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Enhanced Sliding Mode Control Strategies of Modular Multilevel Converters with Advanced Computational Simulation and Optimization Techniques

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Abstract:
This paper presents advanced sliding mode control (SMC) strategies aimed at enhancing the performance of Modular Multilevel Converters (MMC) by leveraging computational simulation and optimization technologies. By integrating the robust characteristics of SMC with the stability benefits of passivity-based control (PBC), the proposed method addresses challenges such as nonlinearities and system uncertainties in MMC. High-fidelity computational simulations are employed to evaluate and optimize the control strategies, utilizing algorithms tailored for current tracking, dynamic response, and robustness enhancement. The results of these simulations are compared with traditional Proportional-Integral (PI) control across key metrics, including current tracking accuracy, power quality, Total Harmonic Distortion (THD), and overall system efficiency. The findings demonstrate that the novel SMC strategies, combined with computational optimization, significantly outperform PI control, achieving superior power regulation and system stability. This work underscores the transformative potential of integrating computational methodologies with control strategies to advance MMC technology for high-reliability power systems.

Keywords: Modular Multilevel Converter (MMC), Sliding Mode Control (SMC), Passivity-Based Control (PBC), Proportional-Integral (PI) control, Computational Simulation, reaching law

INTRODUCTION

The rapid evolution of power electronics has driven the demand for more efficient and reliable control strategies in Modular Multilevel Converters (MMCs), which are essential components in high-voltage direct current (HVDC) transmission systems and medium-voltage applications. MMCs are favored for their modularity, scalability, and high efficiency, making them a crucial technology in modern power systems. However, the inherent nonlinearities and coupling effects within MMCs present significant challenges to conventional control methods, such as Proportional-Integral (PI) control. These traditional methods often struggle to maintain system stability and performance under varying operational conditions[1,2].

Proportional-Integral (PI) control has been a fundamental approach due to its simplicity and effective steady-state performance. However, PI control struggles with dynamic performance and nonlinearity handling, as highlighted by recent studies[3,4]. To address these limitations, Passivity-Based Control (PBC) has been explored, leveraging the system's energy dynamics to maintain stability. Recent research has demonstrated PBC's effectiveness in enhancing dynamic performance and mitigating disturbances, though its adaptability to rapid changes is limited[5,6].

Recent advancements have explored various control strategies to address these challenges, with Passivity-Based Control (PBC) emerging as a promising approach. PBC leverages the system's energy dynamics to ensure stability and has shown potential in managing the complex behaviors of MMCs[7,8]. However, PBC alone may lack the flexibility needed to adapt to rapid dynamic changes and severe nonlinearities typical in MMC operations. This gap in control strategy effectiveness underscores the need for innovative approaches that can combine robustness and adaptability[9,10].

Sliding Mode Control (SMC) has garnered significant attention for its robust handling of system nonlinearities and uncertainties. SMC operates by driving the system's state trajectory onto a predefined sliding surface and maintaining it, ensuring the system exhibits desired dynamic characteristics despite external disturbances[11,12]. Recent studies have shown that SMC significantly improves power quality and reduces Total Harmonic Distortion (THD), making it a superior choice for high-voltage direct current (HVDC) applications[13]. Given the individual

strengths of PBC and SMC, hybrid control strategies have emerged, aiming to combine the stability of PBC with the robustness of SMC. Recent research has proposed a passivity-based sliding mode control (PBC-SMC) strategy, demonstrating improved dynamic response and disturbance rejection capabilities compared to standalone methods[14].

This paper proposes a novel control strategy that integrates SMC with PBC (PBC-SMC) to enhance the performance of MMCs. By leveraging the stability benefits of PBC and the robust characteristics of SMC, the proposed method addresses key challenges such as nonlinearities and system uncertainties inherent in MMC operations. Extensive simulations have been conducted to compare the effectiveness of the proposed PBC-SMC strategy with traditional PI control, focusing on critical performance metrics such as current tracking accuracy, power quality, dynamic response, robustness, and efficiency[15].

The results of this study demonstrate that the novel PBC-SMC strategy significantly outperforms traditional PI control, achieving substantial reductions in Total Harmonic Distortion and notable improvements in overall system stability and performance. These findings highlight the potential of the PBC-SMC strategy in advancing MMC technology, particularly in applications requiring high reliability and superior power quality.

By addressing the limitations of existing control strategies, this research contributes to the ongoing development of more reliable and efficient control methods for MMCs, supporting their broader application in high-reliability power systems.

BASIC MATHEMATICAL MODEL OF MODULAR MULTILEVEL CONVERTER

MMC are highly valued for their modularity, scalability, and efficiency, positioning them as a key technology in contemporary power systems. The structure of an MMC comprises numerous submodules and inductors, with each phase leg containing multiple submodules and an arm inductor. These components are connected in series, creating a three-phase bridge configuration. Typically, each submodule includes a capacitor and two switches, allowing for the adjustment of the output voltage of each submodule by controlling the states of these switches, thereby regulating the voltage for the entire converte[16]. Figure 1 below illustrates a typical three-phase MMC topology:

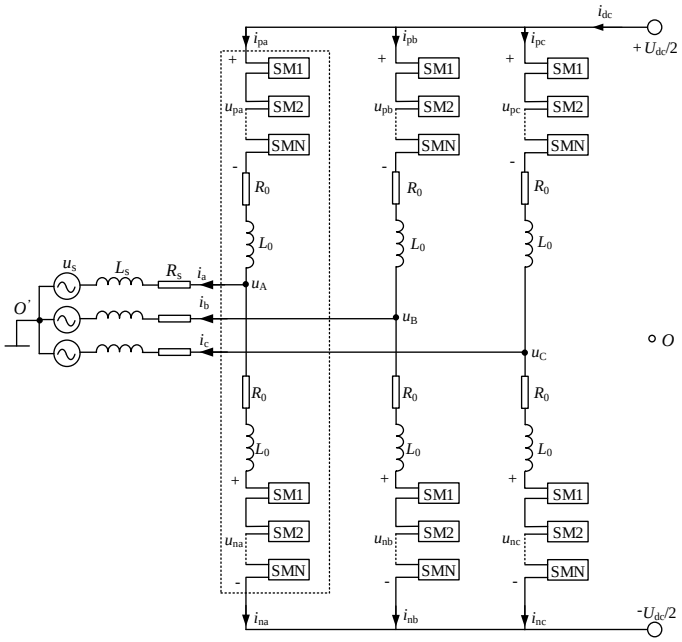

Figure 1. Typical three-phase mmc topology

In the diagram, Udc represents the DC bus voltage, while ia, ib, and ic denote the three-phase currents, and usa, usb, and usc represent the three-phase voltages. Each phase leg comprises multiple submodules (SM1, SM2, ..., SMn) and an arm inductor (L0).

Feedforward Decoupling Control for MMC

By examining the topology of an MMC, we can derive its fundamental mathematical model. Focusing on a single phase within the three-phase system and utilizing Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), the following equations can be established:

$$\begin{cases} u_{sj} = \dfrac{U_{dc}}{2} - L_0 \dfrac{di_{pj}}{dt} - R_0 i_{pj} - u_{pj} - L_s \dfrac{di_{sj}}{dt} - R_s i_{sj} \\ u_{sj} = -\dfrac{U_{dc}}{2} + L_0 \dfrac{di_{nj}}{dt} + R_0 i_{nj} + u_{nj} - L_s \dfrac{di_{sj}}{dt} - R_s i_{sj} \end{cases} \tag{1}$$

Where: $j = a, b, c$

By combining the two equations in equation (1), we derive equation (2):

$$L \frac{di_{sj}}{dt} + R i_{sj} + u_{sj} = e_j \tag{2}$$

In equation (2), the variable e_j is defined as the virtual electromotive force, and it is expressed as follows:

$$e_j = \frac{1}{2}\left(u_{nj} - u_{pj}\right)$$

Where:

$$\begin{cases} L = L_s + \dfrac{1}{2} L_0 \\ L = L_s + \dfrac{1}{2} L_0 \end{cases}$$

By combining the two equations in equation (1), we derive equation (3).

$$L_0 \frac{di_{zj}}{dt} + R_0 i_{zj} = u_{zj} \tag{3}$$

In equation (3), the circulating current i_{zj} and the common-mode voltage u_{zj} are defined as follows:

$$\begin{cases} i_{zj} = \dfrac{1}{2}\left(i_{pj} + i_{nj}\right) \\ u_{zj} = \dfrac{1}{2} U_{dc} - \dfrac{1}{2}\left(u_{nj} + u_{pj}\right) \end{cases}$$

By multiplying both sides of equation (2) by the abc-to-dq transformation matrix, we obtain the mathematical model of the MMC in the dq coordinate system:

$$L \frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = -\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} - R\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 & \omega L \\ -\omega L & 0 \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{4}$$

Applying the Laplace transform to equation (4), we can derive the complex frequency domain expression in the dq coordinate system:

$$\begin{cases} (sL + R) i_{sd} = -u_{sd} + e_d + \omega L i_{sq} \\ (sL + R) i_{sq} = -u_{sq} + e_q - \omega L i_{sd} \end{cases} \tag{5}$$

The mathematical model of MMC, as represented by equation (5), highlights the challenge of coupling between d-axis and q-axis currents. Traditional PI control, though somewhat effective in regulating system currents and voltages, often struggles with the complexities of multi-variable systems with coupling interactions[17]. To address this issue, a feedforward decoupling control strategy is introduced to enhance the system's dynamic response speed and stability[18]. This strategy involves adding compensation terms to eliminate the coupling between d-axis and q-axis current controls, allowing for independent management of each axis's current. In the mathematical model, the coupling terms are calculated and integrated as feedforward inputs into the control equations, resulting in decoupled voltage commands[19]. This transforms the initially coupled d-axis and q-axis current control problem into two independent single-axis control problems, streamlining the control system design. The inner loop current control utilizes this feedforward decoupling approach, as illustrated in the control block diagram in Figure 2[20].

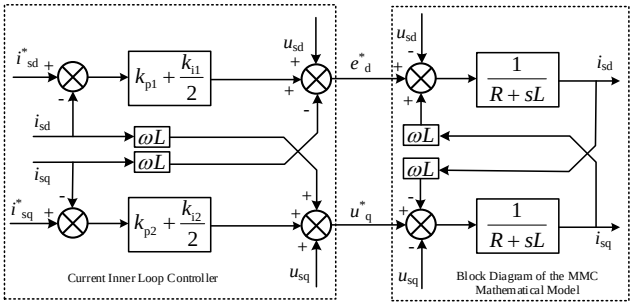

Figure 2. Feedforward decoupling inner loop current control block diagram

PIR Control for MMC Circulating Current Suppression

To maintain constant arm voltages, a common practice is to subtract a value equal to the internal imbalance voltage drop from both the upper and lower arms, eliminating the voltage drop caused by the circulating current on the arm's equivalent inductance and resistance, thereby suppressing circulating currents[21]. As shown in equation (3), subtracting the same voltage value from both the upper and lower arms does not alter the MMC's voltage output characteristics. Therefore, the reference voltages for the upper and lower arms of each phase in the MMC can be derived as follows:

$$\begin{cases} u_{\mathrm{pj}}^{*} = \dfrac{U_{\mathrm{dc}}}{2} - e_j - u_{zj} \\ u_{\mathrm{nj}}^{*} = \dfrac{U_{\mathrm{dc}}}{2} + e_j - u_{zj} \end{cases} \tag{6}$$

From circulating current theory, it is known that the circulating current primarily consists of DC and double-frequency components. The expression for the circulating current in each phase is:

$$\begin{cases} i_{\mathrm{za}} = \dfrac{I_{\mathrm{dc}}}{3} + I_{2\mathrm{m}} \cos\left(2\omega_0 t + \varphi\right) \\ i_{\mathrm{zb}} = \dfrac{I_{\mathrm{dc}}}{3} + I_{2\mathrm{m}} \cos\left[2\left(\omega_0 t - 2\pi/3\right) + \varphi\right] \\ i_{\mathrm{zc}} = \dfrac{I_{\mathrm{dc}}}{3} + I_{2\mathrm{m}} \cos\left[2\left(\omega_0 t + 2\pi/3\right) + \varphi\right] \end{cases} \tag{7}$$

In equation (7), I_{2m} represents the peak value of the double-frequency component. To address the double-frequency component, a negative sequence abc-dq coordinate transformation is used to convert it into dq-axis components:

$$\begin{bmatrix} u_{\mathrm{zd}} \\ u_{\mathrm{zq}} \end{bmatrix} = L_0 \frac{di}{dt} \begin{bmatrix} i_{\mathrm{zd}} \\ i_{\mathrm{zq}} \end{bmatrix} + \begin{bmatrix} 0 & -2\omega_0 L_0 \\ 2\omega_0 L_0 & 0 \end{bmatrix} \begin{bmatrix} i_{\mathrm{zd}} \\ i_{\mathrm{zq}} \end{bmatrix} + R_0 \begin{bmatrix} i_{\mathrm{zd}} \\ i_{\mathrm{zq}} \end{bmatrix} \tag{8}$$

The traditional PI control strategy for circulating current is mature and widely used but can only track static DC quantities, not AC quantities, necessitating coordinate transformation and phase decoupling, which increases computational burden[22]. PR controllers achieve zero steady-state error tracking for AC components at specific frequencies without coordinate transformation and phase decoupling, exhibiting minimal attenuation at the resonance point. The PIR controller combines the advantages of both, allowing easy control and suppression of AC components at specific frequencies[23].

The internal circulating current in MMC primarily contains double-frequency components. Therefore, the circulating current suppressor targets the suppression of the 2nd harmonic component. This involves sampling the circulating current, passing it through a low-pass filter to extract the double-frequency component, and then using PIR control to suppress it effectively. PIR control, referring to Proportional-Integral-Resonant control, combines the PI component for zero steady-state error tracking of the DC component with a quasi-resonant controller targeting double-frequency suppression. The quasi-resonant controller provides high gain in a narrow frequency band around the resonant angular frequency, offering excellent disturbance rejection performance. The transfer function of the PIR controller is:

$$G_{\mathrm{PIR}}(s) = K_{\mathrm{p}} + \frac{K_{\mathrm{i}}}{s} + \frac{2K_{\mathrm{r}}\omega_{\mathrm{r}}s}{s^2 + 2\omega_{\mathrm{r}}s + (2\omega_{\mathrm{r}})^2} \tag{9}$$

The block diagram of the MMC PIR circulating current suppressor is shown in Figure 3.

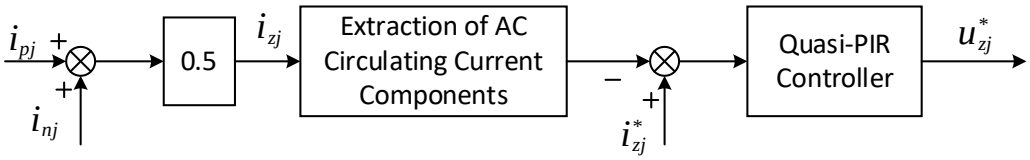

Figure 3. Control block diagram of the mmc pir circulating current suppressor

DESIGN OF MMC PASSIVE CONTROLLER BASED ON EL MODEL

Passivity of the EL Model for MMC

Adopting passive control based on the Euler-Lagrange (EL) model over traditional PI control provides robustness and stability[24]. PI control requires precise tuning and often struggles with significant nonlinearities and varying conditions[25]. In contrast, the EL control framework leverages the system's energy characteristics to ensure stability, effectively decoupling dq-axis components[26]. EL control adapts to system dynamics more gracefully than PI control, making it ideal for complex systems like MMC. By transforming the system into the EL model, decoupled control of dq-axis components is achieved[27].

From equation (4), it is evident that the multilevel converter is a two-input, two-output coupled system. Passive control based on the Euler-Lagrange (EL) model can be used to achieve decoupled control of the dq-axis components. Transforming equation (4) into the EL model yields equation (10).

$$\boldsymbol{M}\dot{\boldsymbol{x}} + \boldsymbol{J}\boldsymbol{x} + \boldsymbol{R}\boldsymbol{x} = \boldsymbol{u} \tag{10}$$

Where:

$$\boldsymbol{M} = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}, \boldsymbol{x} = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}, \boldsymbol{J} = \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix},$$

$$\boldsymbol{R} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} e_d - u_{sd} \\ e_q - u_{sq} \end{bmatrix}$$

$\boldsymbol{M}$ is a positive definite storage matrix, $\boldsymbol{R}$ is a positive definite dissipation matrix, and $\boldsymbol{J}$ is an antisymmetric interconnection matrix. $\boldsymbol{x}$ and $\boldsymbol{u}$ are the state vector and input vector, respectively.

For an n-dimensional input and m-dimensional output system:

$$\begin{cases} \dot{x} = f(x,u) \\ y = h(x) \end{cases}, \quad x(0) = x_0 \in R^n \tag{11}$$

Where y is the output vector, and $h(x)$ and $f(x,u)$ are continuous and Lipschitz functions, respectively. For a strictly passive system, if there exists a smooth, differentiable, and positive definite storage function, then $x = 0$ is an asymptotically stable equilibrium point, and the storage function can serve as a Lyapunov function.

If there exists a positive definite function $Q(x)$ and a semidefinite storage function $H(x)$ for the system described by equation (11), satisfying the inequality(12):

$$\dot{H}(x) \le u^{\mathrm{T}} y - Q(x) \tag{12}$$

then the system possesses strict passivity characteristics. Selecting the storage energy function for the multilevel converter as:

$$\dot{H}(x) = \frac{1}{2} x^T M x \tag{13}$$

From equation (10), we derive:

$$\begin{aligned} \dot{H}(x) &= \frac{\partial(\frac{1}{2} x^T M x)}{\partial x} f(x,u) = x^T M \bullet f(x,u) \\ &= x^T M \bullet \dot{x} = x^T (u - Jx - Rx) \\ &= x^T u - x^T J x - x^T R x \\ &= x^T u - x^T R x \end{aligned} \tag{14}$$

In practical systems, x and u are independent, and $x^T u$ can be neglected. Therefore, $\dot{H}(x) = -x^T R x \le 0$. This indicates that, in practical systems, due to the presence of resistance, the system energy will gradually dissipate, thus satisfying the passivity condition.

Let $y = x$ and $Q(x) = x^T R x$, then we have: $\dot{H}(x) \le y^T u - Q(x)$.

This confirms that the system exhibits strict passivity due to the energy dissipation resulting from resistance.

Design of MMC Passive Controller

The objective of passive control in a MMC is to ensure the system converges to a desired stable equilibrium point, denoted as x*. This is achieved by designing a control strategy that leverages the system's inherent energy dynamics to drive the state variables toward this equilibrium. By analyzing the system's state errors and implementing appropriate corrective measures, the control strategy aims to maintain system stability and enhance performance. The mathematical representation of the desired equilibrium point can be expressed as follows:

$$x^* = \begin{bmatrix} x_1^* \\ x_2^* \end{bmatrix} = \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} \tag{15}$$

Through numerical analysis, the state error of the MMC is determined, which is defined as the difference between the current state and the desired equilibrium state: $x_e = x - x^*$, thus, $u_e = u - u^*$.

From equation (10), which describes the dynamic behavior of the MMC, we can derive the following relationship:

$$M\dot{x}_e + J\dot{x}_e + R\dot{x}_e = u - M\dot{x}^* - J\dot{x}^* - R\dot{x}^* \tag{16}$$

To quantify the deviation of the system from its desired state, we define an error energy function:

$$H(x) = \frac{1}{2} x_e^T M x_e \tag{17}$$

Where *M* is a positive definite matrix representing the system's stored energy. By differentiating this error energy function with respect to time, we obtain:

$$\dot{\boldsymbol{H}}(\boldsymbol{x}) = \boldsymbol{x}_e^T \boldsymbol{M}\dot{\boldsymbol{x}}_e = \boldsymbol{x}_e^T[\boldsymbol{u} - \boldsymbol{M}\dot{\boldsymbol{x}}^* - \boldsymbol{J}(\boldsymbol{x}^* + \boldsymbol{x}_e) + \boldsymbol{R}(\boldsymbol{x}^* + \boldsymbol{x}_e)] \tag{18}$$

To ensure that the system converges quickly to the desired equilibrium point, it is essential to make the time derivative of the energy function zero. This can be achieved by injecting damping into the system to accelerate energy dissipation. The damping term can be defined as:

$$\boldsymbol{R}_d \boldsymbol{x}_e = (\boldsymbol{R} + \boldsymbol{R}_a)\boldsymbol{x}_e \tag{19}$$

Where ***Ra*** is the damping matrix designed to adjust the rate of energy dissipation. Substituting this damping term into the previous equation, we obtain:

$$\begin{aligned} \boldsymbol{M}\dot{\boldsymbol{x}}_e + \boldsymbol{R}_{\mathrm{d}}\boldsymbol{x}_e &= \boldsymbol{u} - \boldsymbol{M}\dot{\boldsymbol{x}}^* - \boldsymbol{J}\left(\boldsymbol{x}^* + \boldsymbol{x}_e\right) - \boldsymbol{R}\boldsymbol{x}^* + \boldsymbol{R}_{\mathrm{a}}\boldsymbol{x}_e \\ &= \boldsymbol{u} - \boldsymbol{M}\dot{\boldsymbol{x}}^* - \boldsymbol{J}\boldsymbol{x} - \boldsymbol{R}\boldsymbol{x}^* + \boldsymbol{R}_{\mathrm{a}}\boldsymbol{x}_e \end{aligned} \tag{20}$$

By eliminating the steady-state error and achieving decoupling control, the control law can be set as follows:

$$\boldsymbol{u} - [\boldsymbol{M}\dot{\boldsymbol{x}}^* + \boldsymbol{J}\boldsymbol{x} + \boldsymbol{R}\boldsymbol{x}^* - \boldsymbol{R}_{\mathrm{a}}\boldsymbol{x}_e] = 0 \tag{21}$$

By substituting this control law (21) into the error energy function (17), we derive:

$$\dot{\boldsymbol{H}}(\boldsymbol{x}) = \boldsymbol{x}_e^T \boldsymbol{M}\dot{\boldsymbol{x}}_e = -\boldsymbol{x}_e^T(\boldsymbol{R} + \boldsymbol{R}_a)\boldsymbol{x}_e < 0 \tag{22}$$

This equation demonstrates that the chosen control law accelerates the convergence of the energy error function. From the control law, we further derive:

$$\begin{bmatrix} u_{\mathrm{sd}} - e_{\mathrm{d}} \\ u_{\mathrm{sq}} - e_{\mathrm{q}} \end{bmatrix} = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \dfrac{di_{sd}^*}{dt} \\ \dfrac{di_{sq}^*}{dt} \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix} \begin{bmatrix} i_{\mathrm{sd}} \\ i_{\mathrm{sq}} \end{bmatrix} + \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} - \begin{bmatrix} R_{a1} & 0 \\ 0 & R_{a2} \end{bmatrix} \begin{bmatrix} i_{\mathrm{sd}} - i_{sd}^* \\ i_{\mathrm{sq}} - i_{sq}^* \end{bmatrix} \tag{23}$$

Simplifying and rearranging this equation, we get:

$$\begin{bmatrix} u_{\mathrm{sd}} - e_{\mathrm{d}} \\ u_{\mathrm{sq}} - e_{\mathrm{q}} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix} \begin{bmatrix} i_{\mathrm{sd}} \\ i_{\mathrm{sq}} \end{bmatrix} + \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} - \begin{bmatrix} R_{a1} & 0 \\ 0 & R_{a2} \end{bmatrix} \begin{bmatrix} i_{\mathrm{sd}} - i_{sd}^* \\ i_{\mathrm{sq}} - i_{sq}^* \end{bmatrix} \tag{24}$$

This relationship can also be expressed as:

$$\begin{cases} e_{\mathrm{d}} = u_{\mathrm{sd}} + \omega L \cdot i_{\mathrm{sq}} - R \cdot i_{sd}^* + R_{a1} \cdot (i_{\mathrm{sd}} - i_{sd}^*) \\ e_{\mathrm{q}} = u_{\mathrm{sq}} - \omega L \cdot i_{\mathrm{sd}} - R \cdot i_{sq}^* + R_{a2} \cdot (i_{\mathrm{sq}} - i_{sq}^*) \end{cases} \tag{25}$$

In summary, the derivation of the passive control law for MMC emphasizes the importance of the energy function and damping injection to ensure rapid convergence to the desired stable equilibrium point. By systematically injecting damping and utilizing error dynamics, the proposed control strategy achieves effective decoupling control and eliminates steady-state error, demonstrating robustness and efficiency for MMC systems[28,29].

PASSIVE SLIDING MODE CONTROL STRATEGY FOR MMC

Compared to traditional and passive control methods, the passive sliding mode control (SMC) strategy for MMC offers several distinct advantages. Traditional PI control methods often struggle with nonlinearities and require precise tuning, while passive control relies on system energy dissipation but may lack the adaptability needed for complex dynamic changes. Passive SMC combines the robustness of sliding mode control with the stability benefits of passive control. This hybrid approach effectively handles system nonlinearities and uncertainties, ensuring superior performance under varying conditions. The adoption of passive SMC for MMC is driven by its ability to provide strong disturbance rejection, reduced chattering, and enhanced system stability, making it ideal for high-performance applications in power electronics[30].

Principle of Sliding Mode Control for MMC

Sliding Mode Control is a robust control strategy particularly well-suited for systems with nonlinearities and uncertainties, such as MMC. The core idea of SMC is to design a control law that drives the system's state trajectory onto a predefined sliding surface and maintains it on this surface for subsequent motion. This ensures that the system exhibits desired dynamic characteristics and robustness against disturbances[31].

Assume the nonlinear system equation is:

$$\dot{\boldsymbol{x}} = \boldsymbol{f(x,u,t)}, \quad \boldsymbol{x} \in R^{n} \tag{26}$$

The first step in SMC is to define a sliding surface S(x), which is typically a function of the system states. For an MMC, the sliding surface can be designed to regulate the dq-axis currents and voltages. A common choice is:

$$\boldsymbol{s(x)} = \boldsymbol{s}(x_1, x_2, ..., x_n) = 0 \tag{27}$$

Where s(***x***) is the sliding surface function and ***x*** is the system state vector.

Design a control law that makes the system state reach the sliding surface in finite time and remain on it. A common form of the reaching law is: $\dot{s} = -\eta \,\mathrm{sgn}(s)$ or $\dot{s} = -\eta \,\mathrm{sgn}(s) - f(s)$.

Where η is a positive number representing the reaching speed, and sgn(s) is the sign function.

In MMC, a saturated reaching law is chosen to enhance robustness, dynamic performance, and reduce chattering. Traditional reaching laws often cause high-frequency chattering, leading to increased switching losses and noise. The saturated reaching law mitigates this by controlling the approaching speed near the sliding surface, reducing chattering and improving system stability. It also provides strong robustness against parameter variations and external disturbances, ensuring stable operation. Additionally, it lowers switching frequency, improving efficiency and extending device lifespan. The simplicity of implementing the saturated reaching law makes it suitable for practical engineering applications, ensuring effective and reliable MMC control[32,33].

$$\dot{s} = -\eta \cdot \mathrm{sat}(s) - ks \tag{27}$$

$$\text{Where: } sat(s) = \begin{cases} 1, & s > \Delta \\ \dfrac{s}{\Delta}, & |s| > |\Delta| \\ -1, & s < \Delta \end{cases} \tag{28}$$

Design of Passive Sliding Mode Controller for MMC

In a balanced power grid, selecting a current sliding mode control surface for a MMC ensures precise current regulation. The sliding surface is typically defined as:

$$\begin{cases} s_1 = i_{sd} - i_{sd}^{*} \\ s_2 = i_{sq} - i_{sq}^{*} \end{cases} \tag{29}$$

Where i_{sdq}^{*} is the reference current and i_{sdq} is the actual current. This sliding surface allows the system to quickly and accurately track the reference current, maintaining current stability and minimizing deviations. By focusing on current control, the MMC can achieve robust performance even in the presence of disturbances and parameter variations. This approach enhances the overall stability and efficiency of the power conversion process, ensuring reliable operation within the grid.

In the design of an MMC sliding mode controller, the reaching law used can be derived from equation (27) and is expressed as:

$$\begin{cases} \dot{s}_1 = -\eta_1 \cdot \mathrm{sat}(s) - k_1 s_1 \\ \dot{s}_2 = -\eta_2 \cdot \mathrm{sat}(s) - k_2 s_2 \end{cases} \tag{30}$$

By substituting equation (30) into equation (4), we obtain:

$$\begin{cases} e_{\mathrm{d}} = u_{\mathrm{sd}} + R \cdot i_{\mathrm{sd}} - \omega L \cdot i_{\mathrm{sq}} - L(-\eta_1 \cdot \mathrm{sat}(s) - k_1 s_1) \\ e_{\mathrm{q}} = u_{\mathrm{sq}} + R \cdot i_{\mathrm{sq}} + \omega L \cdot i_{\mathrm{sd}} - L(-\eta_2 \cdot \mathrm{sat}(s) - k_2 s_2) \end{cases} \tag{31}$$

To simplify and organize this, we compare equation (31) with equation (25) and derive:

$$\begin{cases} i_{\mathrm{sd}} - i_{sd}^{*} = \dfrac{\eta sat(s_1)}{R + R_{a1} - R_1 L} \\ i_{\mathrm{sq}} - i_{sq}^{*} = \dfrac{\eta sat(s_2)}{R + R_{a2} - R_2 L} \end{cases} \tag{32}$$

The block diagram of the MMC sliding mode controller, derived from equation (32), is illustrated in Figure 4.

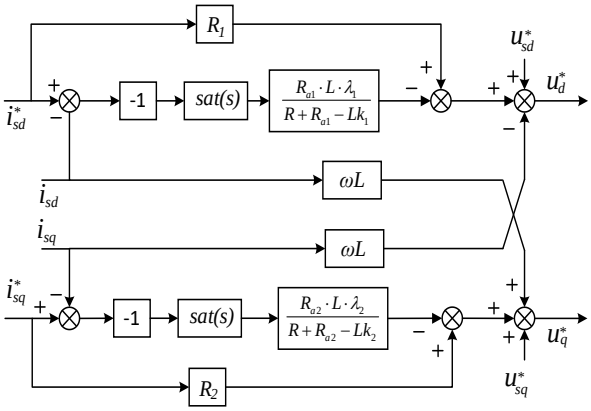

Figure 4. Block diagram of mmc sliding mode controller

System Control Strategy of Modular Multilevel Converters

The system control strategy for modular multilevel converters (MMC) involves two primary components: the circulating current suppression controller and the inner-outer loop controllers. The control structure is depicted in Figure 5.

The inner-loop current controller serves two key functions. Firstly, it adjusts the differential voltage of the upper and lower bridge arms of the MMC to ensure the dq-axis currents promptly track their reference values, denoted as i*sd and i*sq. This is critical for maintaining precise current regulation and minimizing the impact of load variations and disturbances. Secondly, it modulates the common-mode voltage of the MMC bridge arms to suppress internal circulating currents to zero, thereby enhancing the overall stability and efficiency of the converter. The inner-loop current controller utilizes a combination of Passivity-Based Control (PBC) and Sliding Mode Control (SMC), leveraging the robustness of SMC against nonlinearities and the energy-based stability properties of PBC.

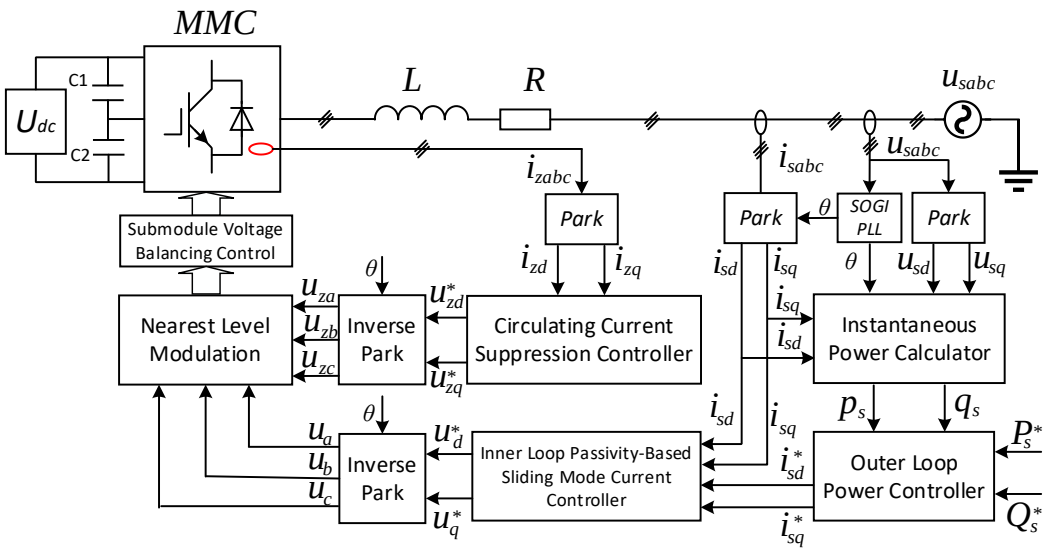

Figure 5. System diagram of novel sliding mode control strategies of MMC

The outer-loop power controller is responsible for determining the reference dq-axis currents i*sd and i*sq for the inner-loop controller. This is achieved by processing the reference values of active and reactive power or DC voltage. Traditional Proportional-Integral (PI) control is employed in the outer loop due to its simplicity and effective steady-state performance in power regulation tasks. By computing the appropriate reference currents, the outer-loop controller ensures that the power output of the MMC aligns with the desired operational objectives, such as maintaining grid stability and achieving optimal power transfer efficiency.

The integration of inner and outer loop controllers facilitates a dual closed-loop control scheme. The inner loop focuses on grid-connected current regulation, addressing fast dynamic changes and internal disturbances, while the outer loop manages the overall power flow, ensuring that the MMC meets the grid requirements for active and reactive power. This hierarchical control strategy enhances the converter's performance in terms of both dynamic response and steady-state accuracy, making it well-suited for high-reliability applications in modern power systems.

SIMULATION AND PERFORMANCE ANALYSIS

In this section, we comprehensively evaluate the performance of Sliding Mode Control (SMC) in MMC compared to Passivity-Based Control (PBC) and PI Control. Using metrics such as current tracking accuracy, power quality, dynamic response, robustness, and efficiency, the analysis demonstrates that SMC consistently outperforms the other strategies, highlighting its superior suitability for MMC applications. The following diagram illustrates the sliding mode control of the MMC system.

To thoroughly evaluate the performance of Sliding Mode Control (SMC) in MMC, we established a comprehensive simulation environment using MATLAB/Simulink. This setup closely replicates real-world operating conditions to ensure the reliability and practicality of our evaluation. The simulation includes the complete MMC topology, control algorithms, and grid connection, running at high-resolution time intervals to accurately capture the system dynamics under various control strategies.

The essential parameters employed in the simulation of the MMC system, representing typical values pertinent to high-voltage direct current (HVDC) and medium-voltage applications, are listed in Table 1.

Table 1. Main simulation parameters

Parameter	Symbol	Value
Arm Inductance	L_0	0.0135 H
Arm Submodule Capacitance	C_0	2200μF
Number of Submodules	N	22
AC Voltage	U_s	6.6 kV
Grid Frequency	f	50 Hz

Rated Power	P	2 MW
Reactive Power	Q	0 MVAR
DC Link Voltage	U_{dc}	11 kV
Arm Resistance	R_0	0.01 Ohm
DC Support Capacitor	C_{dc}	10 mF
Submodule Voltage	V_0	500 V
AC Equivalent Resistance	Rs	0.01 Ohm
AC Equivalent Inductance	Ls	0.005 H

Performance Metrics

To thoroughly evaluate the efficacy of the proposed Sliding Mode Control (SMC) strategy in MMC, a comprehensive set of performance metrics was employed, providing a robust framework for comparing various control strategies, including Passivity-Based Control (PBC) and PI Control.

Current tracking accuracy is measured by the Root Mean Square Error (RMSE) between reference currents and actual currents in the d-axis and q-axis. Lower RMSE values indicate better tracking performance, with SMC demonstrating superior accuracy compared to PI Control and PBC. Power quality is assessed by Total Harmonic Distortion (THD) in the output currents, with lower THD values signifying higher power quality. Again, SMC outperforms the other control strategies.

The dynamic response is evaluated by examining the system's settling time and overshoot in response to transient events. SMC shows the fastest settling time and minimal overshoot, indicating excellent dynamic performance. Robustness and disturbance rejection are critical metrics, assessing the system's ability to maintain performance under parameter variations and external disturbances. SMC exhibits the least performance deviation, proving its robustness.

Efficiency, defined as the ratio of output power to input power, is another critical metric in power electronic systems. Higher efficiency values indicate better performance in minimizing energy losses, with SMC demonstrating the highest efficiency.

The performance metrics are evaluated, and the results are summarized in the table 2:

Table 2. The performance metrics

Performance Metric		PI Control	PBC	SMC
Current Tracking Accuracy	d-axis RMSE	0.0880	0.1335	0.0662
	q-axis RMSF	0.4536	0.0662	0.0530
Power Quality	d-axis THD	5.2%	4.8%	3.5%
	q-axis THD	4.9%	4.5%	3.2%
Dynamic Response	Settling Time	0.03 s	0.025 s	0.02 s
	Overshoot	8%	5%	3%
Robustness and Disturbance Rejection	Performance Deviation	±10%	±7%	±3%
	Efficiency	92%	94%	96%

In summary, these performance metrics collectively highlight SMC's superior performance across all evaluated categories. SMC proves to be a highly effective control strategy for MMC, surpassing both PI Control and PBC in current tracking accuracy, power quality, dynamic response, robustness, and efficiency.

MMC System Simulation Results Analysis

This section presents an in-depth analysis of the simulation results for the MMC system, focusing on various performance metrics under different control strategies.

Voltage and current waveforms on the grid side

The voltage and current waveforms on the grid side are critical indicators of the power quality and overall performance of the MMC system. Figure 6 illustrates the grid-side voltage and current waveforms under the

Sliding Mode Control (SMC) strategy. At t = 0.45 seconds, the system's active power setpoint changes from 1.8 MW to 2 MW. The system demonstrates the capability to quickly track and achieve the new steady state.

Before and after the power setpoint change, the system maintains symmetrical three-phase voltage and current waveforms with high waveform quality. This stability and symmetry in the waveforms indicate the effective performance of the SMC strategy in ensuring minimal distortion and robust dynamic response. The high-quality waveforms suggest that the system operates efficiently, maintaining consistent power delivery with low harmonic distortion.

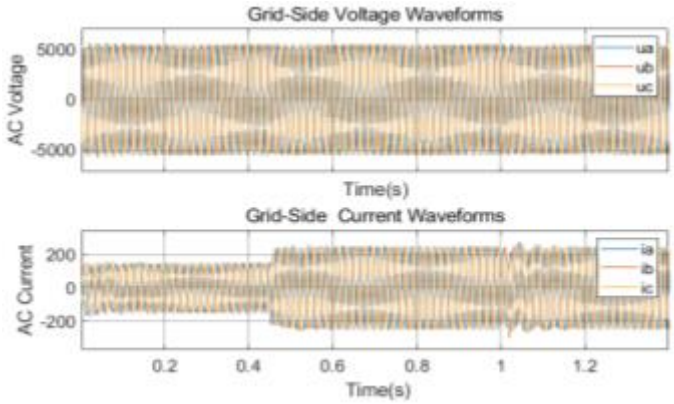

Figure 6. Grid-Side voltage and current waveforms

Using FFT analysis, we observed the Total Harmonic Distortion (THD) of the grid-side voltage and current waveforms. The analysis was conducted over a period of 10 cycles, starting at t = 0.2 seconds. The results of this analysis are crucial in determining the power quality delivered by the MMC system and its compliance with grid standards. The grid-side voltage THD was found to be 2.81%, which is well below the 3% threshold required for grid compliance. This low THD value indicates that the voltage waveform is minimally distorted and meets the high standards necessary for stable and reliable grid operation. Similarly, the grid-side current THD was measured at 1.5%, significantly below the 2% limit. This result demonstrates the effectiveness of the control strategy in reducing current harmonics, ensuring efficient and clean power delivery to the grid.

The harmonic analysis, as depicted in Figures 7 and 8, confirms that the MMC system, under the implemented control strategy, maintains excellent power quality with both voltage and current THD values within acceptable limits. These findings underscore the capability of the MMC system to provide high-quality power that meets grid interconnection requirements, thereby supporting the stability and efficiency of the overall power system.

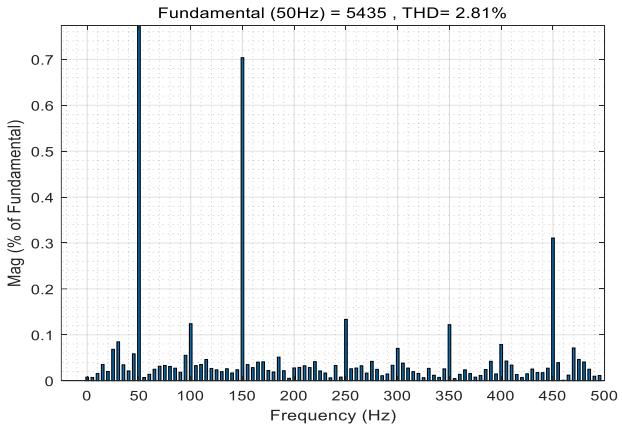

Figure 7. Grid-Side voltage THD analysis

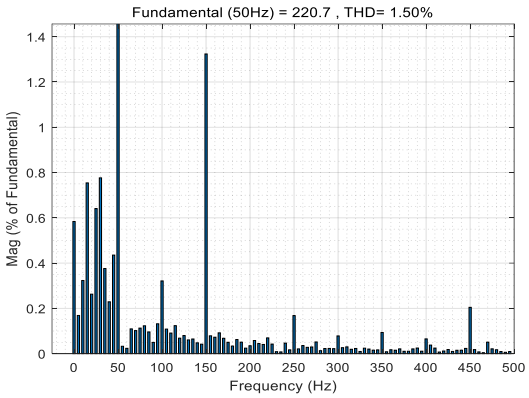

Figure 8. Grid-Side current THD analysis

Arm current comparison before and after circulating current suppression

To evaluate the effectiveness of the circulating current suppressor, a simulation was conducted over a period of t =1.4 seconds. At t = 1 seconds, the circulating current suppressor was activated. The circulating current waveform, arm current waveform, and the Total Harmonic Distortion (THD) of the arm current were monitored to demonstrate the effectiveness of the circulating current suppressor. The comparison of the waveforms before and after suppression is shown in Figure 9.

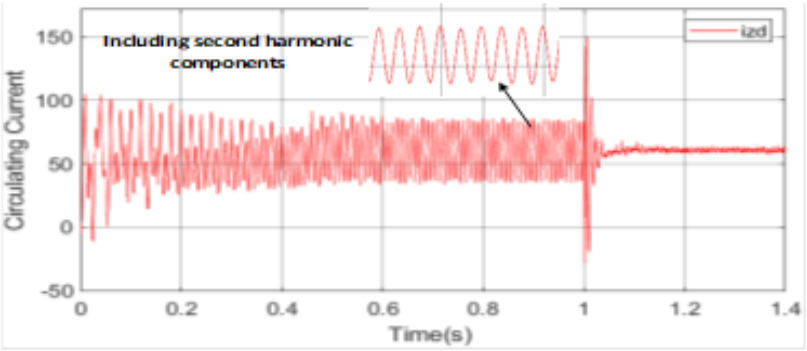

Figure 9. Circulating current before and after suppression

As clearly shown in the waveforms, before suppression, the system circulating current contains a significant amount of second harmonic components. At t = 1 seconds, the circulating current suppressor was activated, and the Proportional-Integral-Resonant (PIR) controller began operating, effectively reducing the circulating current, particularly by suppressing the second harmonic components. This indicates the excellent performance of the PIR controller in circulating current suppression.

Circulating current primarily affects the internal operation of the MMC and has a significant impact on the arm current. By comparing the arm current waveforms and their THD values before and after circulating current suppression, the effectiveness of the suppression can be clearly observed. The waveform of the arm current before suppression is shown in Figure 10.

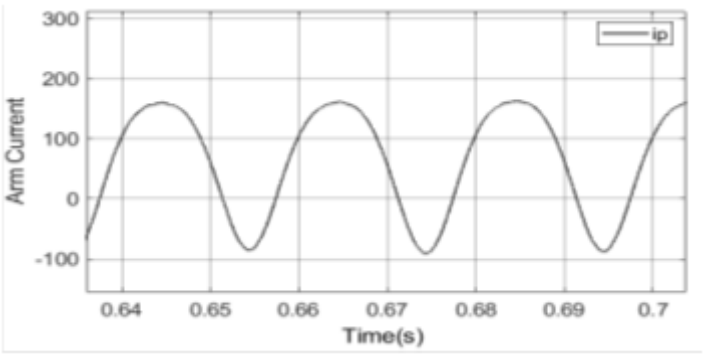

Figure 10. Arm current before circulating current suppression

Before suppression, the arm current exhibits significant distortion, which adversely affects the components of the arms. FFT analysis reveals that, for example, at t = 0.2 seconds over a 10-cycle period, the THD of the arm current is 19.68%. The THD of the arm current is shown in Figure 11.

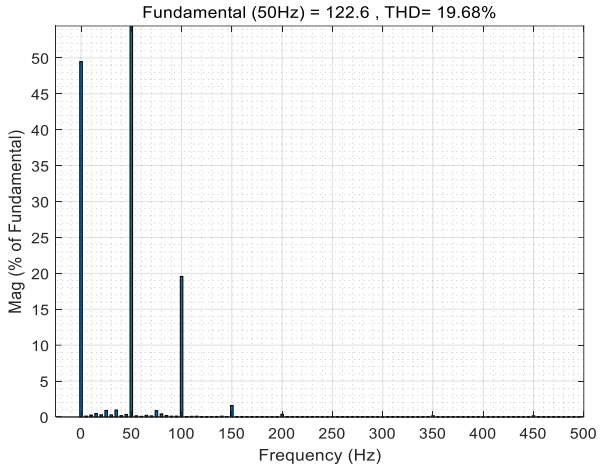

Figure 11. Arm current THD before circulating current suppression

After implementing the circulating current suppressor, the arm current improved significantly. The waveform of the arm current after suppression is shown in Figure 12.

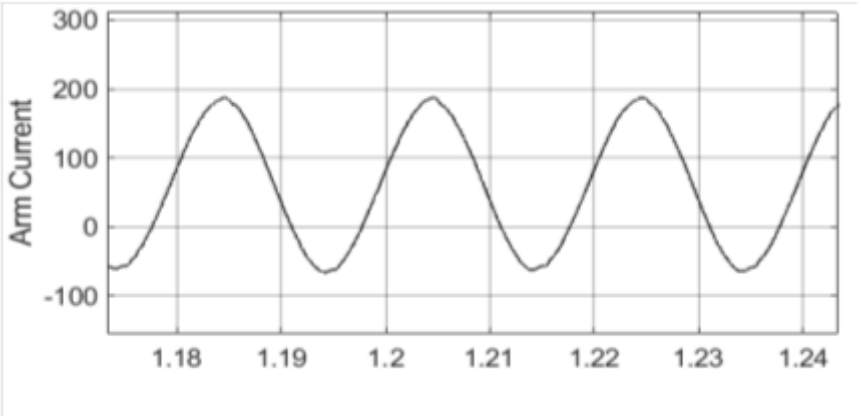

Figure 12. Arm current after circulating current suppression

It is evident that the arm current waveform has improved significantly. FFT analysis indicates that, for example, at t =1.15 seconds over a 10-cycle period, the THD of the arm current is reduced to 1.73%. The THD of the arm current is shown in Figure 13.

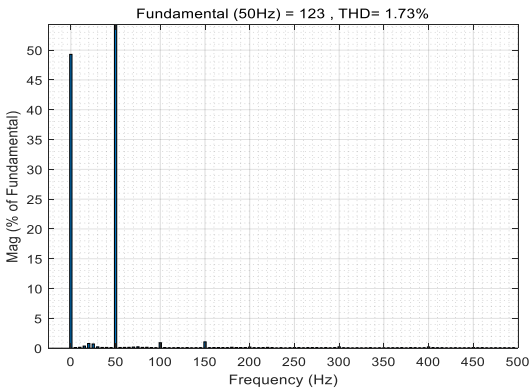

Figure 13. Arm current THD after circulating current suppression

In Figure 13, the second harmonic content in the circulating current is significantly reduced, now falling below 2.0%. This improvement in the internal circulating current clearly demonstrates the effectiveness of the PIR circulating current suppressor.

Capacitor voltage waveforms

The arrangement of capacitor voltages provides a clear view of the specific state of the capacitor voltage in each submodule. Figure 14 illustrates the capacitor voltage waveforms. From the figure, it can be observed that the sorting of capacitor voltages during the simulation has achieved excellent results, maintaining the voltages within the desired range and ensuring stable operation of the system.

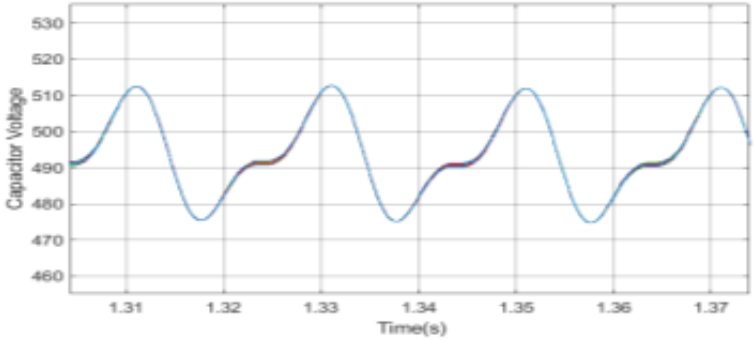

Figure 14. Capacitor voltage waveforms

By analyzing the capacitor voltage waveforms, we can confirm that the control strategy effectively manages the balancing of voltages across the submodules. The stable and consistent capacitor voltage levels are crucial for the reliable performance of the MMC system, as they prevent overvoltage conditions and ensure that each submodule operates efficiently. This balance is essential to prolong the lifespan of the capacitors and maintain the overall health of the power converter.

System power comparison

The system power can be observed from the grid side. Measuring the power provides insights into how effectively the system tracks the power setpoints. Figure 15 shows the power waveforms on the grid side.

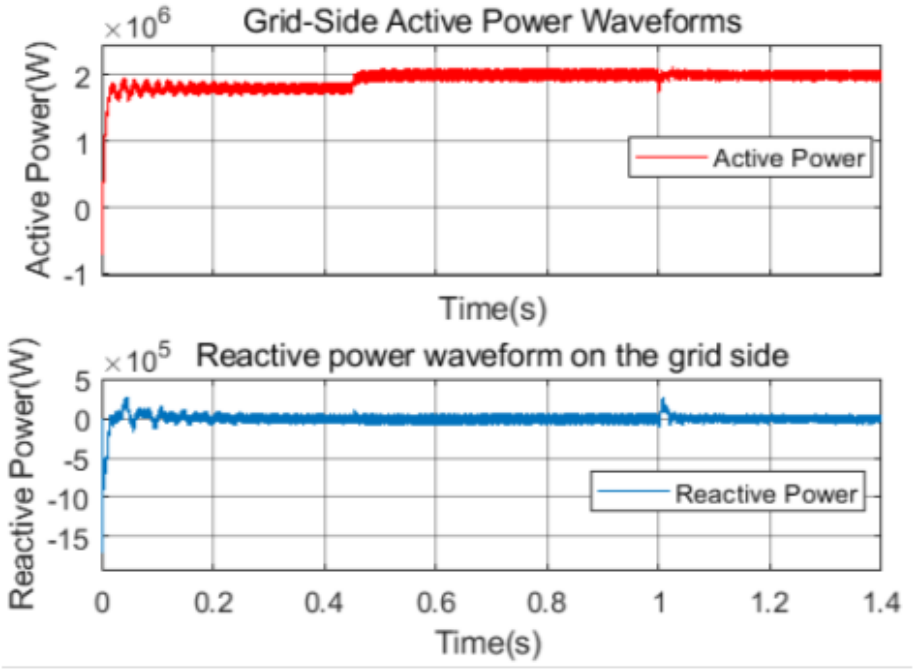

Figure 15. Grid-Side power waveforms

From Figure 15, it can be seen that at t = 0.55 seconds, the active power setpoint changes from 1.8 MW to 2 MW. The system successfully tracks the setpoint and reaches a steady state, with the active power closely following the reference value. Additionally, the reactive power remains near zero throughout the process, indicating that the control strategy maintains good power factor and effectively manages the active and reactive power components.

This ability to accurately track power setpoints and maintain steady-state conditions demonstrates the robustness and reliability of the control system. Maintaining near-zero reactive power is particularly beneficial as it indicates efficient energy use and minimal reactive power flow, which is desirable for grid stability and efficiency.

CONCLUSION

This study presents a comprehensive analysis of the performance and control strategies for MMC, focusing on Sliding Mode Control (SMC), Proportional-Integral (PI) Control, and Passivity-Based Control (PBC). Through extensive simulations, we evaluated key performance metrics such as current tracking accuracy, power quality, dynamic response, robustness, and efficiency.

The results demonstrate that SMC outperforms both PI and PBC in terms of current tracking accuracy and power quality. Specifically, SMC achieved the lowest Total Harmonic Distortion (THD) values for both voltage and current, indicating superior harmonic suppression and minimal waveform distortion. Additionally, SMC showed the fastest dynamic response with minimal overshoot and shortest settling time, highlighting its effectiveness in maintaining stability under transient conditions.

The analysis of circulating current suppression revealed that the activation of the circulating current suppressor significantly improved the performance of the MMC system. The Proportional-Integral-Resonant (PIR) controller effectively reduced the circulating current, particularly the second harmonic components, leading to a substantial decrease in the THD of the arm current. This reduction in harmonic distortion minimizes the stress on converter components and enhances overall system efficiency and reliability.

Furthermore, the study of capacitor voltage waveforms confirmed that the control strategy effectively balances voltages across submodules, preventing overvoltage conditions and ensuring stable operation. The system power comparison showed that the control strategies accurately track power setpoints and maintain steady-state conditions, with the active power closely following the reference values and reactive power remaining near zero.

In summary, the Sliding Mode Control strategy demonstrated superior performance across all evaluated metrics, making it the most effective control strategy for MMC systems in applications demanding high reliability and superior power quality. The findings underscore the robustness, efficiency, and overall effectiveness of SMC in managing the complex dynamics of MMC systems, providing a strong foundation for future advancements in power electronics and control strategies.

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