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Closed loop inner current control of Grid Connected MMC based microgrid solar system in dq Frame

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***Abstract*—The microgrid solar system integrates renewable energy sources, such as solar photovoltaic panels, into the grid through an MMC, enabling efficient and reliable power conversion. The inner current control strategy is critical for maintaining the stability and performance of the microgrid under varying operating conditions. In this paper paper presents a comprehensive study on the closed-loop inner current control of a Grid-Connected Modular Multilevel Converter (MMC) based microgrid solar system, employing the dq (direct-quadrature) frame for control reference.it will elaborates on the design and implementation of the closed-loop inner current control system, discussing the selection of control method and appropriate control parameters . The control scheme's effectiveness is evaluated through extensive simulation studies.**

***Index Terms*—Modular multilevel Converter(MMC), PV system grid-connected, current control.**

I. Introduction

The integration of renewable energy sources and the demand for efficient power transmission have led to the widespread adoption of Modular Multilevel Converters (MMCs) in modern power systems. [1] [2] [3]
Modular Multilevel converters offer several advantages, including high modularity and scalability, allowing for easy expansion or modification of the system. Additionally, its ability to tolerate faults within individual submodules enhances the system's reliability. Overall, the MMC circuit has proven to be a versatile and efficient solution for applications such as high-voltage direct current (HVDC) transmission and renewable energy integration. [] Their modular design allows for scalability, ensuring the adaptation to a wide range of power requirement With high efficiency and low harmonic generation, MMCs minimize energy losses during the conversion process, additionally, Their modularity allows for flexible and adaptable control strategies that can be customized to suit different applications and operating conditions [4]

The paper's structure is outlined as follows:in section I we present a concise introduction to the MMC converter,section II focuses on establishing a mathematical model for the MMC,In Section III, we establish a control strategy for inner currents,A simulation is conducted in section IV and performance of the proposed controller is investigated .Finally, the conclusion is provided in section V.

II. MMC Mathematic Model

1) circuit configuration : The MMC circuit is an advanced voltage source converter, which utilizes multiple submodules (SMs) interconnected in a specific configuration. Each submodule consists of a series-connected set of semiconductor switches (typically insulated gate bipolar transistors, IGBTs) and capacitors. These submodules are arranged in arms, often in a symmetrical fashion to ensure balanced operation. The arms are connected in parallel and are controlled independently to achieve the desired output voltage waveform.

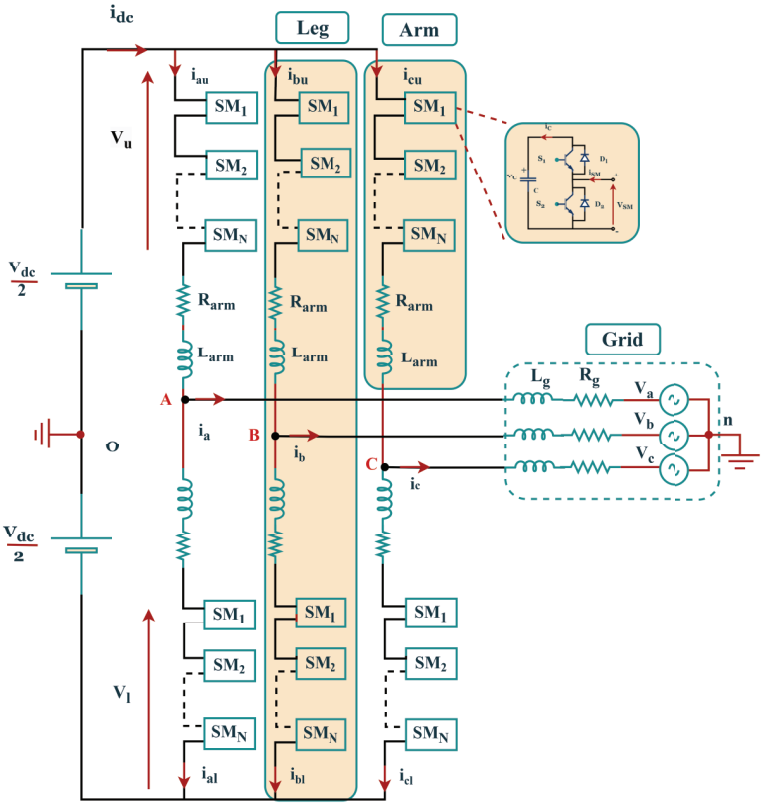


Fig. 1: Circuit diagram for MMC

Each sub module is controlled separately where the individual voltages V_{SM} add up to form a multilevel, nearly sinusoidal staircases waveform [5]
The dynamic equations used for the submodule capacitor voltages are provided by

$$C\frac{V_{SMu}}{dt} = i_{au}S_j \tag{1}$$

$$C\frac{V_{SMl}}{dt} = i_{al}S_j \tag{2}$$

V_{dc}	Dc bus voltage
i_{dc}	DC bus current
i_u	upper arm current
i_l	lower arm current
i_{zj}	AC circulating current
i_{comm}	common mode current
i_{diff}	differential current
i_g	Grid current
i_{oj}	Phase output current
i_{SM}	Submodule current
V_g	Grid voltage
V_c	Capacitor voltage
V_{SM}	Submodule Output Voltage
Vu_j	upper arm voltage of the phase j
Vl_j	lower arm voltage of the phase j
V_{oj}	Inverter output voltage
V_{diff}	differential voltage
L	Arm inductor
R	Arm resistance
Lg	Grid inductor
Rg	Grid resistance
C	Submodule Capacitor

TABLE I: the parameters of MMC

S_1	S_2	V_{SM}	Capacitor
ON	OFF	V_c	Charging
OFF	ON	0	Uncharged

TABLE II: Switching States of SM

where $S_j = 1$ when submodule is ON and $S_j = 0$ when Submodule is OFF Modular Multilevel Converter is mainly composed of N identical submodules per arm that are connected in series. The MMC circuit consists of multiple arms, typically six, for a three-phase system. Each arm is responsible for generating a portion of the output voltage.

Submodules (SMs): Within each arm, multiple submodules are connected in series. The number of SMs per arm can vary based on the desired voltage and power levels. Each submodule contains switching devices, typically Insulated Gate Bipolar Transistors (IGBTs), for controlling current and voltage.

DC Capacitors: Each submodule contains a DC capacitor. These capacitors store and provide energy, ensuring that the output voltage remains stable. [6]
Considering a phase circuit of MMC to simplify the model each arm will be represented by a voltage source in series with the arm inductance ad resistance where,

a specific SM configuration can improve the performance of an MMC in terms of power flow control and fault tolerance, without significantly increasing its cost or complexity. best balance between complexity and functionality can be found in bipolar configurations like the SC-SM and CD SM,though the HB-SM is still an option if negative voltage levels are not required. [7]
circulating current equations [8]

Using Kirchhof voltage law (KVL), the dynamics of the MMC is defined by the following equations:

$$\frac{V_{dc}}{2} - V_{uj} - V_g = (Ri_{uj} + L\frac{di_{uj}}{dt}) + (R_g i_o j + L_g \frac{di_g}{dt}) \quad (3)$$

$$-\frac{V_{dc}}{2} + V_{lj} - V_{oj} = -(Ri_{lj} + L\frac{di_{lj}}{dt}) + (R_g i_o j + L_g \frac{di_g}{dt}) \quad (4)$$

the upper and the lower arm voltages depend on the state of the switches and also the voltage of the capacitors of the modules

$$V_{uj} = \sum_{n=1}^{k} S_{ujk}.V_{cujk} \quad (5)$$

$$V_{lj} = \sum_{n=1}^{k} S_{ljk}.V_{cljk} \quad (6)$$

by defining the phase current i_{oj} and the circulating current i_{zj}, where j refers to the three phases of MMC (a, b, and c)

$$i_{zj} = \frac{i_{uj} + i_{lj}}{2} \quad (7)$$

$$i_{oj} = i_{uj} - i_{lj} \quad (8)$$

The upper and lower arm currents can be expressed by:

$$i_{uj} = i_{zj} + \frac{i_{oj}}{2} \quad (9)$$

$$i_{lj} = i_{zj} - \frac{i_{oj}}{2} \quad (10)$$

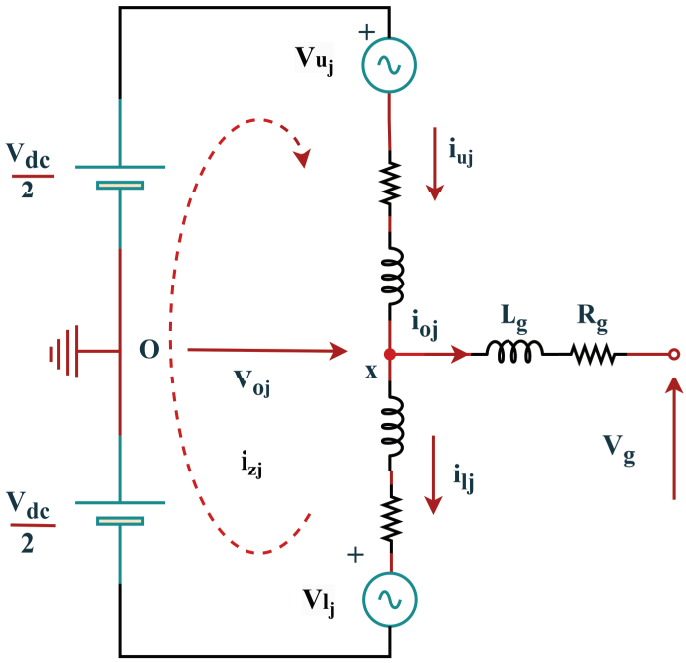


Fig. 2: Single-phase equivalent circuit of the 3Ph MMC

the equations 3 and 4 can be written as follows:

$$V_{oj} = \frac{V_{up} - V_{low}}{2} - \frac{L}{2}\frac{di_{xi}}{dt} - \frac{R}{2}i_{xi} \quad (11)$$

$$2L\frac{di_{zj}}{dt} - 2Ri_{zj} = V_{dc} - (V_{uj} + V_{lj}) \quad (12)$$

$$V_{diff} = \frac{V_u - V_l}{2} \quad (13)$$

In the MMC, the common mode current and differential current are expressed by:

$$i_{comm} = \frac{i_u - i_l}{2} \tag{14}$$

$$i_{diff} = \frac{i_u - i_l}{2} \tag{15}$$

$$i_{uj} = \frac{i_a}{2} + i_{diff} \tag{16}$$

$$i_{lj} = \frac{i_a}{2} - i_{diff} \tag{17}$$

2) MMC model in dq frame: The following system dynamics in dq-frame are obtained by applying the standard abc/dq transformation to (3). [9]

$$L \begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix} - \begin{bmatrix} R & \omega L \\ \omega L & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} e_d \\ e_q \end{bmatrix}$$

where e_d e_q are the grid voltages in dq frame
As indicated in the previous equation, the system dynamics in the dq-frame exhibit significant coupling. To mitigate this coupling, the decoupling control scheme illustrated in Figure 4 is applied in the following manner.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} -\omega L \\ \omega L \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} + \begin{bmatrix} u_i d \\ u_i q \end{bmatrix}$$

where u_{id} u_{iq} are the control output from the PI controller

III. Overall MMC control

As indicated in equation (20), the system dynamics in the dq-frame exhibit significant coupling. To mitigate this coupling, the decoupling control scheme illustrated in Figure 2 is applied in the following manner. MMC control diagram consists of various

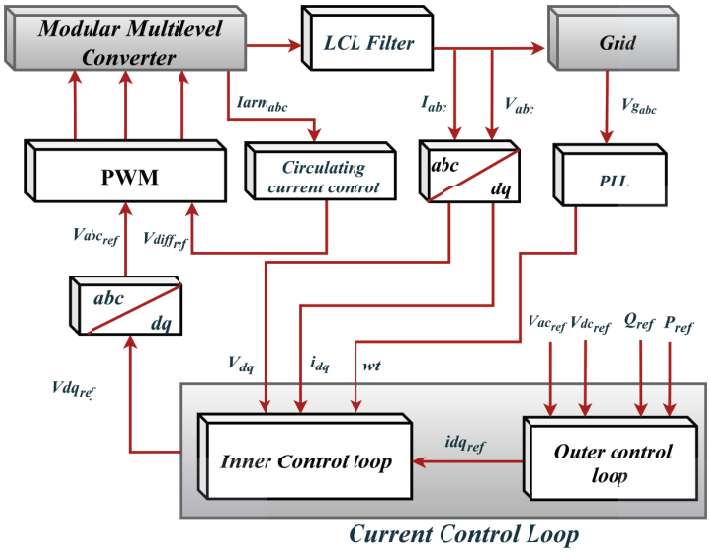


Fig. 3: Control Diagram of MMC

control loops and signal processing elements like filters, d-q axis transformations, and a phase-locked loop (PLL). The main control loops include AC current control and leg current control. [10] .When it comes to inverters with multi-variable control, cascaded current-voltage control is utilized. This control consists of an inner voltage loop and an outer current loop. By introducing multiple feedback variables [11], the controller becomes more flexible and improves the power quality of both the local load voltage and the current exchanged with the grid [12].

the inner control loop generates the reference voltage signal using decoupling current control and voltage feed forward control [13] while The outer control loop sets the desired power exchange between the MMC and the grid. It calculates the reference power values based on grid requirements, system load, or other control objectives. [14] The outer-loop control provides a total of three distinct control modes: active/reactive power control, DC voltage control, and AC voltage control. [15]

The choice of power converter control and modulation techniques for an MMC depends on the specific applications in which it is utilized. To illustrate, solar photovoltaic (PV) systems often make use of sinusoidal pulse width modulation (SPWM) techniques coupled with proportional integral control [16]

The LCL filter plays a crucial role in improving the current quality. It effectively reduces high-frequency harmonics and decreases the ripple caused by switching frequencies in the current waveform [17] Phase-Shifted PWM is a modulation technique that involves generating multiple PWM signals with controlled phase offsets when MMC is operating under unbalanced voltage

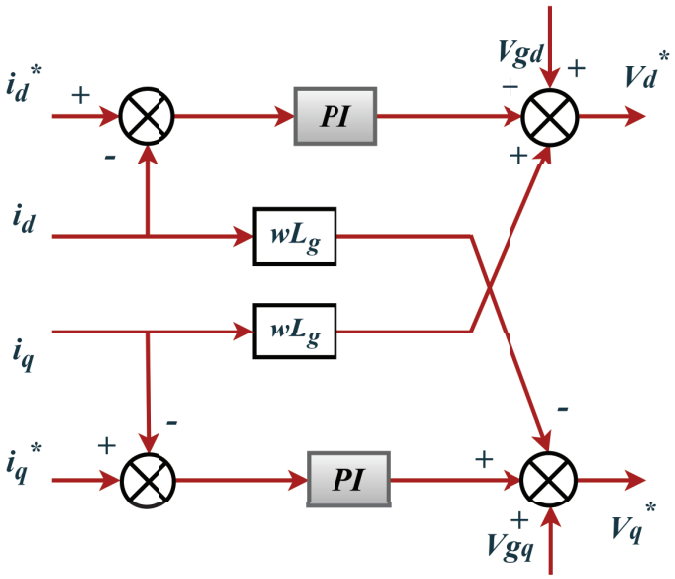


Fig. 4: Inner control loop

conditions, there are additional components, including positive-sequence and zero-sequence circulating currents [18] a dual-vector current controller is proposed to reduce AC-side active power ripple when unbalanced voltages .it also introduces a control approach that accounts for all components of circulating currents under such conditions.

IV. Simulation Results

The proposed control technique aims to regulate the power flow and and control the output current and ensure stability in the three-phase Modular Multilevel converter, Matlab/Simulink software is used to create a three-phase MMC inverter with a resistor-inductor load in order to validate the suggested control scheme.

The diagram of the circulating current in Figure 5 shows that the circulating current is very much like a pure direct current (dc).the circulating current is approaching zero, indicating a balanced condition.In summary, a circulating current plot signifies

a well-controlled and balanced operation, contributing to system stability and efficiency.

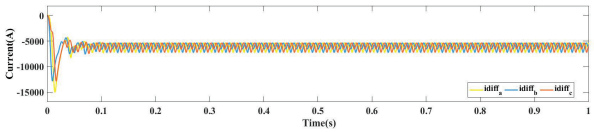
As shown in Figure 6 ,before using PI controller the output voltage signal exhibit irregularities and distortions furthermore the absence of precise control mechanisms that lead to deviations from the desired sinusoidal waveform, resulting in higher Total Harmonic Distortion (THD) levels.however after control, lower THD levels are noticed compared to the uncontrolled state, thereby improving the overall quality of the output voltage signal which emphasizes the effectiveness of the controller.

At the same time, Figure 7(a) and (b) show the results obtained by using PI controller ,a more balanced output current is noticed and the waveform looks almost exactly like a smooth, pure sine wave with very little distortion.

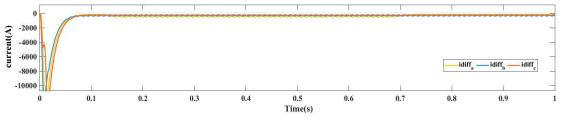
The FFT Analysis of the output voltage and output current are illustrated in Figure 8 and Figure 9 respectively ,the introduction of PI control helped in reducing harmonic distortions in the output voltage and current waveform.which demonstrates the effectiveness of the control strategy in improving the power quality of the MMC's outputs.

Parameter	Symbol	Value
Number of submodules	N	4
Switching frequency	F_s	$5000Hz$
Nominal Frequency	f	$50Hz$
Angular frequency -	w	$2 * pi * f$
AC System voltage	V_{AC}	$8KV$
Filter inductor	L_g	$0.004H$
Filter capacitor	C_g	$1\mu F$
Submodule capacitance	C	$1000\mu F$
Arm inductance	L_{arm}	$0.004H$
Arm resistance	R_{arm}	$0.1ohm$
Dc bus voltage	V_{dc}	$35.36e + 3V$

TABLE III: Simulation parameters of three phase MMC



(a) circulating current in MMC

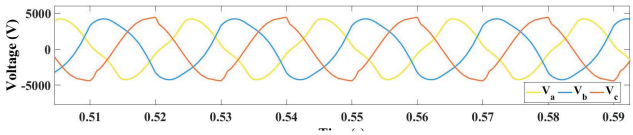


(b) Circulating current using PI controller

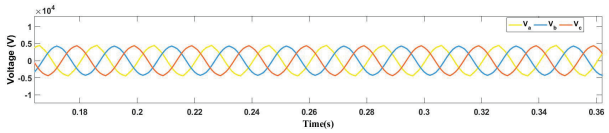
Fig. 5: Comparison of Circulating Current: Pre and Post Control

V. Conclusion

Future investigations in the control of Modular Multilevel Converters MMC are likely to focus on several key areas including the development of more sophisticated control algorithms to enhance the performance of MMC, this could involve the use of artificial intelligence, machine learning, and predictive control methods to improve the converter's dynamic response and efficiency furthermore research on how MMC can contribute to grid stability and integration of renewable energy sources

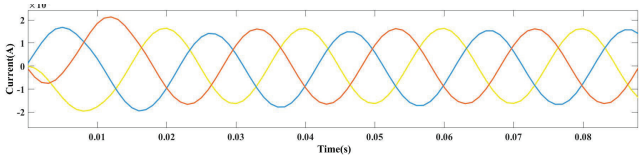


(a) Output voltage with phase shifted PWM

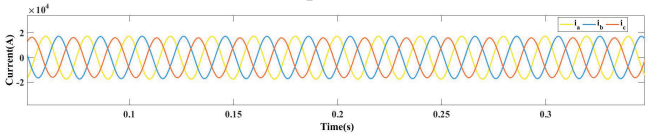


(b) Output voltage after control

Fig. 6: Converter output voltage before and after control

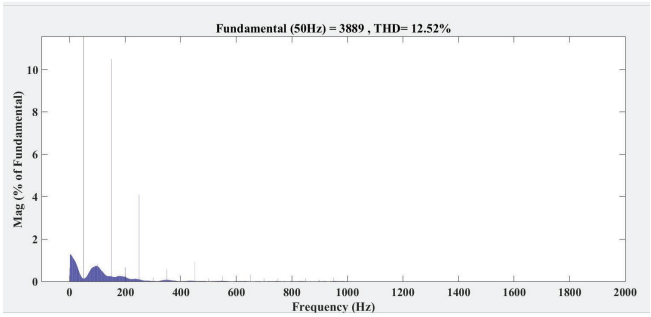


(a) output current

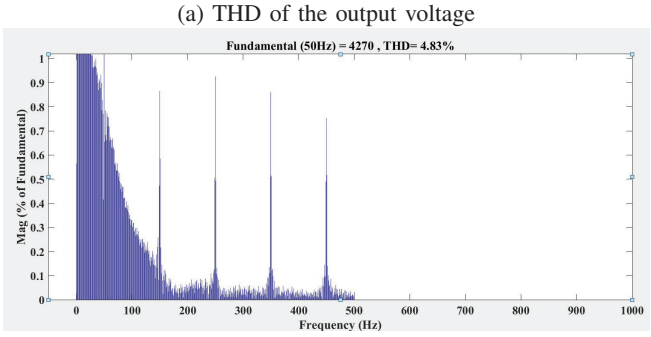


(b) output current using PI controller

Fig. 7: Comparison of output Current: Pre and Post Control

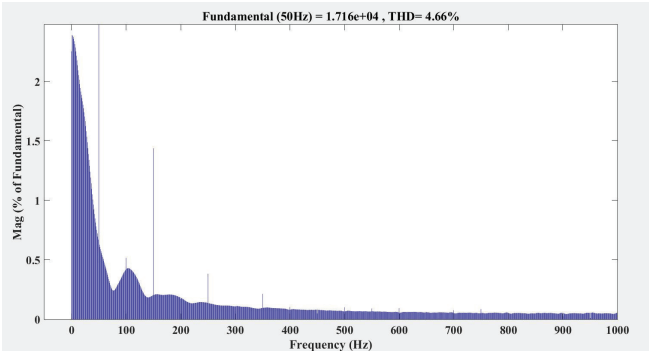


(a) THD of the output voltage

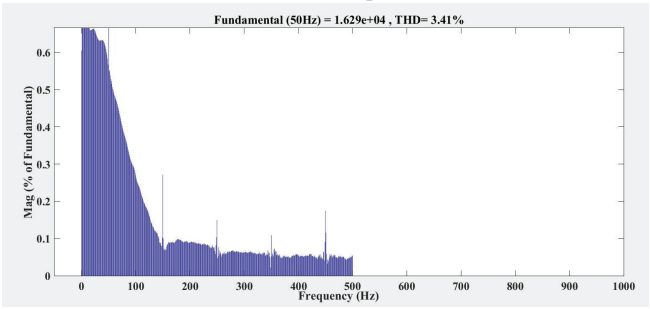


(b) THD of the output voltage using PI controller

Fig. 8: Comparison of output voltage THD Pre and Post Control



(a) THD of the output current



(b) THD of the output current using PI controller

Fig. 9: Comparison FFT analysis of output current Pre and Post Control

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