AC}\) of the synchronous generator, respectively. \(C_{eq}\) is the MMC equivalent capacitance, which corresponds to the rotor inertia of the generator. Eq. (1) can be obtained from rotor motion equation of the generator and the above correspondence.

\[
\begin{align*}
P_M - P_{AC} - D_\omega (\omega - \omega_n) &= J_\omega \frac{d\omega}{dt} \\
P_S - P_E - D_v (v_{v_{\Sigma}}^* - v_{\Sigma}) &= C_{eq} v_{\Sigma} \frac{dv_{\Sigma}}{dt}
\end{align*}
\]

where \(v_{v_{\Sigma}}^*\) is the reference value of the sum of the capacitor voltages of all submodules, and \(v_{\Sigma}\) is the actual value of it. \(D_\omega\) and \(D_v\) are the damping coefficients of the synchronous generator and the converter, respectively.

![FIGURE 3. Principle of converter simulate generator inertia.](image)
The equivalent capacitance is shown in Eq. (3).

\[ 6N \frac{1}{2} C_{SM} v^2 = \frac{1}{2} C_{eq} V^2_{dc} \]  

(2)

where the \( C_{SM} \) is capacitance of one sub-module capacitor, and \( N \) is the number of sub-modules in one arm. Assuming that the capacitance values are consistent, then \( v_c = V_{dc} / N \).

The equivalent capacitance is shown in Eq. (3).

\[ C_{eq} = \frac{6}{N} C_{SM} \]  

(3)

In addition, the capacitor voltage of the MMC sub-module in Eq. (1) corresponds to the angular frequency of the generator. That is, the change of \( v_c \) reflects the fluctuation of output power. The input and output power are balance in steady state, and capacitor voltage is constant. And during transient sub-module capacitance of MMC can buffer power fluctuations. In order to simulate the inertia of the generator, it is necessary to establish the relationship between \( v_c \sum \) and \( \omega \). Here, it is proposed to make the submodule capacitor voltage average value and VSG rotation speed be linear relationship, which is \( \omega = \frac{1}{\sqrt{6}} v_c \sum \). So, there is Eq. (4).

\[ C_{eq} v \sum \frac{dv_c}{dt} = C_{eq} k^2 \frac{d\omega}{dt} = J \frac{d\omega}{dt} \]  

(4)

From Eq. (4), \( J = C_{eq} k^2 \). The range of \( k \) is determined by the allowable operating range of submodule capacitor voltage. The outer loop control structure of the converter can be obtained from the above equations as shown in Fig. 4. In the figure, \( \theta \) is the phase of AC voltage vector of converter side. The active control loop adjusts the angular frequency of the converter output voltage based on the average value of the capacitor voltages of all sub-modules. For example, when the average value of the module voltage is less than the given value, it indicates that sub-module capacitor energy storage has converted into transient power support to grid. It is helpful for the grid to maintain frequency stability. Then the capacitor voltage controller \( k \) output angular frequency adjustment \( \Delta \omega \). And the phase of the MMC output voltage vector is changed by the integral link \( 1/s \) to maintain the active power balance between the MMC AC and DC sides. The energy buffer characteristics of the sub-module capacitors provide inertia for the grid. And the capacitor voltage in the steady state will be slightly lower than the rated value. The phase difference between the AC voltage vector of the converter and the grid voltage vector will increase, stabilizing at the new operating point. After that, other power sources or energy storage devices may inject power into this converter from the DC network, and the voltage of the sub-modules in this converter will gradually recover, which can continuously provide greater inertia support power to the AC system, equivalent to increasing the system’s moment of inertia.

The reactive power control loop is similar to the synchronous generator excitation controller. The reactive power output is controlled by adjusting the amplitude of the AC voltage. \( Q_{ed} \) and \( Q \) are reactive power reference and feedback values, respectively. \( K_Q \) is the proportional coefficient of reactive power controller, whose output is the AC voltage amplitude adjustment amount \( \Delta V_{ac} \) of MMC, and \( V_{ac0} \) is the rated AC voltage. The phase angle \( \theta \) and the amplitude \( V_{amp} \) calculated above are connect with the inner control loops to obtain converter voltage control signals \( V_d \) and \( V_q \) in synchronous rotating coordinates. During a transient DC fault, the DC voltage will quickly drop to 0, the capacitor voltage control loop (\( V_{eq}^2 \)) in Fig. 4 can maintain the active power balance of the converter valve AC and DC side.

According to the hybrid MMC grid-connected circuit structure, in the synchronous rotating dq coordinate system, the AC side voltage and current relationship is obtained as shown in Eq. (5):

\[ \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} -R_L & \omega L_0 \\ -\omega L_0 & -R_L \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} U_{sd} - V_{cd} \\ U_{sq} - V_{cq} \end{bmatrix} \]  

(5)

where \( \omega = \omega_0 + \Delta \omega \), and \( R_L \) is the equivalent resistance of the MMC AC side reactor. From Eq. (5), there is a linear relationship between the three vectors, grid voltage, MMC AC side voltage, and grid-connected impedance. So, the AC current reference signal can be directly calculated by the MMC AC grid impedance matrix as shown in Eq. (6):

\[ \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} -R_L & \omega L_0 \\ -\omega L_0 & -R_L \end{bmatrix}^{-1} \begin{bmatrix} U_{sd} - V_{cd} \\ U_{sq} - V_{cq} \end{bmatrix} \]  

(6)

Thus, the converter current inner loop control structure is obtained as shown in Fig. 5.
In this figure, the phase angle used in the coordinate transformation, and the dq axis voltages $V_{cd}$ and $V_{cq}$ of the converter are all calculated from the outer loop of the autonomous control in Fig. 4. In Fig. 5, a conventional current closed-loop control structure based on a PI regulator is used for the inner current loop itself. $I_{dref}$ and $I_{qref}$ are the active current and reactive current reference values, $i_d$ and $i_q$ are their feedback values respectively. $U_{sd}$ and $U_{sq}$ are the grid voltage dq axis components, respectively. It can be seen from the autonomous control structure in Fig. 4 that the voltage of the sub-module in the dynamic process will fluctuate, and there is no direct closed-loop control for the DC voltage in the system. In order to ensure that the DC bus voltage of the distribution network is basically constant, avoid excessive fluctuations in the transient process, and improving the power quality of it, the DC bus voltage closed-loop control can be realized by using the free variable, the total number of sub-modules with on-state of the upper and lower arms. As shown in Fig. 5, $V_{dcref}$ is the reference value of DC voltage, and its feedback $V_{dc}$ are connected with P or PI controller which outputs the common mode component $V_{dc, com}$ of the modulated signals. That is the DC component of the modulated signals, superimposed with the AC modulation signals of six arms. So, DC voltage control is realized by directly changing the DC component of the bridge arm output voltage. In Fig. 5 $V_j (j=a,b,c)$ is three-phase AC control signal, added with the DC voltage control loop output signal $V_{dc, com}$. Finally, $V_{ju}$ and $V_{jn}$ (j=a, b, c) are the upper and lower arm control signals respectively.

It can be known from the above control structure that the voltage of the MMC sub-module is independent of the DC voltage control, which is different from the traditional half-bridge MMC control method. The total number of sub-modules with on-state in the upper and lower arms of each phase during dynamic process is no longer constant. It can be used as free variable of controlling DC voltage. The sub-module capacitor voltage sum, that is, the bridge arm energy storage, directly reflects the AC and DC side power balance. The control variables of active loop adjust the phase of output voltage vector, which is similar to the power angle adjustment of traditional generators and realizes active power dynamic control. The above control strategy is used for the full half-bridge hybrid topology, which can facilitate the rapid clearing and riding through of transient DC faults. When the short-circuit fault occurs in the DC bus of the distribution network (the DC voltage is too low and the DC current is over-current), the DC component of the upper and lower arms modulation signals can be directly set to 0 to suppress the DC short-circuit current from rising. After the fault clearing (DC current is low), the DC voltage is raised according to a given slope to avoid an impact when recovering.

**B. STABILITY ANALYSIS**

In order to analyze the stability of the proposed control strategy, it is necessary to establish the state equation of the whole system, including the control part and the MMC main circuit part. The angular frequency state equation is obtained from power the balance relationship between AC and DC side of the MMC in steady-state. State equations (7) and (8) can be obtained from Eq. (1) and the structure of outer control loop in Fig. 4.

$$C_{eq}v_{d\Sigma} \frac{dv_{d\Sigma}}{dt} = P_S - P_E = \frac{3}{2}(U_{sd}i_d + U_{sq}i_q) - P_{DC} (7)$$

In the equations, “d” represents differential. The $P_{DC}$ is the output power on the DC side of the converter. In steady state, $v_{d\Sigma} = V_{dc}$ can be brought into Eq. (7) and simplified as Eq. (8).

$$\frac{dv_{d\Sigma}}{dt} = \frac{3}{C_{eq}}(U_{sd}i_d + U_{sq}i_q) - P_{DC} (8)$$

Definition $\delta$ is the angle between the converter side voltage vector and the grid voltage vector of the synchronous rotating coordinate, as shown in Fig. 6.

**FIGURE 6. Valve side and grid side voltage vector in synchronous rotating coordinate.**

Under the synchronous rotation coordinates of the valve side voltage vector orientation ($V_{cd} - V_{eq}$ as the coordinate axis), $V_{cd} = V_0$, $V_{eq} = 0$, and there is $P_E = V_0 \cdot i_0$ in steady state. The dq axis component of the grid voltage under the rotating coordinate of Fig. 6 is

$$\begin{align*}
U_{sd} &= E \cdot \cos \theta \\
U_{sq} &= -E \cdot \sin \theta 
\end{align*} (9)$$

From Fig.4 and Fig.5, the state equations of the control system are shown as Eq. (10):

$$\begin{align*}
d\theta &= \frac{1}{k}(v_{eq}^2 - v_{d\Sigma}^2) + \omega_0 \\
dv_{amp} &= K_Q \cdot (Q_{ref} - Q) (10)
\end{align*}$$

where $Q$ is reactive power feedback value. It can be calculated with Eq. (11).

$$Q = E \cdot \cos \theta \cdot i_d + E \cdot \sin \theta \cdot i_d (11)$$

From the impedance analysis in the next paragraph, it can be seen that the outer loop parameters determine the low-frequency characteristics of the system, and the current inner loop determines the high-frequency characteristics of it. Therefore, the current inner loop can be ignored when studying the autonomous control characteristics of the system. Finally, considering constant transmission power of the converter DC side, linearize Eq. (5), (8) and (10), and the system small-signal state equations are obtained as Eq. (12):

$$dX = AX (12)$$
TABLE 1. System parameters.

| Parameter | Value |
|-----------|-------|
| AC voltage | 10 kV |
| DC voltage | ±10.5 kV |
| Sub-module capacitance | 18 mF |
| Arm reactance | 6 mH |
| Rated capacity | 30 MW |

where

\[
X = \begin{bmatrix}
\Delta V_c^2 \\
\Delta V_{amp} \\
\Delta \theta \\
\Delta i_d \\
\Delta i_q
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
3U_{sd0} \\
0 \\
0
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
-1 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
V_{cp} \\
sL0 \omega_0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

In matrix \(X\), \(\Delta\) stands for small disturbance, and subscript 0 represents the steady state value. Let the rated working point of the converter be as shown in Table 1.

Consider that the virtual inertia coefficient \(k\) of the capacitor voltage average control loop varies from 10 to 100, with the step size being 10, and the integral coefficient \(K_Q\) of reactive power control loop takes a fixed value of 0.15. The system eigenvalues change as shown in Fig. 7 (a). The arrow in the figure points to the direction of the eigenvalues changing. As the parameter \(k\) increases, the eigenvalues 3 and 4 move to the left half plane, while the 1 and 2 move to the right half plane. So, excessive \(k\) value will cause system instability. Then, consider the reactive control loop integral coefficient \(K_Q\) variation range 0.15-1.5, changing step size being 0.15. The eigenvalues 3 and 4 move a small amount, and 1 and 2 move quickly to the left half plane. However, the eigenvalue 5 moves to the right half plane. Based on the above eigenvalues variation law, \(k\) can be selected as 40, and \(K_Q\) is 0.75 to ensure the rapid response of the system and a certain stable boundary.

C. IMPEDANCE ANALYSIS

The system transfer function matrix can be derived from the small signal state Eq. (12) and the inner current loop also included. In order to facilitate the calculation of system impedance, the dq axis modulation signals \(u_{1} = [\Delta V_{sd} \ \Delta V_{cq}]\), and the phase of AC voltage vector \(u_{2} = \Delta \theta\) of converter side, are selected as input variables. The dq axis current of the converter \([\Delta i_d \ \Delta i_q]\) and the square of capacitance voltage \(\Delta V_c^2\) are as output variables. The system transfer function is simplified as Eq. (13).

\[
\begin{align*}
\Delta i_d &= B_4 (M_0 B_0 + B_1) \cdot u_2 + B_4 B_2 \cdot u_1 \\
\Delta i_q &= B_4 B_2 (M_0 B_0 + B_1) \cdot u_2 + B_3 \cdot u_1 \\
\Delta V_{amp} &= k_Q \Delta Q \\
\Delta i_{dref} &= \frac{1}{sL_0} (U_{sd0} \cdot \Delta \theta - \Delta V_{amp}) \\
\Delta i_{qref} &= \frac{1}{sL_0} (U_{sd0} \Delta \theta - 0) \\
\Delta V_{sd} &= PI \cdot (\Delta i_{dref} - \Delta i_d) \\
\Delta V_{cq} &= PI \cdot (\Delta i_{qref} - \Delta i_q)
\end{align*}
\]

In the equation:

\[
A_1 = \begin{bmatrix}
-R & \omega_0 \\
\omega_0 & -R \\
0 & 0
\end{bmatrix}, \quad B_0 = \begin{bmatrix}
-i_{d0} \\
-i_{q0} \\
0
\end{bmatrix}, \quad B_1 = \begin{bmatrix}
\frac{U_{sd0}}{sL_0} \\
\frac{-U_{sd0}}{sL_0}
\end{bmatrix}
\]

\[
B_2 = \begin{bmatrix}
-1 & 0 \\
0 & 0
\end{bmatrix}, \quad B_3 = \begin{bmatrix}
\frac{3U_{sd0}}{C_{eq}^5} \\
\frac{3U_{sd0}}{C_{eq}^5}
\end{bmatrix}
\]

\[
M_0 = \frac{3}{C_{eq}^5} (U_{sd0} i_{d0} - U_{sd0} i_{q0}), \quad B_4 = (I - A_1 - B_0 B_2), \quad PI = k_{cp} + \frac{k_{ci}}{s}
\]

It is a two-input two-output linear system. In the equation, \(k_{cp}\) and \(k_{ci}\) are the proportional and integral coefficients of the current regulator. The system small signal transfer function
structure is obtained from linearization equations (13) as shown in the Fig. 8.

From Fig. 8, we can get the system impedance model under the proposed control strategy. Take the impedance $z_{dd}$ between $\Delta V_{cd}$ and $\Delta i_d$ as an example, the impedance characteristic of $z_{dd}$ shown in Fig. 9. Furthermore, the theoretical impedance curve of $J = 6$, $J = 60$, $J = 600$ ($J = C_{eq} \cdot k^2$) is drawn as shown in Fig. 10.

According to the theoretical derivation and impedance scanning results, from Fig. 9, it can be seen that the system has an inductive characteristic in the high frequency region ($> 300$Hz), which is similar to the traditional double closed-loop control strategy. The proposed virtual inertia control method mainly affects the impedance of the system in the low-frequency region. From Fig. 10, it can be seen that the moment of inertia mainly affects the position of the impedance zero/pole on both sides of 50Hz. As the moment of inertia $J$ increases, the position of the impedance zero/pole on both sides of 50Hz will move to 50Hz point.

**IV. SIMULATION AND ANALYSIS**

In order to verify the proposed MMC autonomous control strategy, a full-bridge-half-bridge hybrid MMC model in DC distribution network is built based on PSCAD. Taking the DC network voltage as the control target, the inner and outer loop control structures of Fig. 4 and Fig. 5 are used. The outer active power loop imitates the generator inertia, and the inner current control loop tracking its given value. There are 12 sub-modules in series for each arm, including 6 half bridge modules and 6 full bridge ones. The grid voltage is 10kV, and DC rated voltage $\pm 10kV$, rated power 30 MW, reactance of arms 5mH. In the simulation, the AC phase voltage peak and the AC current peak are used as the reference value to normalize the system, and the active power is normalized by system rated capacity. And the controller parameters are determined by the aforementioned small signal analysis. The simulation is carried out for the off-grid operation and the grid-connected mode respectively, to verify that the designed autonomous control structure can simultaneously adapt to all the operating modes of distribution networks. First, the AC side of the converter is connected to the passive load that is islanding operation. When $t=1.5$ s, a 5 MW load is connected to the AC side of the system, and the load step changes to approximately 25 MW at $t=3$ s. The simulation results are shown in Fig. 11. The variable label “1” in the figure is the output waveform of the conventional double closed-loop control method used for the hybrid topology MMC, and the output waveform with label “2” is of the autonomous control strategy. Fig. 11 (a) and 11 (b) are
waveforms of tracking the given values for the active power and d-axis (active axis) current of the converter. As shown in the conventional control strategy, there is an oscillation process after the converter is unlocked and during the power step rise, which is a weak damping characteristic, and the active current deviates from the expected value at steady state. For the autonomous control strategy, due to the virtual inertia of the system, the transient active power oscillation process can be eliminated. At the same time, with the inner current loop, the d-axis current reference is quickly tracked during the transient process, and there is no steady-state error. Fig. 11(c) is the frequency response during power step change. Compared with traditional control methods, MMC capacitors release inertia energy, which can speed up frequency recovery during transients. So, the virtual inertia generated by the MMC capacitor helps the system transient frequency recovery.

Secondly, verify the grid-connected operation characteristics of the converter autonomous control. At $t=4s$, the active power step changes from 0MW to 30 MW. The simulation results are shown in Fig. 12. Fig. 12(a) shows the d, q-axis current waveform. The d, q-axis current reference values ramp up due to the inertial characteristics of the autonomous control during the step. Current feedback $i_d$ and $i_q$ track
their given values throughout the dynamic process. Fig. 12(b) shows the valve AC voltage rotation angular velocity increment $\Delta \omega$ which is the output of the capacitor voltage control loop, and the valve AC voltage phase (angle). As shown in the figure, the outer loop characteristics of autonomous control are similar to those of the synchronous generator. When the output power increases, the generator will increase the output of the prime mover and the rotor will accelerate. For the converter, the valve side voltage rotation speed will be increased, and the phase difference will be increased between the valve side and grid side voltage vector. This can adjust the output power of the converter for tracking the given value. Fig. 12(d) shows the DC voltage and angular frequency curves during the power rise. The DC voltage and the angular frequency of AC voltage deviate slightly from the rated value to achieve energy buffering and return to the rated value at steady state.

Finally, DC short-circuit current suppression capability of the hybrid MMC under the autonomous control strategy is verified. At $t=8s$, there is a DC bipolar short-circuit fault, and it is cleared after 100 ms. The simulation results are shown in Fig. 13, where the Fig. 13 (a) shows the DC voltage and current waveform during the short circuit. And Fig. 13 (b) shows the dq axis current references and feedbacks, with small fluctuations in current feedback during the DC fault. Fig. 13(c) shows the sum of arm capacitor voltages of the converter upper arms ($V_{aus}$, $V_{bus}$, $V_{cus}$ corresponding to the upper arm of A, B and C phase). And the waveform of the lower arm is symmetric with it. Based on the control strategy shown in Fig. 4, the energy buffer characteristics of sub-module’s equivalent capacitance is used to simulate the generator inertia, this causes the bridge arm capacitor voltage to rise slightly during the transient process. Fig. 13(d) shows the three-phase upper arm current ($I_{au}$, $I_{bu}$, $I_{cu}$) of the converter. During the DC fault, the DC voltage control loop rapidly reduces the DC component of the modulated signal, so, the DC voltage output is close to 0. This suppresses the DC short-circuit current from rising, and ensures that the bridge arm current fluctuates within the allowable range, thereby realizing the transient DC fault clearing function.

V. CONCLUSION

A converter autonomous control structure based on MMC capacitor energy storage is proposed. And additional inner current loop was added for improving the current control capability. It can suppress current fluctuations and realizes transient DC fault ride through. By analyzing the impedance of the system, it can be seen that an appropriate value of $J$ can maintain positive impedance characteristic at the low frequency part of the system. It can avoid the low frequency oscillation among multiple converters in the DC distribution network.

For the island operation mode, the comparison of simulation results between the traditional control and the autonomous control strategy shows that the proposed control method can effectively suppress the current oscillation when the load step changing in the DC network. For DC short-circuit faults, the hybrid topology MMC can use the DC voltage control loop to quickly reduce the DC output voltage of the converter and suppress the rise of the short-circuit current. In summary, autonomous control technology applied to hybrid topology MMC is suitable for DC distribution network, with advantages such as DC fault clearing capability, providing certain inertia for DC network and so on. It has broad application prospects in DC distribution networks with high proportion of power electronic equipment and large amount of new energy integration.
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