

Low voltage ride-through control of MMC valve in large-scale wind power systems based on transformer load forecasting

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Abstract

INTRODUCTION: This paper investigates a fault ride-through control strategy for modular multilevel converter (MMC) based converter valves under low-voltage ride-through (LVRT) requirements in large-scale wind power transmission. **OBJECTIVES:** To develop an enhanced LVRT control integrating hierarchical voltage balancing, dual-loop current control, and Transformer-based feedforward for improved dynamic response. **METHODS:** Positive-/negative-sequence dual current inner-loop controller designed. Hierarchical submodule capacitor voltage balancing proposed. Transformer load forecasting using self-attention dynamically corrects active power reference. **RESULTS:** Typhoon HIL validation under single-phase ground fault shows: negative-sequence current suppressed >90%; submodule capacitor voltage deviation decreases from 10% to 4.5%; circulating current effectively eliminated. **CONCLUSION:** The strategy meets LVRT requirements in large-scale wind power transmission applications.

Keywords: Modular Multilevel Converter, Negative-Sequence Current Control, Low Voltage Ride-Through, Circulating Current Suppression, Self-Attention Mechanism, Transformer-based Load Forecasting

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1. Introduction

As wind power integrates into power systems, its influence on grid stability has become ever more pronounced. Large-scale wind power projects are often sited at considerable distances from main load centers, necessitating high-voltage direct current (HVDC) transmission to enable long-distance, high-capacity energy transfer. HVDC transmission employing modular multilevel converter (MMC) offers advantages such as a modular architecture, reduced switching losses, and superior output waveform quality [1]. These advantages have made it a crucial solution for offshore wind power transmission and large-scale onshore renewable energy integration [2].

According to grid regulations, wind turbines must have low-voltage ride-through (LVRT) capability, ensuring they remain operational and connected to the grid during voltage dips to facilitate system restoration [3]. However, when asymmetric faults occur in the AC grid, the MMC experiences unbalanced voltage conditions. This leads to several issues, including negative-sequence currents, double-frequency active power oscillations, exacerbated arm circulating currents, and sub-module capacitor voltage imbalances [4-6]. In severe cases, this may result in converter valve blocking or even equipment damage. Pursuing MMC control strategies tailored to LVRT conditions is of paramount importance [7,8].

Researchers worldwide have conducted ongoing, in-depth studies on unbalanced control and LVRT technologies for

MMC [9,10]. Regarding LVRT control, some scholars have proposed an LVRT strategy for MMC-based photovoltaic grid-connected systems using model predictive control [11]. This method predicts and adjusts step by step. It reduces circulating currents and maintains a steady DC-side output. In doing so, it balances AC and DC transmission—a trait that is uncommon among today's control techniques. In circulating-current suppression, a recent approach eliminates the need for arm current sensors [12]. It then enables control in the abc stationary frame, raising system reliability. Other scholars have proposed a composite circulating-current control strategy that combines quasi-PR control with virtual impedance to suppress both second-order and higher-order harmonics [13,14]. In the context of sub-module capacitor voltage balancing, some studies have addressed transient overvoltage issues during grid fault emulation [15–17]. They proposed an enhanced sub-module capacitor energy-balancing control method to maintain capacitor voltage stability during faults [18].

In large wind power systems, random changes in AC load and the unpredictable nature of renewable energy sources make balancing DC power more difficult. This raises the performance standards for low-voltage ride-through (LVRT) functionality in power electronic switching assemblies. If load or power variation trends can be predicted in advance, the converter valve's control commands can be adjusted proactively before voltage dips occur. This improves dynamic response performance during fault ride-through [19].

In recent years, transformer models have demonstrated superior performance in time series forecasting, thanks to their self-attention mechanism [20–23]. These advantages include parallel computing capability and modeling of long-term patterns. Each time point's information receives a distinct level of importance. On its own, it can pinpoint which time steps and inputs matter most for producing a correct forecast. A lot of recent work employs the transformer and attention techniques for wind power and load prediction [24]. These methods work better than older ones. Introducing feedforward prediction techniques into LVRT control can further improve the system's proactive adaptability.

To meet LVRT requirements in large-scale wind power integration scenarios, a comprehensive fault-ride-through strategy is developed. First, the power characteristics of MMC under unbalanced voltage are derived. A current controller is built to reduce negative-sequence currents and limit power swings. Also, a step-by-step method is used to maintain balanced voltages across the submodule capacitors. This includes inter-phase, inter-arm, and intra-arm balancing, which keep voltage stable during LVRT. Based on this foundation, a method using a transformer model to predict load over a brief period is introduced. It works like a feedforward auxiliary loop, shifting the active power setpoint on the fly. Hardware-in-the-loop (HIL) simulation is used to test whether the proposed strategy works when a single line touches the ground and causes a fault. Protection recommendations for severe phase-to-phase short-circuit faults are also provided [25].

2. Low voltage ride-through rules

When more wind power is added to the grid, connecting wind farms has a stronger impact on stability. Early on, wind power output was small. So during a grid fault, turbines would simply disconnect to stay safe. Large wind farms can change how power flows where they tie into the grid. That is why new grid rules now require LVRT. Under these rules, turbines must keep running when the voltage dips and stay on until the fault is cleared.

2.1. LVRT technique

In 2009, China established a test rule for integrating wind energy into the grid. This rule provided simple instructions on how wind turbines should handle low voltage situations. Figure 1 shows that if the voltage at the wind farm's grid connection point drops to 20% of its normal value, the wind turbines must remain connected to the grid for 625 milliseconds and must not stop operating. The grid-connection voltage of a wind farm shall recover to at least 90% of its normal level within 2 seconds of a fault occurring. During this period, wind turbines must remain connected to the grid. In addition, when a wind farm remains connected to the grid during a fault, its active power must return to the level prior to the fault. Once the fault has been cleared, the power should increase by at least 10% of its rated value per second.

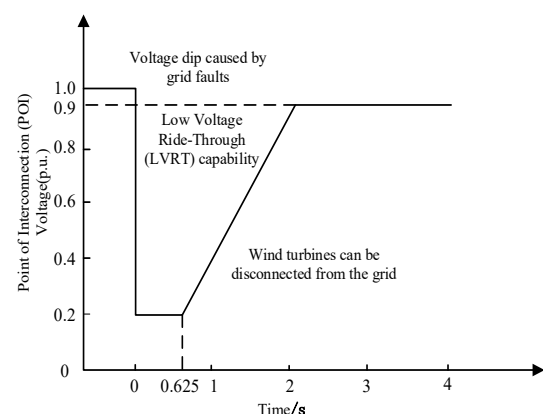


Figure 1. LVRT standard stipulated

Whenever a doubly-fed induction generator (DFIG) is directly connected to an AC grid, a voltage drop may cause excessive current on the motor's rotor side. This can cause an increase in the DC voltage and oscillations in the converter current. This occurs because the stator flux cannot keep up with the sudden voltage change, resulting in the generation of a DC component. At the same time, the rotor continues to rotate, increasing slip and inducing overvoltage and overcurrent in the rotor circuit. If the fault is asymmetric, negative-sequence components worsen the phenomenon. In severe cases, this may damage the converter or the rotor windings.

2.2. Contribution of flexible HVDC transmission to LVRT

In a basic, flexible HVDC setup with two ends, if the AC grid on the inverter side loses voltage, the wind turbines cannot deliver all their power. This can cause a power imbalance on the DC side and lead to an increase in DC voltage. If no chopping or power derating measures are taken, the wind turbine risks tripping.

A multi-terminal flexible HVDC system has several converter stations that can help control power. This setup makes it easier for the system to keep power balanced. The system uses a method that links DC voltage with active power. When a voltage drop occurs at a converter station, others can automatically adjust their transmission power. Consequently, the active power generated by the wind turbines can still be successfully transmitted, thereby avoiding overvoltage and overcurrent on the rotor side and enabling low-voltage operation without relying on chopping circuits or power derating control.

Consequently, from the AC side, meeting low-voltage needs in flexible HVDC systems depends not only on the wind turbines' own control. More importantly, the whole system must coordinate power and keep the grid's voltage steady. Multi-terminal flexible DC systems provide wind farms with a more robust low-voltage operation solution through coordinated coordination across stations.

3. MMC model formulation

3.1. MMC topology

The MMC is the main structure used in flexible DC converter valves. The ability to balance the voltage across submodule capacitors directly affects the system's transient response characteristics during low-voltage operation, thereby laying the groundwork for future research on fault-ride-through control strategies.

In Figure 2, $u_k(k=a,b,c)$ represents the equivalent electromotive force of phase k . R_{AC} and L_{AC} are the resistance and reactance on the AC side. R_0 and L_0 represent the resistance and reactance in each arm. U_{dc} and I_{dc} refer to the DC voltage and current. The layout is balanced, with three phases and six branches. Each branch connects N submodules(SMs) in a row.

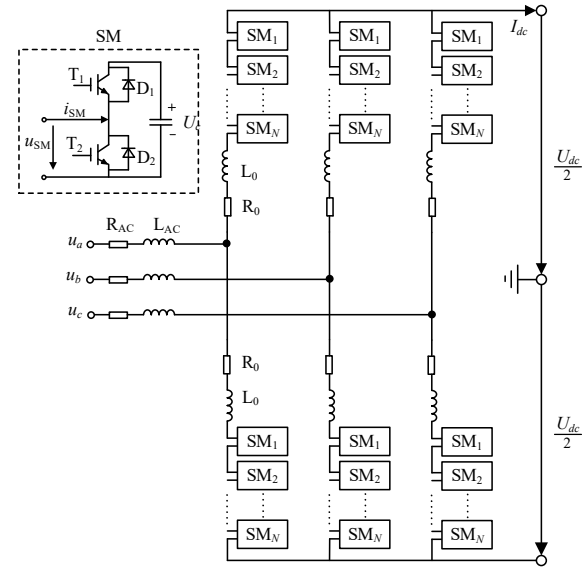


Figure 2. Equivalent circuit diagram of the modular multilevel converter

The internal structure of an MMC sub-module is shown within the dashed box in Figure 2. Each sub-module contains two series IGBTs and a parallel capacitor. The positive directions of sub-module voltage and current are indicated in Figure 2, where i_{SM} and u_{SM} represent the current flowing into the sub-module and the sub-module output voltage, respectively. The sub-module has the following four operating states:

- (1) If $i_{SM} > 0$ and T_1 is on while T_2 is off, the current moves through D_1 to charge the capacitor. The voltage from the sub-module is the same as the voltage across the capacitor, and the sub-module is inserted into the circuit.
- (2) If $i_{SM} > 0$ and T_1 is off while T_2 is on, the current flows out via T_2 , and does not go through the capacitor. The sub-module's output voltage is 0, so it is bypassed.
- (3) If $i_{SM} < 0$ and T_1 is on while T_2 is off, the capacitor discharges via T_1 . the voltage from the sub-module matches the capacitor's voltage, so the sub-module is inserted into the circuit.
- (4) If $i_{SM} < 0$ and T_1 is off while T_2 is on, the current flows out via D_2 , bypassing the capacitor. The output voltage is zero, and the sub-module is in bypass mode.

Therefore, during MMC operation, maintaining a constant number N of inserted sub-modules per phase keeps the DC voltage constant, i.e., $U_{dc} = NU_c$.

3.2. MMC mathematical model

Controlling the modular multilevel converter requires understanding its operating principles. Based on its equivalent circuit, a mathematical model was developed in a three-phase frame. In this frame, the voltage and current of the modular multilevel converter exhibit sinusoidal variations, making it impossible for the controller to maintain system

stability without error. If the Parker transformation is applied, the model is converted to the dq rotating frame. With the grid voltage as the reference, the active and reactive currents become stable DC values. Then a PI controller follows the output current fast. To facilitate the analysis of the MMC, the definitions of grid voltage and current are given in equations (1) and (2):

$$\begin{cases} u_{sa} = u_m \sin(\omega t) \\ u_{sb} = u_m \sin\left(\omega t - \frac{\pi}{3}\right) \\ u_{sc} = u_m \sin\left(\omega t + \frac{\pi}{3}\right) \end{cases} \quad (1)$$

$$\begin{cases} i_{sa} = i_m \sin(\omega t - \varphi) \\ i_{sb} = i_m \sin\left(\omega t - \frac{\pi}{3} - \varphi\right) \\ i_{sc} = i_m \sin\left(\omega t + \frac{\pi}{3} - \varphi\right) \end{cases} \quad (2)$$

Modeling under abc stationary coordinates

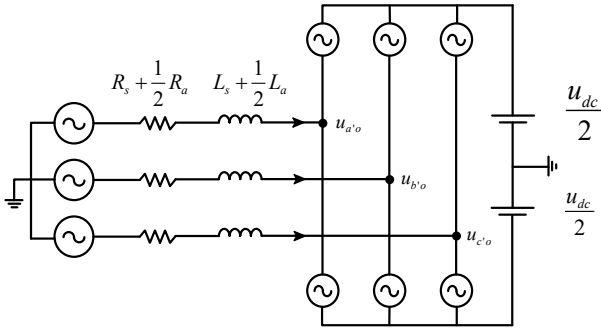


Figure 3. Topology diagram of the MMC model

It is necessary to establish the relationship between the equivalent AC point of the MMC $u_{a'o}$, $u_{b'o}$, $u_{c'o}$ and the output current. The output current and the controlled voltages $u_{a'o}$, $u_{b'o}$, $u_{c'o}$ are used to create a suitable controller that manages how much current the MMC outputs.

Figure 3 shows the MMC's equivalent circuit, where the arms' inductance and resistance are represented on the grid side. It is important to note that the equivalent connection points $u_{a'o}$, $u_{b'o}$, $u_{c'o}$ between the MMC and the AC grid are not physically present. They are derived by considering the arm inductances and resistances reflected to the grid side. As labeled in Figure 3, u_{sa} , u_{sb} , u_{sc} are the voltages on the grid side; i_{sa} , i_{sb} , i_{sc} are the corresponding currents. The grid-side equivalent inductance and resistance are $L_s + L_a/2$ and $R_s + R_a/2$, respectively. For the MMC, its AC phase voltages are $u_{a'o}$, $u_{b'o}$, $u_{c'o}$, and the DC-side voltage is u_{dc} .

For the MMC tied to the grid, voltage and current satisfy:

$$\begin{cases} u_{sa} = u_{a'o} + \left(L_s + \frac{1}{2}L_a\right) \frac{di_{sa}}{dt} + \left(R_s + \frac{1}{2}R_a\right) i_{sa} \\ u_{sb} = u_{b'o} + \left(L_s + \frac{1}{2}L_a\right) \frac{di_{sb}}{dt} + \left(R_s + \frac{1}{2}R_a\right) i_{sb} \\ u_{sc} = u_{c'o} + \left(L_s + \frac{1}{2}L_a\right) \frac{di_{sc}}{dt} + \left(R_s + \frac{1}{2}R_a\right) i_{sc} \end{cases} \quad (3)$$

Let $s_{ijk}(t)$ be the switching function of a sub-module, where $i = A, B, C$ (phase), $j = p$ (upper arm) or n (lower arm), and $k = 1, \dots, N$ (sub-module index in the arm). Then the MMC's AC-side phase voltages $u_{a'o}$, $u_{b'o}$, $u_{c'o}$ can be expressed as:

$$\begin{cases} u_{a'o} = \frac{1}{2}(u_{an} - u_{ap}) = \sum_{i=1}^N s_{ani}(t)E - \sum_{i=1}^N s_{apt}(t)E \\ u_{b'o} = \frac{1}{2}(u_{bn} - u_{bp}) = \sum_{i=1}^N s_{bni}(t)E - \sum_{i=1}^N s_{bpt}(t)E \\ u_{c'o} = \frac{1}{2}(u_{cn} - u_{cp}) = \sum_{i=1}^N s_{cni}(t)E - \sum_{i=1}^N s_{cpt}(t)E \end{cases} \quad (4)$$

The resulting mathematical model in the ABC stationary frame is composed of equations (3) and (4).

dq rotating reference frame model

As discussed earlier, in the ABC stationary frame, the MMC's three-phase output voltages and currents vary sinusoidally with time. This time-varying nature complicates both analysis and controller design. Then, the model built in the stationary frame is converted via the Park transformation to the dq rotating frame, enabling us to study the MMC's control characteristics in two-phase coordinates.

Under the constant-magnetomotive-force principle, the vector sum of voltage and current stays the same before and after Park transformation. The Park matrix is given by:

$$\begin{cases} u_{a'o} = \frac{1}{2}(u_{an} - u_{ap}) = \sum_{i=1}^N s_{ani}(t)E - \sum_{i=1}^N s_{apt}(t)E \\ u_{b'o} = \frac{1}{2}(u_{bn} - u_{bp}) = \sum_{i=1}^N s_{bni}(t)E - \sum_{i=1}^N s_{bpt}(t)E \\ u_{c'o} = \frac{1}{2}(u_{cn} - u_{cp}) = \sum_{i=1}^N s_{cni}(t)E - \sum_{i=1}^N s_{cpt}(t)E \end{cases} \quad (5)$$

Equation (4), when transformed by equation (5), yields the following MMC mathematical model in the two-phase dq frame:

$$\begin{cases} u_{sd} = u_{d'o} + \left(L_s + \frac{1}{2}L_a\right) \frac{di_{sd}}{dt} + \left(R_s + \frac{1}{2}R_a\right) i_{sd} - \omega \left(L_s + \frac{1}{2}L_a\right) i_{sq} \\ u_{sq} = u_{q'o} + \left(L_s + \frac{1}{2}L_a\right) \frac{di_{sq}}{dt} + \left(R_s + \frac{1}{2}R_a\right) i_{sq} + \omega \left(L_s + \frac{1}{2}L_a\right) i_{sd} \end{cases} \quad (6)$$

In equation (6), u_{sd} and u_{sq} are the dq-frame equivalents of the grid-side voltages u_{sa} , u_{sb} , u_{sc} ; similarly, $u_{d'o}$ and $u_{q'o}$ are derived from the grid-side voltages $u_{a'o}$, $u_{b'o}$, $u_{c'o}$, while i_{sd} and i_{sq} are derived from the grid currents i_{sa} , i_{sb} , i_{sc} . Here, $\omega = 2\pi f_s$ is the grid angular frequency, with f_s being the grid voltage frequency.

Equation (6) gives the MMC model in the two-phase rotating frame. Converting it into the complex frequency domain yields the transfer function that takes $u_{d'o}$ and $u_{q'o}$ as inputs and outputs i_{sd} and i_{sq} :

$$\begin{cases} i_{sd} = \frac{-u_{d'o} + u_{sd} + \omega(L_s + \frac{1}{2}L_a)i_{sq}}{(L_s + \frac{1}{2}L_a)s + (R_s + \frac{1}{2}R_a)} \\ i_{sq} = \frac{-u_{q'o} + u_{sq} - \omega(L_s + \frac{1}{2}L_a)i_{sd}}{(L_s + \frac{1}{2}L_a)s + (R_s + \frac{1}{2}R_a)} \end{cases} \quad (7)$$

The block diagram of the transfer function model of equation (7) is shown in Figure 4.

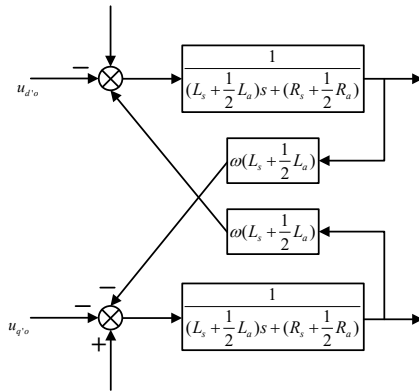


Figure 4. MMC transfer function block diagram in the dq frame

From Figure 4, we see that the MMC's transfer function in dq coordinates represents a standard two-input, two-output system, with coupling between the two inputs $u_{d'o}$ and $u_{q'o}$. When regulating the MMC's output current, if i_{sd} and i_{sq} are not decoupled, we cannot achieve independent control of them. Specifically, $u_{d'o}$ influences i_{sd} , but $u_{q'o}$ also affects it; likewise, $u_{q'o}$ controls i_{sq} , while $u_{d'o}$ also has an effect.

4. Fault ride-through control strategy

4.1. Negative-sequence current suppression control

The MMC enables independent regulation of both active and reactive power. In addition, the stability of the DC bus voltage in an HVDC system is directly influenced by its power balance. During LVRT, the grid voltage may experience asymmetric sags, which generate negative-sequence components. In such cases, the control objectives of the MMC extend beyond maintaining grid connection to also

suppressing the impact of negative-sequence currents on the system. Hence, we must deeply analyze how power is exchanged between the MMC and the AC system.

In a three-phase system with no neutral line, after performing the Clark transformation, the instantaneous power theory gives the following expression for active power at the converter bus in the $\alpha\beta$ stationary frame:

$$P_s = u_{sa}i_{sa} + u_{sb}i_{sb} + u_{sc}i_{sc} = \frac{3}{2}(u_{s\alpha}i_{s\alpha} + u_{s\beta}i_{s\beta}) \quad (8)$$

In this expression, $u_{s\alpha}$ and $u_{s\beta}$ are the voltage variables in stationary coordinates, and $i_{s\alpha}$ and $i_{s\beta}$ are the corresponding current variables.

When an unbalanced condition occurs on the AC side of the MMC, the system's voltage and current will contain both positive-sequence and negative-sequence components.

$$\begin{cases} u_{s\alpha} = u_{s\alpha}^+ + u_{s\alpha}^- \\ u_{s\beta} = u_{s\beta}^+ + u_{s\beta}^- \\ i_{s\alpha} = i_{s\alpha}^+ + i_{s\alpha}^- \\ i_{s\beta} = i_{s\beta}^+ + i_{s\beta}^- \end{cases} \quad (9)$$

Substituting these components into the active power expression yields:

$$P_s = \frac{3}{2}(u_{s\alpha}^+i_{s\alpha}^+ + u_{s\beta}^+i_{s\beta}^+) + \frac{3}{2}(u_{s\alpha}^-i_{s\alpha}^- + u_{s\beta}^-i_{s\beta}^-) + \frac{3}{2}(u_{s\alpha}^+i_{s\alpha}^- + u_{s\beta}^+i_{s\beta}^-) + \frac{3}{2}(u_{s\alpha}^-i_{s\alpha}^+ + u_{s\beta}^-i_{s\beta}^+) \quad (10)$$

Transforming equation (10) into the generalized synchronous rotating coordinate system gives:

$$P_s = \frac{3}{2}(u_{sd}^-i_{sd}^+ + u_{sq}^-i_{sq}^+ + u_{sd}^+i_{sd}^- + u_{sq}^+i_{sq}^-)\cos 2\omega t + \frac{3}{2}(u_{sq}^-i_{sd}^+ + u_{sd}^-i_{sq}^+ - u_{sd}^-i_{sq}^+ - u_{sq}^-i_{sd}^+)\sin 2\omega t + \frac{3}{2}(u_{sd}^+i_{sd}^+ + u_{sq}^+i_{sq}^+) + \frac{3}{2}(u_{sd}^-i_{sd}^- + u_{sq}^-i_{sq}^-) \quad (11)$$

The superscripts + and - indicate the positive and negative sequence parts, and subscripts d and q correspond to the rotating-frame d - and q -axis components. The instantaneous reactive power is then given by:

$$Q_s = \frac{3}{2}(u_{sq}^+i_{sd}^- + u_{sd}^-i_{sq}^+ - u_{sd}^+i_{sq}^- - u_{sq}^-i_{sd}^+)\cos 2\omega t + \frac{3}{2}(u_{sq}^-i_{sd}^+ - u_{sd}^-i_{sq}^+ + u_{sd}^+i_{sq}^- - u_{sq}^-i_{sd}^+)\sin 2\omega t + \frac{3}{2}(-i_{sq}^+u_{sd}^+ + i_{sd}^+u_{sq}^+) + \frac{3}{2}(i_{sq}^-u_{sd}^- + i_{sd}^-u_{sq}^-) \quad (12)$$

Equations (8) to (12) show that by canceling the unbalanced current from asymmetric faults, we can keep the three phase currents balanced. So in our dual-loop control, we set the outer-loop's target for that unbalanced current to zero.

As a result, the inner-loop's active and reactive parts of that current both become zero. This means we have achieved the suppression goal.

4.2. Sub-module capacitor voltage balancing control

During LVRT, voltage sags lead to a redistribution of energy within the arms, which exacerbates the voltage

fluctuations of sub-module capacitors. If left uncontrolled, this may trigger overvoltage protection, resulting in converter valve blocking. Therefore, hierarchical capacitor voltage balancing control is a crucial component of the LVRT strategy. This paper adopts a hierarchical control structure to achieve capacitor voltage balance across phases, between arms, and within each arm.

Inter-phase capacitor voltage balancing control

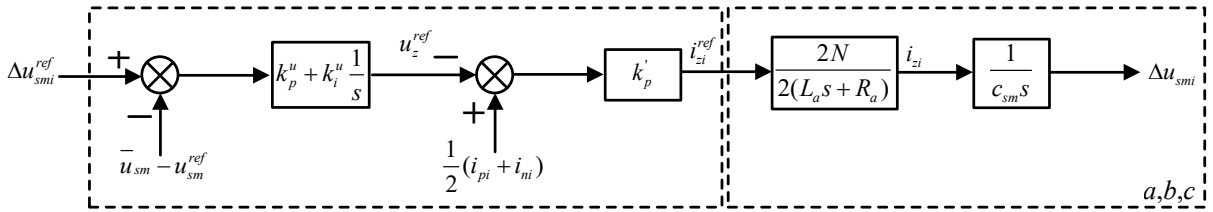


Figure 5. Inter-phase capacitor voltage balancing among sub-modules.

Figure 5 presents the inter-phase balancing control scheme for sub-module capacitor voltages. The outer-loop PI control forces the phase's average sub-module voltage $\bar{u}_{sm}$ of the phase to follow its rated value u_{sm}^{ref} . Here, the rated sub-module voltage equals the average of all sub-module voltages in that phase. Define circulating current $i_z = (i_p + i_n)/2$. Then the average sub-module capacitor voltage relates to the circulating current via:

$$\begin{cases} \bar{u}_{sm} = \frac{1}{6N} \sum_{i=1}^3 \sum_{j=1}^{2N} u_{smij} \\ i_z = \frac{1}{2} (i_n + i_p) \end{cases} \quad (13)$$

The inter-phase capacitor voltage's PI loop outputs i_z^{ref} , which serves as the setpoint for that phase's circulating current control. Adjusting the current from the DC link into the arms changes the phase's input power, thereby controlling the average arm voltage.

Phase-to-phase voltage balancing employs circulating current control as its inner loop. A proportional controller is used here to improve the response speed of the inner-loop current control. On the AC side, the MMC's grid voltage is half of the upper arm voltage minus the lower arm voltage. Since the circulating current control keeps arm voltages in sync, the voltage at the AC connection point remains unchanged. Therefore, phase-to-phase balancing has no effect on the grid current. This balancing strategy redistributes energy among the three phases of the MMC while also maintaining power and state of charge (SOC) balance among the power units within the energy storage system.

Inter-arm capacitor voltage balancing control

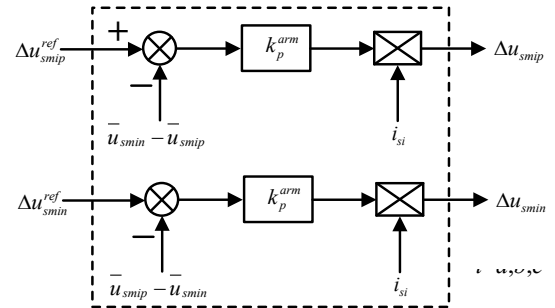


Figure 6. Capacitor voltage balancing control for sub-modules across arms

Figure 6 shows a balancing scheme for average capacitor voltages between the two arms within a phase. The average values for the arms are given as, respectively:

$$\begin{cases} \bar{u}_{smip} = \frac{1}{N} \sum_{j=1}^N u_{smij} \\ \bar{u}_{smin} = \frac{1}{N} \sum_{j=N+1}^{2N} u_{smij} \end{cases} \quad (14)$$

In the figure, $\bar{u}_{smip}$ denotes the upper arm's average sub-module capacitor voltage, $\bar{u}_{smin}$ denotes the lower arm's average, and i_s stands for the phase grid-connected current.

The control goal is to balance these two arm voltages, i.e., $\Delta u_{smip}^{ref} = \Delta u_{smjn}^{ref} = 0$

Because the grid current goes through both the arms in equal magnitude but opposite directions (each arm carries $0.5 i_s$), the inter-arm voltage balancing scheme adjusts power flow into the arms by redistributing this grid current within them. This control adds symmetric voltage corrections to the two arms and, under steady-state conditions, does not alter the AC-side output voltage.

Intra-arm capacitor voltage equalization for sub-modules

Figure 7 presents a control block diagram for balancing capacitor voltages across sub-modules. Here, $i = a, b$ and c indicates the phase. This balancing scheme enables active power exchange among modules within a single arm, so that sub-module capacitor voltages u_{smij} level out and its rated value u_{sm}^{ref} .

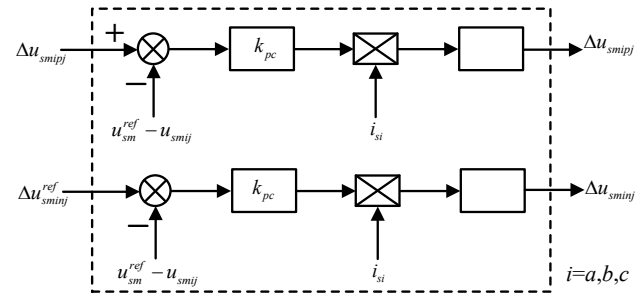


Figure 7. Block diagram of capacitor voltage balancing among sub-modules

Let the reference direction of grid-connected current i_s be positive. Then i_{sp} flows in the same direction as i_s , whereas i_{sn} flows opposite to i_s . The control logic based on the current direction and submodule voltage deviation is shown in Table 1:

Table 1. Capacitance-voltage balancing control logic

Grid-Connected Current Direction	Arm	Current Direction and Charging	Voltage Comparison	Insertion Time Variation	Capacitor Voltage Variation
$i_s > 0$	Upper Arm	$i_{sp} > 0$	$u_{smij} > u_{sm}^{ref}$	Decrease	Decrease
			$u_{smij} < u_{sm}^{ref}$	Increase	Increase
	Lower Arm	$i_{sp} < 0$	$u_{smij} > u_{sm}^{ref}$	Increase	Decrease
			$u_{smij} < u_{sm}^{ref}$	Decrease	Increase
$i_s < 0$	Upper Arm	$i_{sp} < 0$	$u_{smij} > u_{sm}^{ref}$	Increase	Decrease
			$u_{smij} < u_{sm}^{ref}$	Decrease	Increase
	Lower Arm	$i_{sp} > 0$	$u_{smij} > u_{sm}^{ref}$	Decrease	Decrease
			$u_{smij} < u_{sm}^{ref}$	Increase	Increase

Overall, the current-direction-aware sub-module balancing control successfully handles a range of voltage imbalances, keeping all sub-module capacitor voltages near their rated value u_{sm}^{ref} .

4.3. LVRT control assisted by transformer-based load forecasting

In the aforementioned LVRT control strategy, the MMC responds only after a voltage dip has occurred. This passive response may not be sufficient to address severe power mismatches caused by sudden load changes or wind power fluctuations. In large-scale wind power transmission systems,

random AC load variations combined with strong wind power intermittency exacerbate DC-side power mismatches. If we can use predictive tools to anticipate changes in load or power before voltage dips occur, we can adjust converter valve commands in advance. This allows the system to enter a better operating state before a fault occurs, thereby enhancing LVRT dynamic performance.

Figure 10 shows the internal structure of the encoder and decoder built in layers. Each encoder layer has two building blocks: attention with multiple heads sublayer and FFN (feed-forward network) sublayer. For the decoder, an additional masked multi-head attention sublayer is added to prevent future time-step information from leaking into the prediction, ensuring that only past data is used. After each

sublayer, we apply a residual connection followed by layer norm.

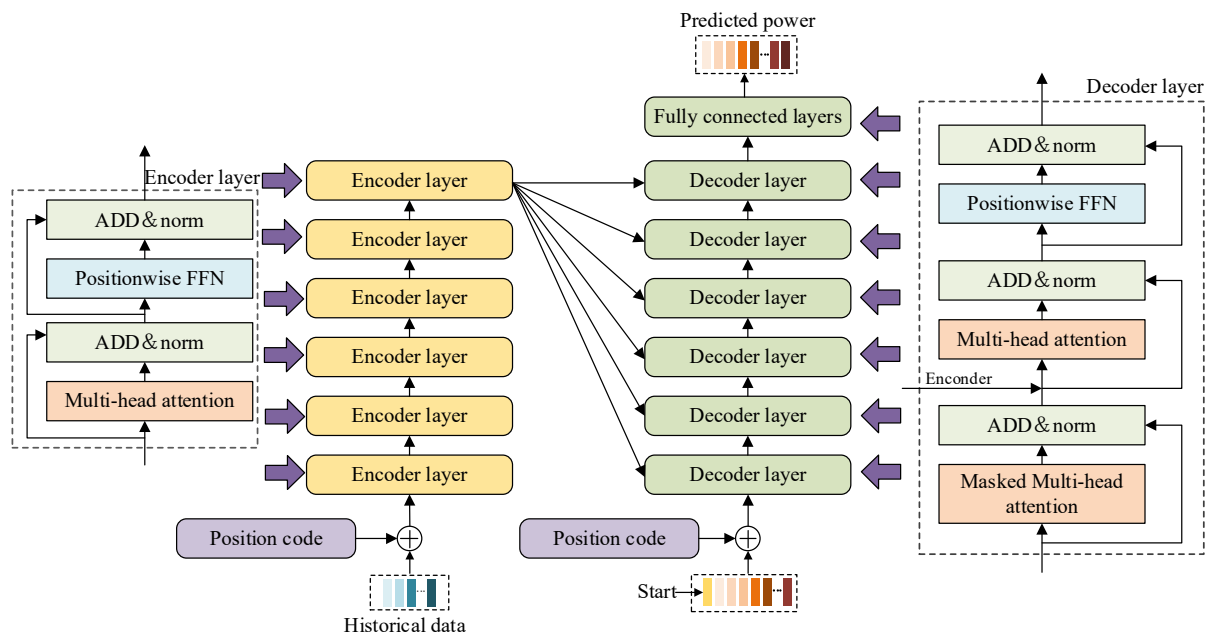


Figure 8. The transformer stack

As shown in Fig. 9, the attention with multiple heads mechanism runs several independent heads in parallel to compute scaled dot-product attention. Thus, the model learns diverse dependencies from various subspaces. Head outputs are merged and linearly transformed. The FFN uses two linear layers separated by a ReLU to boost expressive power.

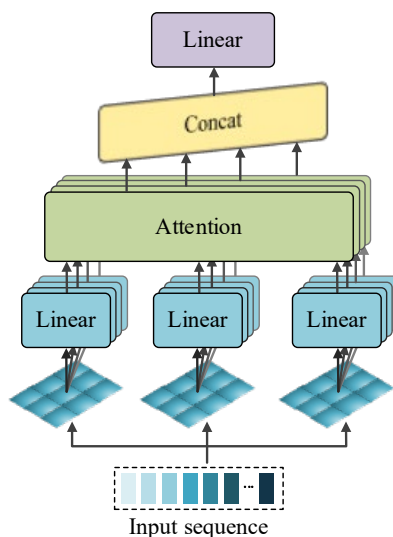


Figure 9. Attention with multiple heads

Here is how the prediction model works. Its input consists of past load records, wind power readings, and time stamps. These go through a linear layer and a position-encoding step to produce embedding vectors. Then the encoder and decoder gradually extract useful patterns. At the end, a fully connected layer gives the load forecast for the next time window.

These prediction results serve as feedforward signals used to actively adjust the MMC's active power reference value. When a significant increase in load is predicted, the active power is increased in advance. For predicted load decreases, the reference value is reduced accordingly. This feedforward correction runs in parallel with the existing inner-loop controller, which handles both positive and negative sequences in a dual current-loop setup. It only fine-tunes the outer power-loop reference without changing the original structure. As a result, when an actual grid voltage dip occurs, the system already sits in a better operating state, improving both LVRT response speed and robustness.

To summarize, Figure 10 gives the system's complete control architecture.

Figure 11 shows the architecture of the Transformer-based load forecasting model. It includes feature embedding, a Transformer encoder-decoder, a prediction layer, and feedforward correction of the MMC active power reference value.

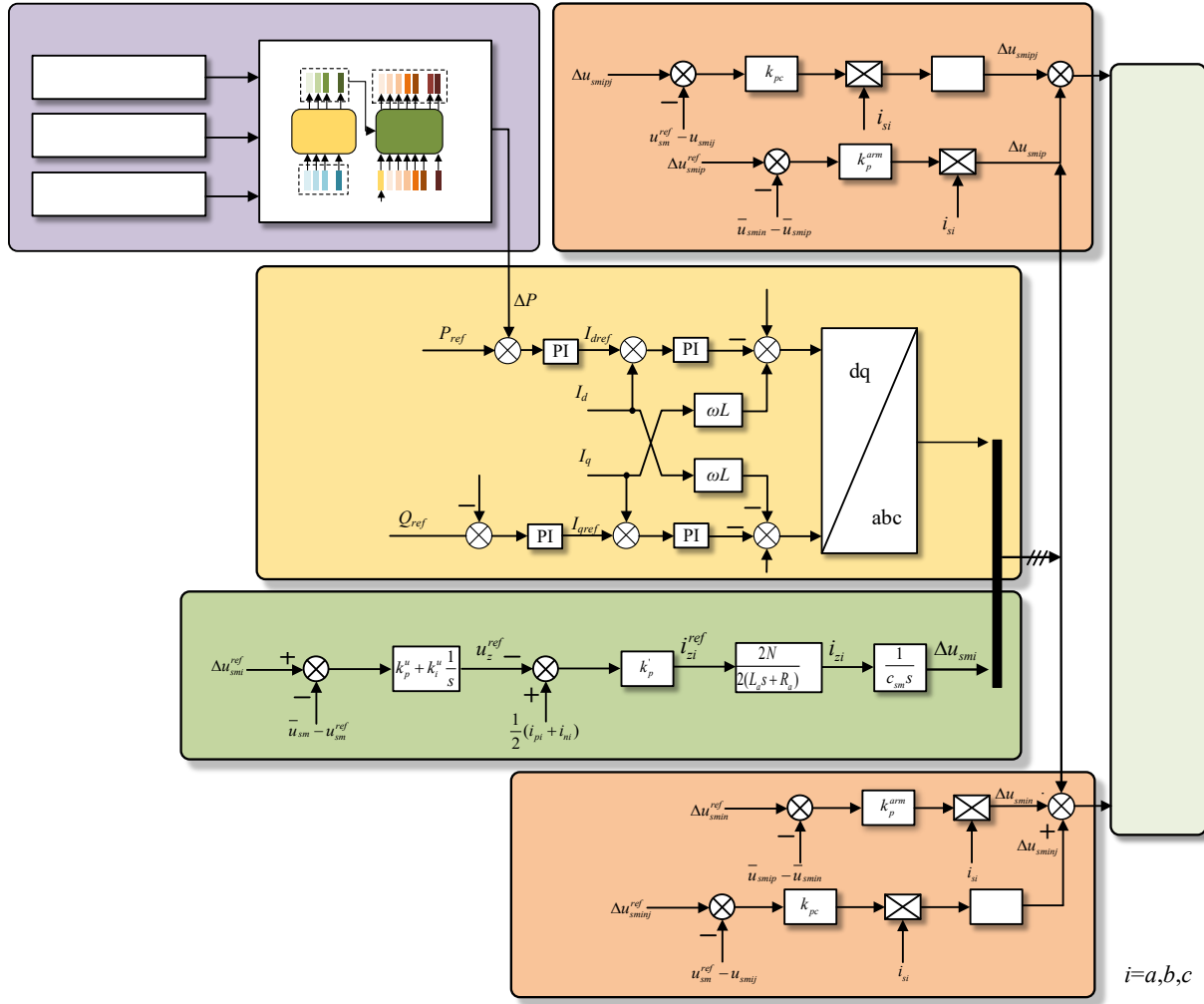


Figure 10. Overall control structure diagram

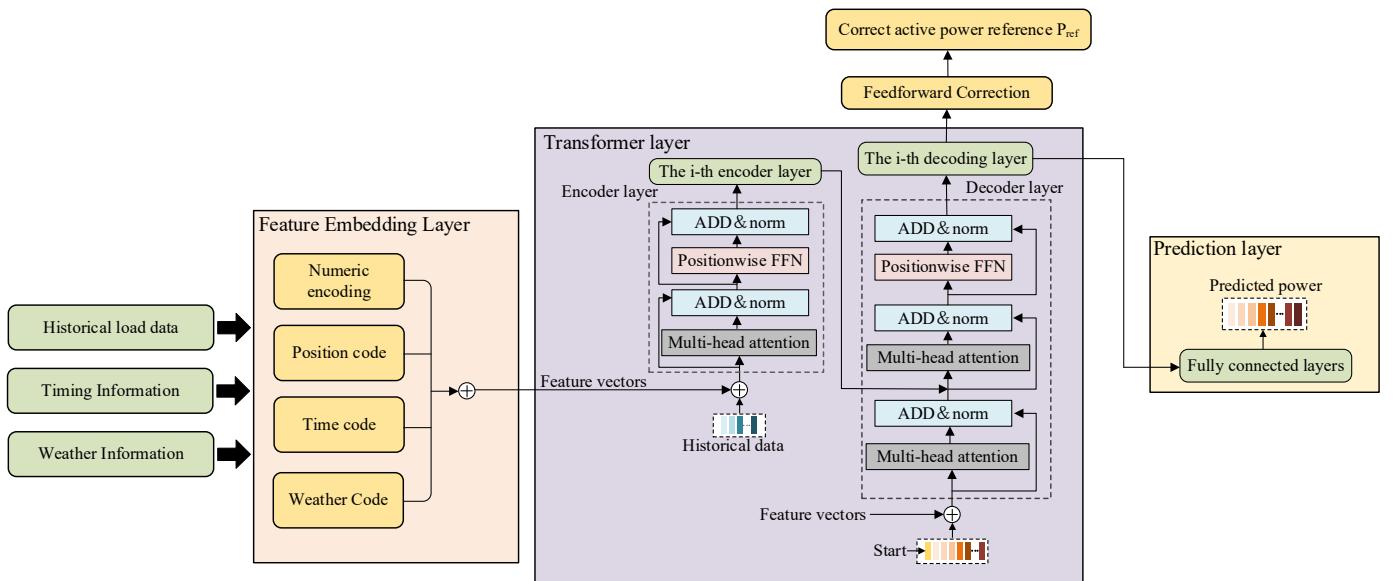


Figure 11. Transformer-based load forecasting model

5. HIL experimental

In earlier chapters, we put forward a complete control scheme to meet the LVRT requirements of the MMC valve. The scheme comprises two parts: a dual-loop inner current controller that handles both positive and negative sequences, plus a multi-level submodule capacitor-voltage-balancing control.

To test how well this scheme works in real hardware, and given the safety and cost limits of high-power lab experiments, this chapter uses a Typhoon HIL-based hardware-in-the-loop (HIL) setup. An 11-level MMC valve model is built within the Typhoon HIL Control Center software. By comparing system responses with and without the scheme, its advantages during LVRT are confirmed.

Table 2 holds the parameter values for our simulation.

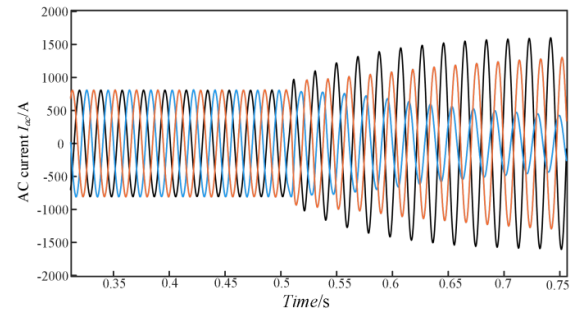
Table 2. Simulation parameters

Parameters	Parameter Values
Active Power (MW)	10
Reactive Power (Mvar)	2
System Inductance (mH)	6.5
Submodule Capacitance (F)	0.003
Submodule Capacitor Voltage (V)	2000
Number of Submodules per Bridge Arm	10
Bridge Arm Inductance (mH)	5
Carrier Frequency (Hz)	2500
DC Bus Voltage (kV)	10

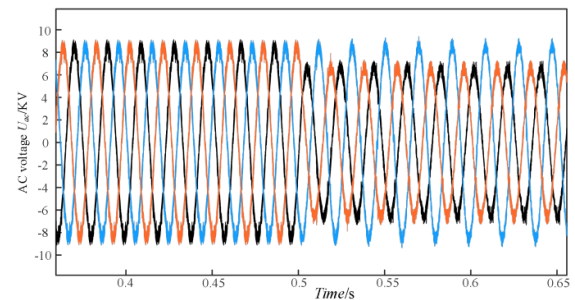
To show why the proposed control scheme is necessary, we first run a baseline simulation with no control under the same fault conditions. A phase-A metallic ground-fault occurs at $t = 0.5$ s. When the fault occurs, the phase voltage falls to 0.5 p.u. of its rated value. Fig 12 illustrates the system's dynamic responses both before and after the fault.

From Fig 12(a), the AC current becomes highly asymmetric after the fault. The instantaneous magnitude of phase-A current rises sharply, and its waveform is distorted. Fig 12(b) reveals notable differences in the three-phase voltage magnitudes. A clear negative-sequence component is present. Fig 12(c) shows large positive-negative oscillations in the DC current at the fault instant. The power becomes severely unbalanced. Fig 12(d) indicates that the active power exhibits large double-frequency oscillations with slow decay. Fig 12(e) shows a sharp increase in the arm circulating current, with a prominent double-frequency

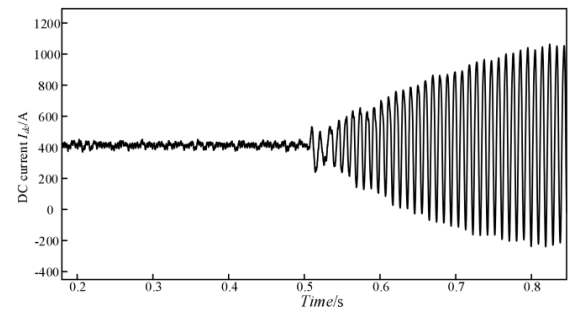
component. Fig 12(f) presents severe fluctuations in the upper arm submodule capacitor voltages, with deviations exceeding $\pm 10\%$ of the rated value. Fig 12(g) further compares the submodule voltages. A significant voltage deviation between the arms is observed, and the system cannot maintain stable operation. The above results indicate that the system does not possess LVRT capability without the control strategy.



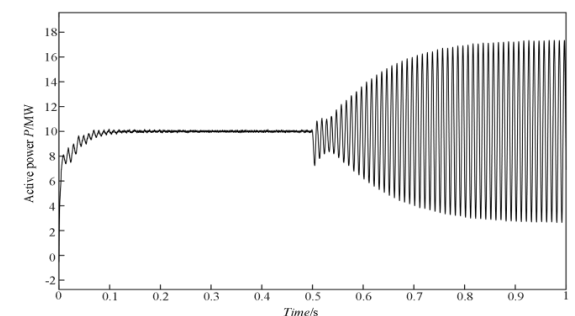
(a) AC current



(b) AC voltage



(c) DC current



(d) Active power

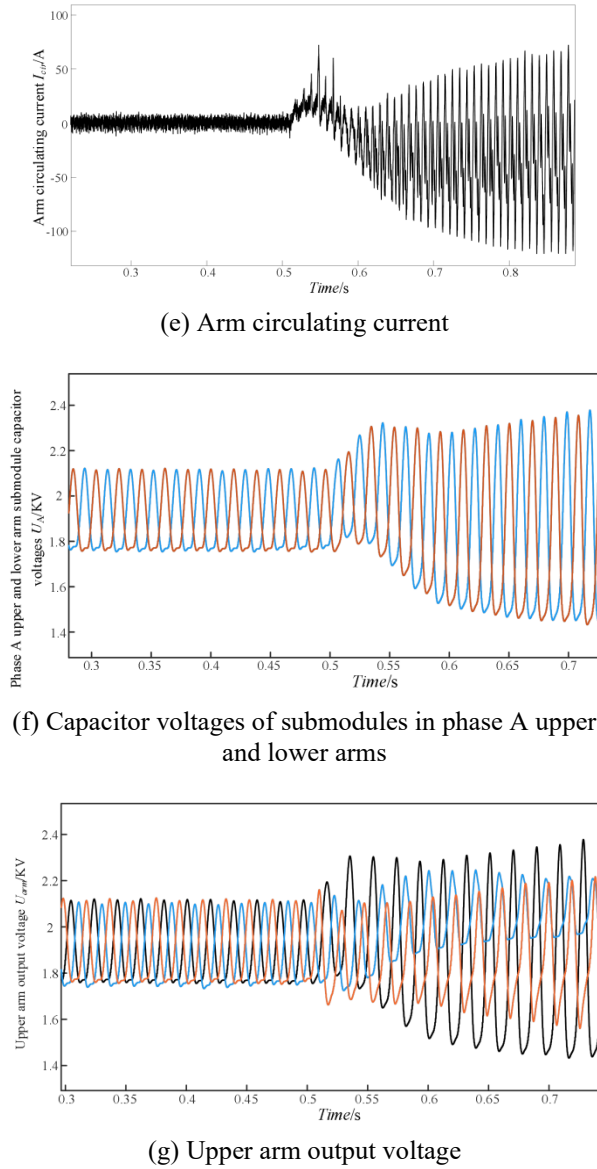


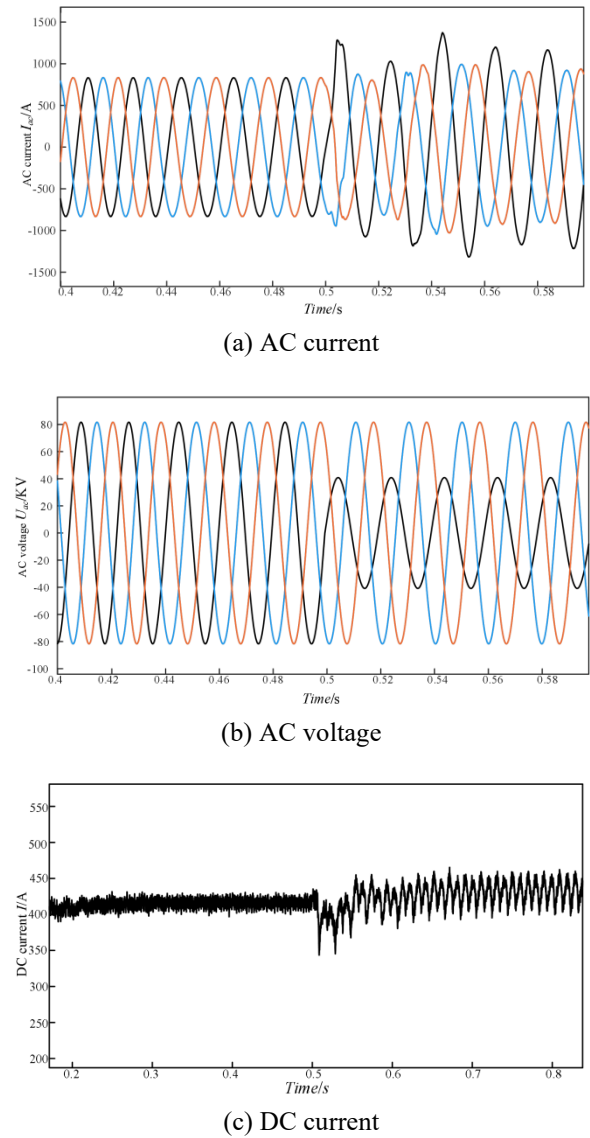
Figure 12. System response without control strategy

To address the issues mentioned above, this chapter proposes a unified control scheme. The scheme includes a dual-current inner loop for positive and negative sequences, as well as hierarchical submodule capacitor voltage balancing. To validate the scheme, parallel simulations were conducted under identical fault conditions. The resulting system responses are shown in Figure 13.

Figures 13(a) and 13(b) show that after a fault, the AC current rises sharply while the AC voltage becomes unbalanced. However, the proposed control strategy effectively suppresses the negative-sequence current, keeping the three-phase currents symmetric. Figure 13(c) shows that the DC current experiences a brief transient fluctuation at the fault instant but quickly stabilizes under the controller's regulation. This demonstrates good LVRT capability. Figure 13(d) reveals that the active power

exhibits no strong double-frequency ripple. Hence, using positive- and negative-sequence control is capable of eliminating power fluctuations. In Figure 13(e), significant suppression of the arm circulating current is observed, which demonstrates the effectiveness of the proposed controller handling positive, negative, and zero sequences. Figure 13(f) shows a drop in the three-phase bridge arm output voltage amplitude after the fault, but the waveform remains intact. Figure 13(g) shows that, for phase A, the submodule voltages in the arms remain consistent during the fault. Consequently, the inter-arm balancing control successfully avoids voltage deviation.

As shown by the simulation results, the control method we propose can limit circulating currents and power fluctuations during LVRT, thereby ensuring stable and safe system operation. Furthermore, this method meets the LVRT standards for converter valves used in wind power grid integration.



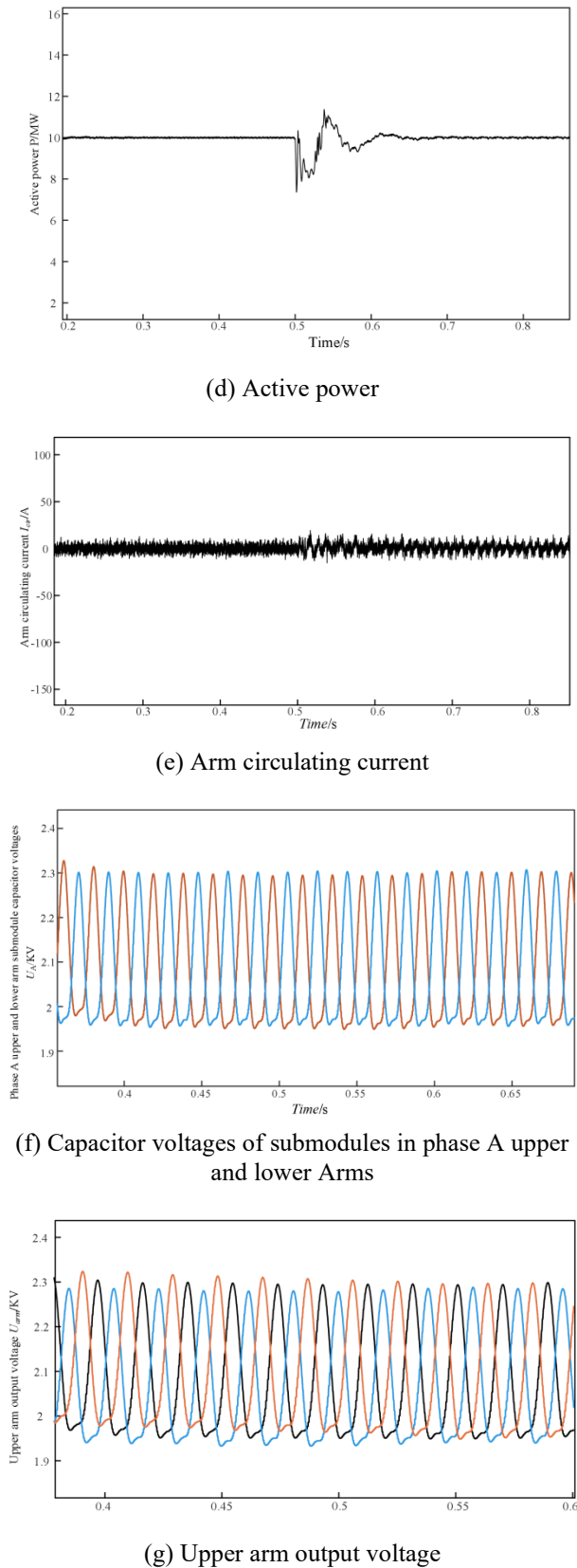
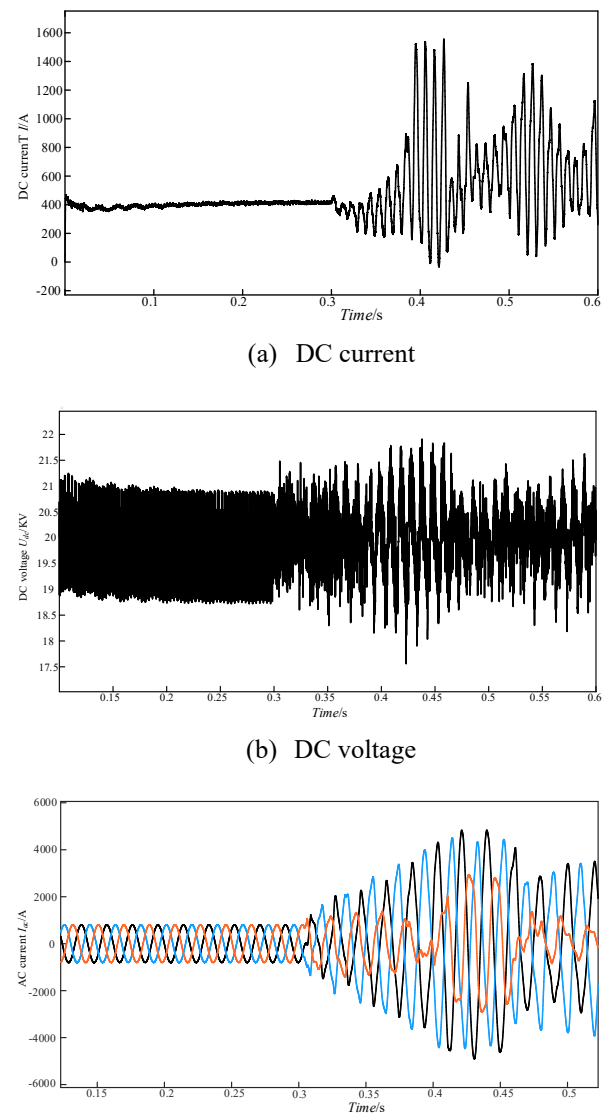


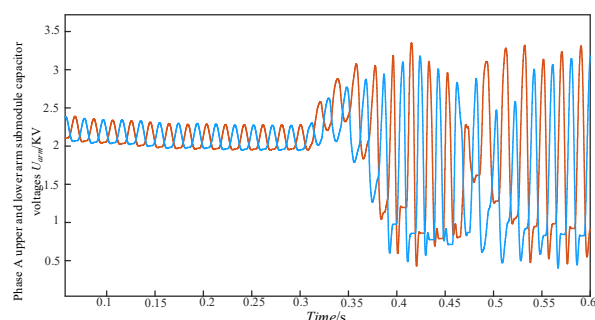
Figure 13. System response under the control strategy

Figure 14 illustrates the system's response to a short circuit between phases A and B at the converter output at $t = 0.3$ s. In Figure 14(a), the DC current exhibits severe oscillations following the fault, with the oscillation amplitude varying in both positive and negative directions. Figure 14(b) shows that the DC bus voltage drops by approximately 15%. Figure 14(c) shows a sharp rise in the AC-side currents of phases A and B. Figure 14(d) indicates that the voltage fluctuations across the submodule capacitors are more pronounced.

It is evident that for severe faults such as phase-to-phase short circuits, LVRT is no longer feasible; the system must enter a protected state. In MMC-HVDC systems, two-phase or three-phase short circuits are considered severe faults. Negative-sequence currents are difficult to effectively suppress, leading to severe oscillations in both DC and AC voltages. This prevents the controller from maintaining normal operation. In such cases, the converter should be shut down immediately, and a trip signal should be sent to open the AC circuit breakers. Subsequently, the system should be taken offline for maintenance.



(c) AC current



(d) Capacitor voltages of submodules in phase A upper and lower Arms

Figure 14. System response under ab phase-to-phase short circuit

6. Conclusion

This paper investigates a fault-ride-through control method for MMC-based flexible DC converter valves, with a focus on LVRT requirements for large-scale wind power grid integration. We propose an integrated control scheme that includes a dual-current inner-loop control and a hierarchical balancing control for sub-module capacitor voltages. This scheme effectively suppresses negative-sequence currents and double-frequency active power fluctuations while maintaining capacitor voltage balance.

A transformer-based short-term load predictor is added as a feedforward helper. The model's self-attention mechanism captures long-term dependencies in the load sequence. By pre-adjusting the active power reference, the model effectively improves dynamic response during fault ride-through.

This paper compares system responses with and without the proposed control scheme on a Typhoon HIL. The comparison results show that the scheme effectively suppresses circulating currents and power fluctuations during asymmetric voltage sags, thereby meeting the requirements for LVRT. For severe faults such as phase-to-phase short circuits, the system must enter a blocking protection state. This study provides a comprehensive theoretical foundation and HIL-based validation for LVRT control of flexible DC converter valves. These research findings have significant practical engineering applications.

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