



# Article Power Ripple Control Method for Modular Multilevel Converter under Grid Imbalances

Mohammed Alharbi<sup>1,\*</sup>, Semih Isik<sup>2</sup>, Abdulaziz Alkuhayli<sup>1</sup> and Subhashish Bhattacharya<sup>2</sup>

- <sup>1</sup> Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia; aalkuhayli@ksu.edu.sa
- <sup>2</sup> Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27606, USA; sisik@ncsu.edu (S.I.); sbhatta4@ncsu.edu (S.B.)
- \* Correspondence: mohalharbi@ksu.edu.sa

Abstract: Modular multilevel converters (MMCs) are primarily adopted for high-voltage applications, and are highly desired to be operated even under fault conditions. Researchers focused on improving current controllers to reduce the adverse effects of faults. Vector control in the DQ reference domain is generally adopted to control the MMC applications. Under unstable grid conditions, it is challenging to control double-line frequency oscillations in the DQ reference frame. Therefore, active power fluctuations are observed in the active power due to the uncontrolled AC component's double line frequency component. This paper proposes removing the active power's double-line frequency under unbalanced grid conditions during DQ transformation. Feedforward and feedback control methods are proposed to eliminate ripple in active power ripple control to eliminate the phase error occurring with the conventional high-pass filters. The system's stability with the proposed controller is tested and compared with a traditional MMC controller using the Nyquist stability criterion. A real-time digital simulator (RTDS) and Xilinx Virtex 7-based FPGA were used to verify the proposed control methods under single-line-to-ground (SLG) faults.

**Keywords:** feedback control system; MMC; HVDC; Nyquist stability criterion (NSC); power system faults; real-time simulator; RTDS

# 1. Introduction

Demand for electrical energy gradually increases with the development of modern technology. Therefore, the global need for sustainable energy is greater than ever. To integrate bulk power from renewable energy sources and reduce carbon emissions, conventional AC power grid infrastructures should be strengthened. However, upgrading existing aged power grids is quite challenging and costly. High-voltage direct-current (HVDC) transmission is a highly economical and versatile alternative for bringing more renewable power from remote locations. Moreover, HVDC transmission allows for bidirectional power flow control, the interconnection of asynchronous or multiple weak AC sources, and more power transfer to long distances [1]. Hence, HVDC transmission accommodates more clean energy sources while carrying more power than that of traditional high-voltage AC (HVAC) transmission.

Until 2003, HVDC transmission applications were designed on the basis of voltage source-based two- or three-level converter (VSC) topologies. In 2003, the modular multi-level converter (MMC) topology was adopted for the Trans Bay Cable project [2]. Since then, the MMC has dominated the market for high-voltage applications due to its simple, modular, and scalable structure [3]. The MMC topology has many advantages over other converter topologies at high voltage, but its performance highly depends on the control structure and modulation technique [4]. A modulation technique such as nearest-level modulation (NLM) or pulse width modulation (PWM) generates switching signals for



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). submodules (SMs). An SM is the smallest power module of an MMC [5–7]. There are several SM types available for MMC applications. A half-bridge SM (HBSM) is the most preferred SM type due to a simple structure where it only consists of two switching elements, such as an IGBT and a storage element, such as a capacitor. The adopted modulation technic decides the SM that is inserted into an MMC arm [8,9]. Unlike the other converter topologies, capacitors are distributed in SMs in MMC arms. Thus, keeping all capacitor voltages around the reference value is critical for proper and stable operation.

For this reason, capacitor voltage balancing and sorting algorithms are utilized to keep the SM capacitor voltage around the reference value [10–12]. If capacitor voltages are not balanced well, the magnitude of the circulating current rises inside an MMC. A circulating current is a negative sequence current at twice the fundamental frequency. Thus, circulating current control methods target eliminating the negative sequence component at double the fundamental frequency during a steady state. However, positive and zero-sequence components also occur under unstable conditions [13]. The DC current was unevenly distributed among phases [14].

The double-grid frequency component causes a ripple increase in active power, DC voltage, and DC current under grid imbalances [15–17]. Harmonic instability may occur in an MMC unless internal dynamics are properly controlled. This may eventually result in an inevitable converter shutdown. Thus, various current control techniques are proposed to dampen the internal dynamics of an MMC to prevent undesired effects of the ripple and possible system shutdown.

In [18], a control strategy based on proportional integral (PI) and resonant (R) controllers is proposed. Even though the control method can eliminate the power ripple, the controllers may not achieve 0 dB response at the resonant frequency for the closed-loop operation. Researchers [19] proposed a control strategy to eradicate the active power ripples of the AC grid based on a proportional resonant (PR) controller. Although no DQ transformation is required in this method, an asymmetric current may still cause improper operation of the PR controller and the protection devices. The authors in [20] proposed to control the arm currents with PI and a vector PI. Although DQ transformation is required, the proposed method achieved better performance than that of the PR controller where no DQ transformation is required under an unstable grid condition. Researchers [21] targeted the circulating current to eliminate the double-grid frequency component during grid imbalance to reduce grid-side disturbances. However, suppressing the circulating current under grid imbalances is challenging, as positive and zero-sequence components also occur. The steady-state error also increases with the number of PI controllers. The authors in [22] proposed a predictive closed-loop averaging control algorithm to eliminate uneven loss distribution due to unbalanced DC, and double-frequency components to indirectly eliminate power ripples. The authors in [23] suggested a dual-vector current control algorithm to separately control positive and negative sequence components with several proportional integral (PI) controllers in the DQ reference frame. However, having multiple PI controllers can further complicate the system and increase computation time. Thus, this method may require a larger look-up table and increase complexity for larger MMC applications.

This paper proposes removing the power ripple under an unbalanced grid-side condition. The AC component of the grid current is controlled in the DQ domain to eliminate the power ripple that increases under grid imbalances. The power fluctuation is eliminated under unbalanced grid voltages. Feedforward and a feedback closed-loop control methods are proposed for suppressing power ripple under grid imbalances. Furthermore, an extraction method of AC components is proposed for power-ripple control to eliminate phase error occurring with conventional high-pass filters. A hardware-in-loop (HIL) setup with a real-time digital simulator (RTDS) and Xilinx Virtex FPGAs were used to verify the effectiveness of the proposed control methods under SLG faults. Result validation shows that the power ripple was significantly reduced with the proposed feedforward and feedback control strategies.

#### 2. MMC Mathematical Model

An MMC has  $N_t$  series-connected submodules (SMs) in a phase arm, as seen in Figure 1. Various SM types are available for MMC applications, and HBSM, seen in Figure 1, was preferred in this paper. An MMC consists of three-phase legs, and each leg contains an upper (positive) and a lower (negative) arm. Each arm has an arm inductor to limit the circulating current amplitude and arm current ripples. Arms operate complimentary to generate the requested voltage. Figure 2 shows a single-line diagram equivalent circuit for an MMC. Kirchhoff's voltage law can be applied to the positive and the negative arms to determine the voltages of arms:

$$v_{u,x} = \frac{V_{DC}}{2} - L_o \frac{di_{u,x}}{dt} - R_o i_{u,x} - v_{m,x}$$
(1)

$$v_{l,x} = \frac{V_{DC}}{2} - L_o \frac{di_{l,x}}{dt} - R_o i_{l,x} + v_{m,x}$$
(2)

where  $v_{u,x}$  and  $v_{l,x}$  are the output voltage of positive and negative arms of phase x ( $x \in a, b, c$ ), respectively.  $v_{m,x}$  is the converter AC side output voltage.  $i_{u,x}$  and  $i_{l,x}$  denote the currents flowing in the arms, respectively.  $V_{DC}$  represents the DC bus voltage.  $L_o$  and  $R_o$  is the MMC arm inductance and resistance, respectively.

Induced voltage across arm inductors and resistors is relatively small compared to the arm valve voltage; thus, it can be ignored. Accordingly, converter AC side output voltage  $v_{m,x}$  is expressed as follows:

$$v_{m,x} = \frac{v_{l,x} - v_{u,x}}{2}$$
(3)

Similarly, currents for upper  $i_{u,x}$  and lower arms  $i_{l,x}$  are expressed as follows:

$$i_{u,x} = i_{z,x} + \frac{i_x}{2}$$
 (4)

$$i_{l,x} = i_{z,x} - \frac{i_x}{2}$$
(5)

where  $i_{z,x}$  is the differential current, and  $i_x$  is the AC side current. The differential current comprises a DC current  $i_{dc,x}$  and circulating current  $i_{circ,x}$ .

Adding Equations (1) and (2) and substituting Equations (4) and (5) gives:

$$i_{z,x} = \frac{i_{u,x} + i_{l,x}}{2} = i_{dc,x} + i_{circ,x}$$
(6)

$$L_o \frac{di_{Z,x}}{dt} + R_o i_{z,x} = \frac{V_{DC}}{2} - \frac{v_{u,x} + v_{l,x}}{2}$$
(7)

Thus, the dynamic of differential voltage  $v_{z,x}$  can be expressed as follows:

$$v_{z,x} = L_o \, \frac{di_{Z,x}}{dt} + R_o \, i_{z,x} \tag{8}$$



Figure 1. Three-phase MMC configuration.



Figure 2. Single-line diagram circuit of MMC.

## 3. MMC Control System

The control system of an MMC mainly consists of SM- and system-level control. Figure 3 shows a typical MMC control structure. Unlike conventional two- and three-level converters, the MMC needs an additional controller to balance SM capacitor voltages and the circulating current (CC) to ensure stable operation. In this paper, the circulating current (CC) control strategy proposed in [16], and the sorting-algorithm-based SM voltage balancing [24] method were implemented.

The most common control method for developing current control systems is vector transformations that convert three-phase voltages and currents into two equivalent vectors. The vector transformation technique benefits VSC control systems, such as independent

active and reactive power control, current limiting without waveform distortions, and relatively less computational burden. DQ vectors rotate with a specified angular speed (e.g.,  $\omega$ ), and three-phase sinusoidal voltages and currents rotate and synchronize with AC grid voltages. Rotating speed is obtained from the phase-locked loop (PLL) circuit. Thus, grid voltages and currents are transformed into DC components in the DQ reference frame under balanced grid conditions [25]. The dynamic behavior of the AC side output voltage of the MMC was derived from Figure 2 as follows:

$$v_{m,x} = v_x + L_e \frac{di_x}{dt} + R_e i_x \tag{9}$$

$$L_e = L + \frac{L_o}{2} \tag{10}$$

$$R_e = R + \frac{R_o}{2} \tag{11}$$

where  $v_x$  and  $i_x$  are the three-phase grid voltages and currents, respectively. *L* and *R* represent the transformer inductance and resistance, respectively.  $L_o$  and  $R_o$  is the MMC arm inductance and resistance, respectively.  $L_e$  and  $R_e$  are the equivalent inductance and resistance of the MMC AC system.

The output voltage of an MMC can be represented in the DQ reference frame as:

$$v_{m,d} = v_d - \omega L_e \, i_q + L_e \frac{di_d}{dt} + R_e \, i_d \tag{12}$$

$$v_{m,q} = v_q + \omega L_e \, i_d + L_e \frac{di_q}{dt} + R_e \, i_q \tag{13}$$

where  $v_{m,d}$  and  $v_{m,q}$  are MMC output voltages in the DQ reference frame.  $v_d$  and  $v_q$  are the DQ grid voltages.  $i_d$  and  $i_q$  represent the DQ grid currents.

The inner current control of an MMC is established on the basis of Equations (12) and (13) to generate reference voltages for gate signals. Reference commands  $i_d^*$  and  $i_q^*$  are typically used to control voltage and power under normal grid conditions. Conventional PI controllers are sufficient for MMC voltage and power controls under balanced conditions.



Figure 3. Overview of MMC control structure.

## Analysis of DQ Vectors

Detailed mathematical derivation and validations of the DQ transformation under unbalanced conditions are essential to ensure proper converter operation. Ideal AC grid voltages and currents are assumed as follows:

$$v_{x}(t) = \begin{bmatrix} v_{a} \\ v_{b} \\ v_{c} \end{bmatrix} = \begin{bmatrix} \hat{v}_{a}\sin(\theta_{a}) \\ \hat{v}_{b}\sin(\theta_{b}) \\ \hat{v}_{c}\sin(\theta_{c}) \end{bmatrix}$$
(14)

$$i_{x}(t) = \begin{bmatrix} i_{a} \\ i_{b} \\ i_{c} \end{bmatrix} = \begin{bmatrix} \hat{I}_{a}\sin(\theta_{a} + \alpha) \\ \hat{I}_{b}\sin(\theta_{b} + \alpha) \\ \hat{I}_{c}\sin(\theta_{c} + \alpha) \end{bmatrix}$$
(15)

$$\theta_{x} = \begin{bmatrix} \theta_{a} \\ \theta_{b} \\ \theta_{c} \end{bmatrix} = \begin{bmatrix} \omega t \\ \omega t - \frac{2\pi}{3} \\ \omega t + \frac{2\pi}{3} \end{bmatrix}$$
(16)

where  $\hat{v}_a$ ,  $\hat{v}_b$  and  $\hat{v}_c$  are the amplitude of the grid voltages.  $\hat{l}_a$ ,  $\hat{l}_b$  and  $\hat{l}_c$  are the amplitude of the three-phase current.  $\alpha$  is the phase shift between the voltage and current.  $\theta_x$  is the phase angle of phase *x*.  $\omega$  is the angular frequency.

The three-phase voltages and currents in Equations (14) and (15) are transformed into the synchronous DQ reference frame, as explained in Appendix A. The DQ reference frame is selected in a way such that the Q-axis grid voltage is adjusted to zero (e.g.,  $v_q = 0$ ). Thus, the DQ vectors of the grid voltages and currents can be written as follows:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} v_{d,dc} + v_{d,ac} \\ v_{q,dc} + v_{q,ac} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} + \frac{1}{3} \begin{bmatrix} -\cos(2\theta_a) & -\cos(2\theta_b) & -\cos(2\theta_c) \\ \sin(2\theta_a) & \sin(2\theta_b) & \sin(2\theta_c) \end{bmatrix} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix}$$
(17)

$$\begin{bmatrix} i_{d} \\ i_{q} \end{bmatrix} = \begin{bmatrix} i_{d,dc} + i_{d,ac} \\ i_{q,dc} + i_{q,ac} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} \cos(\alpha) & \cos(\alpha) & \cos(\alpha) \\ \sin(\alpha) & \sin(\alpha) & \sin(\alpha) \end{bmatrix} \begin{bmatrix} \hat{l}_{a} \\ \hat{l}_{b} \\ \hat{l}_{c} \end{bmatrix} + \frac{1}{3} \begin{bmatrix} \cos(2\theta_{a} + \alpha) & \cos(2\theta_{b} + \alpha) & \cos(2\theta_{c} + \alpha) \\ \sin(2\theta_{a} + \alpha) & \sin(2\theta_{b} + \alpha) & \sin(2\theta_{c} + \alpha) \end{bmatrix} \begin{bmatrix} \hat{l}_{a} \\ \hat{l}_{b} \\ \hat{l}_{c} \end{bmatrix}$$
(18)

From Equations (17) and (18), DQ vectors of the grid voltages and currents comprised DC and AC components. The D axis was 90° out of phase with the Q axis, and AC components of the D and Q axes always had the same amplitudes. AC components had double-line frequency (e.g.,  $2\omega t$ ) and only existed under the unbalanced grid conditions when the amplitudes of the grid voltages (e.g.,  $\hat{v}_a$ ,  $\hat{v}_b$  and  $\hat{v}_c$ ) and the amplitudes of the currents (e.g.,  $\hat{I}_a$ ,  $\hat{I}_b$  and  $\hat{I}_c$ ) are unbalanced. Thus, DQ grid voltages and currents can be simplified in terms of DC and AC components as follows:

$$Y_d(t) = Y_{d,dc} + \hat{Y}_{ac} \sin\left(2\omega t + \delta_Y - \frac{\pi}{2}\right) = Y_{d,dc} + Y_{d,ac}$$
(19)

$$Y_q(t) = Y_{q,dc} + \hat{Y}_{ac} \sin(2\omega t + \delta_Y) = Y_{q,dc} + Y_{q,ac}$$

$$\tag{20}$$

where  $(Y \in v, i)$ .  $\hat{Y}_{ac}$  is the amplitude of the AC components of the DQ vectors; and  $\delta_Y$  represents the initial phase angle.

Under unbalanced grid conditions, conventional PI controllers are insufficient to precisely control AC components, which ultimately cannot satisfy the condition of the zero steady-state error. Resonant controllers must control the double-line frequency oscillation under the unbalanced grid voltages. Thus, the inner current control system was developed on Equations (12) and (13) considering AC and DC components, as shown in Figure 4. Reference commands  $i^*_{d,dc}$  and  $i^*_{q,dc}$  were used to control the DC voltage, active power, and reactive power. Reference commands  $i^*_{d,dc}$  and  $i^*_{q,dc}$  should always be DC components. The reference for  $i^*_{d,ac}$  and  $i^*_{q,ac}$  can be set to zero to suppress the AC components (e.g.,

 $i_{d,ac} = i_{q,ac} = 0$ ) under the unbalanced grid voltages to balance the three-phase grid currents. Figure 5 shows the block diagram of the inner current control loop for tuning the controller parameters.



Figure 4. Inner current control system.



Figure 5. Block diagram of inner current control loop.

#### 4. Proposed Power Control Method

Under unbalanced grid voltages, controlling power using conventional methods results in power ripples because of AC components presented in DQ grid voltages and currents. Active power *P* and reactive power *Q* are given as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$
(21)

From Equations (17) and (18), the DQ vectors of the grid voltages and currents comprise DC and AC components. Thus, the power equation derived in Equation (21) can be rewritten in terms of the DC and AC components as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P_{dc} + P_{ac} \\ Q_{dc} + Q_{ac} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_{d,dc} + v_{d,ac} & v_{q,ac} \\ v_{q,ac} & -(v_{d,dc} + v_{d,ac}) \end{bmatrix} \begin{bmatrix} i_{d,dc} + i_{d,ac} \\ i_{q,dc} + i_{q,ac} \end{bmatrix}$$
(22)

where  $P_{dc}$  and  $P_{ac}$  are the active power's DC and AC components (ripple), respectively.  $Q_{dc}$  and  $Q_{ac}$  are the reactive power's DC and AC components (ripple), respectively.

DC and AC components of grid voltages (e.g.,  $v_{d,dc}$ ,  $v_{q,dc}$ ,  $v_{d,ac}$  and  $v_{q,ac}$ ) and grid currents (e.g.,  $i_{d,dc}$ ,  $i_{q,dc}$ ,  $i_{d,ac}$  and  $i_{q,ac}$ ) are defined in Equations (17) and (18). Thus, power terms in Equation (22) (e.g.,  $v_{d,dc}i_{d,dc}$ ,  $v_{d,ac}i_{d,ac}$ ,  $v_{q,ac}i_{q,ac}$ , ... etc.) can be analyzed to classify each power term. Power term ( $v_{d,dc}i_{d,dc}$ ) belongs to the DC component of the active power. Results also show that ( $v_{d,ac}i_{d,ac} + v_{q,ac}i_{q,ac}$ ) contributes to the active power DC component. The other power terms contribute to the power ripple. Figure 6 shows the active power

analysis under grid imbalances. Initially, the three-phase voltage and current are balanced, where the amplitude of the grid voltage and current are 1 per unit. The phase shift between the voltage and current is 30° (e.g.,  $\alpha = 30^{\circ}$ ). At Time = 10 ms, the three-phase voltage and current become unbalanced, where the amplitude of the grid voltage  $\hat{v}_a$  and grid current  $\hat{l}_a$  become 0.05 and 1.5 per unit, respectively. After 40 ms, the three-phase system becomes balanced, again. Thus, the active and the reactive power can be expressed into AC and DC power as follows:

$$\begin{bmatrix} P_{dc} \\ Q_{dc} \\ P_{ac} \\ Q_{ac} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_{d,dc} & 0 & v_{d,ac} & v_{q,ac} \\ 0 & -v_{d,dc} & v_{q,ac} & -v_{d,ac} \\ v_{d,ac} & v_{q,ac} & v_{d,dc} & 0 \\ v_{q,ac} & -v_{d,ac} & 0 & -v_{d,dc} \end{bmatrix} \begin{bmatrix} i_{d,dc} \\ i_{q,dc} \\ i_{d,ac} \\ i_{q,ac} \end{bmatrix}$$
(23)

Derived equations in Equation (23) indicate that the active and reactive power can independently be controlled using the currents ( $i_{d,dc}$  and  $i_{q,dc}$ ), respectively. The active power fluctuation  $P_{ac}$  and the reactive power fluctuation  $Q_{ac}$  can also be controlled using the currents  $i_{d,ac}$  and  $i_{q,ac}$ , respectively. However, the AC components  $i_{d,ac}$  and  $i_{q,ac}$  cannot be controlled independently as explained in Equations (19) and (20). The AC component amplitudes  $\hat{Y}_{ac}$  should be the same for the D and Q axes, and a phase shift between the AC components in which the D axis lags the Q axis by 90° is required. In this paper, the active power fluctuation control was considered and analyzed.



Figure 6. Active power theoretical analysis (per unit) under unbalanced grid conditions.

#### 4.1. Feedforward Control Method for the Active Power Ripple

Equation (23) shows that the active power ripple could be suppressed (e.g.,  $P_{ac} = 0$ ) by controlling AC component  $i_{d,ac}$  under unbalanced grid conditions. Reference commands for the inner current control system shown in Figure 4 were derived from Equation (23) to eliminate power ripple  $P_{ac}$  as follows:

$$i_{d,dc}^{*}(t) = \frac{\frac{2}{3}P_{dc}^{*} - \left(v_{d,ac} \ i_{d,ac} + v_{q,ac} \ i_{q,ac}\right)}{v_{d,dc}}$$
(24)

$$i_{q,dc}^{*}(t) = \frac{-\frac{2}{3}Q_{dc}^{*} + \left(v_{q,ac}i_{d,ac} - v_{d,ac}i_{q,ac}\right)}{v_{d,dc}}$$
(25)

$$i_{d,ac}^{*}(t) = -\frac{\left(v_{d,ac} \ i_{d,dc} + v_{q,ac} \ i_{q,dc}\right)}{v_{d,dc}}$$
(26)

$$i_{q,ac}^{*}(t) = i_{d,ac}^{*}(t - \mathcal{T})$$
 (27)

where  $P_{dc}^*$  and  $Q_{dc}^*$  are active and reactive power references, respectively.  $\mathcal{T}$  indicates the time-delay constant for the 90° phase shift between DQ vectors.

Equation (27) shows that reference command  $i_{d,ac}^*$  was shifted by 90° to determine reference command  $i_{q,ac}^*$  and satisfy DQ vector characteristics explained in Equations (19) and (20). A simple time-delay function can be used to determine  $i_{q,ac}^*$ . However, the time-delay function may provide excessive delay during transient states (e.g., at the beginning and end of events). Therefore, reference command  $i_{q,ac}^*$  was calculated to eliminate the time-delay function impact. Voltages  $v_{d,ac}$  and  $v_{q,ac}$  can be stated as follows:

$$v_{d,ac}(t) = v_{q,ac}(t - \mathcal{T}) \tag{28}$$

$$v_{q,ac}(t) = -v_{d,ac}(t - \mathcal{T}) \tag{29}$$

Applying time delay T to Equation (26) and substituting it with Equations (28) and (29) yields:

$$i_{q,ac}^{*}(t) = -\frac{\left(v_{q,ac} \ i_{d,dc} - v_{d,ac} \ i_{q,dc}\right)}{v_{d,dc}} \tag{30}$$

Thus, reference command  $i_{q,ac}^*$  is calculated from DC and AC components without the need for the time-delay function.

# 4.2. Feedback Control Loop Method for Active Power Ripple

The feedback control loop systems are widely utilized in industrial practice due to their ability to enhance dynamic performance and reduce the disturbance of systems. From Equation (23), power ripple  $P_{ac}$  can be manipulated by injecting current  $i_{d,ac}$ , while other power terms (e.g.,  $v_{d,ac} i_{d,dc}$  and  $v_{q,ac} i_{q,dc}$ ) are viewed as disturbances to the control system. Hence, the power ripple control shown in Figure 7 was developed with a proportional resonant (PR) controller. Figure 8 shows the block diagram of the power ripple control loop for tuning the controller parameters.



Figure 7. Power ripple controller.



Figure 8. Power ripple closed-loop control block diagram.

## 4.3. Extraction of DC and AC Components

The AC component magnitude and phase angle are critical and should be determined to control power ripple under unbalanced grid voltages. DC and AC components are typically extracted using low-(LPF) and high-pass filters (HPF). However, conventional HPFs cause multiple phase-shift angles to the output. This phase error may result in instability issues for the power ripple control system. The open-loop frequency analysis for the conventional first and higher-order HPFs is shown in Figure 9. Cut-off frequency was 10 Hz. The phase error was about 4.77° at the double-line frequency with the first-order HPF. Using higher-order HPFs increased the phase error. Therefore, DC and AC components of DQ grid voltages and currents were extracted using series-cascaded first-order LPFs as shown in Figure 10, where Y is the input to the filter,  $Y_{dc}$  and  $Y_{ac}$  are DC and AC outputs of the filters.  $\omega_c$  is the cut-off frequency of the LPF, and *i* represents the number of series-connected LPFs. As shown in Figure 11, the phase error was almost zero when using four-series cascaded LPFs.



Figure 9. Frequency analysis for conventional HPFs.



Figure 10. Proposed HPF block diagram.



Figure 11. Frequency analysis for proposed HPFs.

# 5. RTDS Results

Controller validation was tested on the MMC-based HVDC system shown in Figure 12. A real-time digital simulator (RTDS) and Xilinx Virtex 7 FPGAs, seen in Figure 13, were used to verify the power control method under normal and abnormal operating conditions. A Y– $\Delta$  converter transformer eliminates the zero sequence from flow into the MMC. Table 1 shows the system parameters. The MMC system utilized 400 SMs per arm with SM voltage ratings of 1.6 kV.



Figure 12. Simulated three-phase MMC system in RTDS.



Figure 13. HIL testbed.

Symbol	Description	Value	Unit
Р	Base MVA	1000	MVA
$V_{DC}$	DC voltage	640	kV
$v_{abc}$	Line-to-line AC voltage (grid)	400	kV
T	Transformer $(\Delta - Yg)$	333/400	kV
$N_t$	Number of SM per arm (Nt)	400	-
f	Fundamental frequency	60	Hz
Lo	Arm inductance	50	mH
L	Transformer inductance	53	mH
С	SM capacitance	15	mF

Table 1. Parameters of simulated MMC system.

#### 5.1. Feedforward Power Ripple Control Method Validation

The performance of the MMC system was evaluated under single-line-to-ground (SLG) faults to validate the proposed feedforward control method. The SLG fault occurred at the high-voltage side of the converter transformer on phase a. MMC active power performance under the SLG fault with the conventional control and with the proposed feedforward power ripple control is compared in Figure 14. The power ripple of active power under the SLG fault is eliminated using the proposed feedforward power control technique.

Figure 15 shows AC grid-side voltages, active power, reactive power, DQ current vectors  $i_d$  and  $i_q$ , and AC grid current performance under SLG fault. MMC system operating events are as follows:

- 1. At time = 0, the MMC system operates in inverter mode with a unity power factor (P = 1 pu and Q = 0 pu).
- 2. At time = 0.1 s, the SLG fault is initiated.
- 3. At time = 0.3 s, the fault is cleared.
- 4. At time = 0.4 s, active power is ramped from 1 pu to -1 pu within 100 ms (rectifier mode).
- 5. At time = 0.6 s, another SLG fault is initiated.
- 6. At time = 0.8 s, the fault is cleared.

As shown in Figure 15, the feedforward control method was valid to suppress the active power ripple under the SLG fault in an inverter or rectifier mode. Active power precisely tracks its reference command. AC grid voltages and currents are also pure sinusoidal waveforms. The overall dynamic performance of the MMC was acceptable under SLG faults in inverter and rectifier modes.



**Figure 14.** Comparison of active power with conventional and proposed feedforward control method under SLG fault.



**Figure 15.** Dynamic performance of MMC with proposed feedforward control method under SLG faults.

## 5.2. Feedback Power Ripple Control Method Validation

To validate the power control method proposed in Section 4.2, the dynamic performance of the MMC system was studied under SLG fault. MMC active power performance with the proposed feedforward and feedback control techniques under the SLG fault is shown in Figure 16. The feedback control method had higher suppression capability and lower transient oscillation when compared to the feedforward control method.

Figure 17, shows AC grid side voltages, active power, reactive power, DQ current vectors  $i_d$  and  $i_q$ , and AC grid current performance under the SLG fault. The MMC system operating events in this section were similar to those in the case in Section 5.1.



**Figure 16.** Performance comparison of active power with feedback and feedforward control methods under the SLG fault.



**Figure 17.** Dynamic performance of the MMC with the proposed feedback control method under SLG faults.

#### 5.3. Stability Effect of Controller on MMC Systems

A switching power electronic converter's stability and dynamic performance are critical for safe operation. Therefore, stability analysis of feedback-controlled converters is a significant design consideration. Power-electronics-based systems are sensitive to instabilities under impedance interactions between several power-electronics-based subsystems. Therefore, subsystems are divided as a source and load subsystems at a random DC interface point within the system. Numerous stability criteria for DC systems were proposed, such as the Middlebrook [26,27], gain and phase margin [28], energy source analysis consortium [22], three-step impedance [29], and passivity-based stability [30] criteria. Impedance-based stability analysis treats the power-electronics-based system as a black box and tries to predict its stability. The authors in [31,32] indicated that the impedance ratio of the load to the source can be measured at the point of common coupling (PCC). Therefore, the impedance ratio can be considered to be the entire system's open-loop gain, and stability could be observed on the basis of the Nyquist stability criterion (NSC). In this paper, the frequency scanning technique is applied to the system shown in Figure 12 to investigate the system's stability by measuring the MMC impedance and the AC grid's admittance in the DQ domain at different frequencies under a balanced grid condition. The frequency scanning is first applied to a conventional MMC controller under a balanced grid condition. As seen in Figure 18, the Nyquist plot reveals an unstable response with an encirclement around (-1, j0). The same test was applied to the same MMC setup with the proposed feedback controller. As seen in Figure 19, the Nyquist plot does not encircle (-1, j0), which can be interpreted as the system is stable at different frequencies with the proposed controller.



**Figure 18.** Impedance ratio. (**a**) Nyquist plot under balanced grid condition with conventional mmc controller; (**b**) zoom in (-1, j0).



**Figure 19.** Impedance ratio. (a) Nyquist plot under balanced grid condition with the proposed feedback controller; (b) zoom in (-1, j0).

#### 6. Conclusions

This paper implemented active power control using the vector current in the DQ synchronous reference frame for an MMC system under SLG fault. A simple feedforward control method was proposed to eliminate the active power ripples under unbalanced grid voltages. The power fluctuation under the SLG fault is significantly reduced with the feedforward control approach. A feedback loop control method was also proposed to eliminate power ripple with more robustness than that of the feedforward control method. The power ripple feedback control method is significantly reduced with lower oscillation during the fault transient. An extraction technique for AC components was proposed for power ripple controls to eliminate phase error with conventional high-pass filters. The dynamic performance of the MMC-based HVDC system was examined in the RTDS system to verify the effectiveness of the proposed control methods under SLG faults. Results show that the power ripple was significantly reduced with the feedforward and feedback control strategies under unbalanced grid voltages.

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# Appendix A

DQ transformation can be performed by using Park's transformation matrix  $T_{dq}$  as follows:

$$T_{dq} = \frac{2}{3} \begin{bmatrix} \sin(\theta_a) & \sin(\theta_b) & \sin(\theta_c) \\ \cos(\theta_a) & \cos(\theta_b) & \cos(\theta_c) \end{bmatrix}$$
(A1)

$$\left[Y_{dq}\right]_{3\times 1} = \left[T_{dq}\right]_{2\times 3} \left[Y_{abc}\right]_{3\times 1} \tag{A2}$$

where  $Y \in v$ , *i* and  $Y_{dq}$  are DQ voltages and currents.  $Y_{abc}$  is the three-phase grid voltage and current vectors.

Three-phase voltages in Equation (14) are transformed into the synchronous DQ reference frame as follows:

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\theta_a) & \sin(\theta_b) & \sin(\theta_c) \\ \cos(\theta_a) & \cos(\theta_b) & \cos(\theta_c) \end{bmatrix} \begin{bmatrix} \vartheta_a \sin(\theta_a) \\ \vartheta_b \sin(\theta_b) \\ \vartheta_c \sin(\theta_c) \end{bmatrix}$$
(A3)

Equation (A3) can be rewritten as follows:

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} + \frac{1}{3} \begin{bmatrix} -\cos(2\theta_a) & -\cos(2\theta_b) & -\cos(2\theta_c) \\ \sin(2\theta_a) & \sin(2\theta_b) & \sin(2\theta_c) \end{bmatrix} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix}$$
(A4)

Similarly, the three-phase currents in Equation (15) are transformed into the synchronous DQ reference frame as follows:

$$\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\theta_a) & \sin(\theta_b) & \sin(\theta_c) \\ \cos(\theta_a) & \cos(\theta_b) & \cos(\theta_c) \end{bmatrix} \begin{bmatrix} \hat{I}_a \sin(\theta_a + \alpha) \\ \hat{I}_b \sin(\theta_b + \alpha) \\ \hat{I}_c \sin(\theta_c + \alpha) \end{bmatrix}$$
(A5)

$$\begin{bmatrix} i_{d}(t) \\ i_{q}(t) \end{bmatrix} = \frac{1}{3} \begin{bmatrix} \cos(\alpha) & \cos(\alpha) & \cos(\alpha) \\ \sin(\alpha) & \sin(\alpha) & \sin(\alpha) \end{bmatrix} \begin{vmatrix} \hat{l}_{a} \\ \hat{l}_{b} \\ \hat{l}_{c} \end{vmatrix} + \frac{1}{3} \begin{bmatrix} -\cos(2\theta_{a}+\alpha) & -\cos(2\theta_{b}+\alpha) & -\cos(2\theta_{c}+\alpha) \\ \sin(2\theta_{a}+\alpha) & \sin(2\theta_{b}+\alpha) & \sin(2\theta_{c}+\alpha) \end{bmatrix} \begin{vmatrix} \hat{l}_{a} \\ \hat{l}_{b} \\ \hat{l}_{c} \end{vmatrix}$$
(A6)

#### References

- 1. Liang, X.; Abbasipour, M. HVDC Transmission and Its Potential Application in Remote Communities: Current Practice and Future Trend. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1706–1719. [CrossRef]
- Westerweller, T.; Friedrich, K.; Armonies, U.; Orini, A.; Parquet, D.; Wehn, S. Trans Bay cable—World's first HVDC system using multilevel voltage-sourced converter. CIGRÉ Sess. 2010, 2010, 20001169020.
- Montero-Robina, P.; Marquez, A.; Dahidah, M.S.A.; Vazquez, S.; Leon, J.I.; Konstantinou, G.; Franquelo, L.G. Feedforward Modulation Technique for More Accurate Operation of Modular Multilevel Converters. *IEEE Trans. Power Electron.* 2022, 37, 1700–1710.
- Li, P.; Wang, Y.; Li, X.; Yue, B.; Li, R.; Feng, B.; Yin, T. DC Impedance Modeling and Design-Oriented Harmonic Stability Analysis of MMC-PCCF-Based HVDC System. *IEEE Trans. Power Electron.* 2022, 37, 4301–4319. [CrossRef]
- Sun, Y.; Teixeira, C.A.; Holmes, D.G.; McGrath, B.P.; Zhao, J. Low-Order Circulating Current Suppression of PWM-Based Modular Multilevel Converters Using DC-Link Voltage Compensation. *IEEE Trans. Power Electron.* 2018, 33, 210–225. [CrossRef]
- Haq, S.; Biswas, S.P.; Jahan, S.; Islam, M.R.; Rahman, M.A.; Mahmud, M.A.P.; Kouzani, A.Z. An Advanced PWM Technique for MMC Inverter Based Grid-Connected Photovoltaic Systems. *IEEE Trans. Appl. Supercond.* 2021, 31, 0601605. [CrossRef]
- Xu, C.; Lin, L.; Yin, T.; Hu, J. An Improved Phase-Shifted-Carrier Technique for Hybrid Modular Multilevel Converter with Boosted Modulation Index. *IEEE Trans. Power Electron.* 2020, 35, 1340–1352. [CrossRef]
- 8. Hu, P.; Jiang, D. A Level-Increased Nearest Level Modulation Method for Modular Multilevel Converters. *IEEE Trans. Power Electron.* 2015, *30*, 1836–1842. [CrossRef]
- 9. Dekka, A.; Wu, B.; Fuentes, R.L.; Perez, M.; Zargari, N.R. Evolution of Topologies, Modeling, Control Schemes, and Applications of Modular Multilevel Converters. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 1631–1656. [CrossRef]
- 10. Geng, Z.; Han, M.; Xia, C.; Kou, L. A Switching Times Reassignment-Based Voltage Balancing Strategy for Submodule Capacitors in Modular Multilevel HVDC Converters. *IEEE Trans. Power Deliv.* **2021**, *37*, 1215–1225. [CrossRef]
- 11. Alharbi, M.; Isik, S.; Bhattacharya, S. A Novel Submodule Level Fault-Tolerant Approach for MMC with Integrated Scale-Up Architecture. *IEEE J. Emerg. Sel. Top. Ind. Electron.* **2021**, *2*, 343–352. [CrossRef]

- 12. Debnath, S.; Qin, J.; Bahrani, B.; Saeedifard, M.; Barbosa, P. Operation, Control, and Applications of the Modular Multilevel Converter: A Review. *IEEE Trans. Power Electron.* **2015**, *30*, 37–53. [CrossRef]
- 13. Lin, L.; He, J.; Xu, C. Analysis on Circulating Current and Split Capacitor Voltage Balance for Modular Multilevel Converter Based Three-phase Four-wire Split Capacitor DSTATCOM. J. Mod. Power Syst. Clean Energy 2021, 9, 657–667. [CrossRef]
- Ou, Z.; Wang, G.; Zhang, L. Modular Multilevel Converter Control Strategy Based on Arm Current Control Under Unbalanced Grid Condition. *IEEE Trans. Power Electron.* 2018, 33, 3826–3836. [CrossRef]
- 15. Guan, M.; Xu, Z. Modeling and Control of a Modular Multilevel Converter-Based HVDC System Under Unbalanced Grid Conditions. *IEEE Trans. Power Electron.* **2012**, *27*, 4858–4867. [CrossRef]
- 16. Tu, Q.; Xu, Z.; Chang, Y.; Guan, L. Suppressing DC voltage ripples of MMC-HVDC under unbalanced grid conditions. *IEEE Trans. Power Deliv.* **2012**, *27*, 1332–1338. [CrossRef]
- 17. Li, M.; Chang, X.; Dong, N.; Liu, S.; Yang, H.; Zhao, R. Arm-Current-Based Model Predictive Control for Modular Multilevel Converter Under Unbalanced Grid Condition. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, 1. [CrossRef]
- Moon, J.-W.; Park, J.-W.; Kang, D.-W.; Kim, J.-M. A Control Method of HVDC-Modular Multilevel Converter Based on Arm Current Under the Unbalanced Voltage Condition. *IEEE Trans. Power Deliv.* 2015, 30, 529–536. [CrossRef]
- Yang, Z.; Song, P.; Song, J.; Wang, X.; Li, X. An MMC circulating current suppressing controller based on bridge arm common-mode voltage. *IEEE Access* 2020, *8*, 189471–189478. [CrossRef]
- Liang, Y.; Liu, J.; Zhang, T.; Yang, Q. Arm Current Control Strategy for MMC-HVDC under Unbalanced Conditions. *IEEE Trans.* Power Deliv. 2017, 32, 125–134. [CrossRef]
- Qingrui, T.; Zheng, X.; Lie, X. Reduced Switching-Frequency Modulation and Circulating Current Suppression for Modular Multilevel Converters. *IEEE Trans. Power Deliv.* 2011, 26, 2009–2017. [CrossRef]
- 22. Moon, J.W.; Kim, C.S.; Park, J.W.; Kang, D.W.; Kim, J.M. Circulating Current Control in MMC Under the Unbalanced Voltage. *IEEE Trans. Power Deliv.* **2013**, *28*, 1952–1959. [CrossRef]
- 23. Xu, J.; Yu, Y.; Zhao, C. The Predictive Closed-Loop Averaging Control of MMC Phase-Unit Losses under Unbalanced Conditions. *IEEE Trans. Power Deliv.* **2019**, *34*, 198–207. [CrossRef]
- 24. Ismail, H.M.; Kaliyaperumal, S. Enhanced Voltage Sorting Algorithm for Balancing the Capacitor Voltage in Modular Multilevel Converter. *IEEE Access* 2021, *9*, 167489–167502. [CrossRef]
- 25. Middlebrook, R.D. Topics in Multiple-Loop Regulators and Current-Mode Programming. *IEEE Trans. Power Electron.* **1987**, 2, 109–124. [CrossRef]
- 26. Riccobono, A.; Santi, E. Comprehensive review of stability criteria for DC power distribution systems. *IEEE Trans. Ind. Appl.* **2014**, 50, 3525–3535. [CrossRef]
- 27. Yang, Z.; Chen, T.; Luo, X.; Schulting, P.; de Doncker, R.W. Margin Balancing Control Design of Three-Phase Grid-Tied PV Inverters for Stability Improvement. *IEEE Trans. Power Electron.* **2021**, *36*, 10716–10728. [CrossRef]
- Chen, F.; Burgos, R.; Boroyevich, D.; Vasquez, J.C.; Guerrero, J.M. Investigation of Nonlinear Droop Control in DC Power Distribution Systems: Load Sharing, Voltage Regulation, Efficiency, and Stability. *IEEE Trans. Power Electron.* 2019, 34, 9407–9421. [CrossRef]
- Wang, X.; Yao, R.; Rao, F. Three-step impedance criterion for small-signal stability analysis in two-stage DC distributed power systems. *IEEE Power Electron. Lett.* 2003, 1, 83–87. [CrossRef]
- Qi, Y.; Deng, H.; Wang, J.; Tang, Y. Passivity-Based Synchronization Stability Analysis for Power-Electronic-Interfaced Distributed Generations. *IEEE Trans. Sustain. Energy* 2021, 12, 1141–1150. [CrossRef]
- Liu, X.; Zou, Z.; Yang, J.; Tang, J.; Liu, Z.; Buticchi, G.; Wang, Z.; Cheng, M. Stability Assessment of A Radial Grid with Power Converters. *IEEE Open J. Power Electron.* 2022, 3, 61–74. [CrossRef]
- Xiong, L.; Liu, X.; Liu, L.; Liu, Y. Amplitude-Phase Detection for Power Converters Tied to Unbalanced Grids with Large X/R Ratios. *IEEE Trans. Power Electron.* 2022, 37, 2100–2112. [CrossRef]