

Design and implementation of a modern modulation technique for modular multilevel converters

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ABSTRACT

The phase opposition disposition (POD) modulation technique is a sophisticated control strategy employed in modular multilevel converters (MMCs) to achieve high-quality output waveforms with minimized harmonic distortion. POD modulation employs numerous triangular carrier signals, positioned such that carriers above the zero-reference point are in phase, while those below are 180 degrees out of phase. This unique arrangement reduces even-order harmonics and enhances the overall power quality. By comparing a common sinusoidal reference signal with these phase-opposed carriers, pulse width modulation (PWM) signals are generated to control the insertion and bypassing of sub modules within the MMC. The modular structure and balanced switching pattern of POD modulation ensure efficient thermal management and reduced electrical stress on the components, significantly improving the reliability and lifespan of the converter. The technique's inherent scalability and flexibility make it particularly suitable for renewable energy integration, HVDC systems, and industrial motor drives. This paper explores the principles, implementation, and advantages of the POD modulation technique in enhancing the performance and efficiency of MMCs in modern power electronics.

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1. INTRODUCTION

Power electronics is a crucial field in modern technology, impacting a wide range of applications by enabling efficient conversion and control of electrical power [1], [2]. Power electronics plays a vital role in modern technology, enabling efficient energy conversion, control, and management across a wide range of applications. Its impact is seen in renewable energy systems, electric vehicles, smart grids, industrial automation, consumer electronics, telecommunications, aerospace, healthcare, rail transportation, and the internet of things [3], [4]. As technology continues to advance, the importance of power electronics in achieving energy efficiency, reliability, and sustainability will only grow [5].

Power electronics is a branch of electrical engineering that focuses on the conversion, control, and conditioning of electric power using electronic devices [6]. It plays a critical role in modern technology by enabling efficient and precise management of electrical energy, which is essential for a wide range of applications from industrial systems to consumer electronics [7], [8]. Power electronics is a dynamic and essential field that underpins modern electrical engineering and technology [9], [10]. By enabling efficient conversion and control of electrical power, it supports a wide array of applications that improve energy efficiency, reliability, and performance [11], [12]. As technology advances and the demand for sustainable

energy solutions grows, the role of power electronics will become even more critical in shaping the future of energy and power management [13], [14].

Modular multilevel converters (MMCs) represent a significant advancement in power electronics, offering numerous advantages that address the growing demands of modern electrical systems [15], [16]. Their unique modular architecture and operational flexibility make them indispensable in various high-voltage and high-power applications [6], [17]. MMCs play a crucial role in modern power electronics, offering unparalleled advantages in terms of scalability, efficiency, and flexibility [18], [19]. As the demand for efficient and reliable power conversion continues to grow, MMCs will remain a cornerstone technology in advancing the capabilities of power electronic systems [20], [21].

MMCs are increasingly crucial in contemporary power electronics due to their scalability, efficiency, and superior performance in high-voltage and high-power applications. Here are the key reasons why MMCs are important today: [22]

- a. Scalability and flexibility: MMCs consist of submodules that can be added or removed to adjust the voltage and power levels, making them highly scalable and flexible for various applications [23]. They can be tailored for specific needs in industries ranging from renewable energy integration to electric vehicle charging [24].
- b. High efficiency: MMCs operate at lower switching frequencies, which reduces switching losses and improves overall efficiency [25]. They produce a high-quality output waveform with lower harmonic distortion, minimizing the need for additional filtering [26].

As a result of their modular design, scalability, and high efficiency, MMCs are extensively employed in high-voltage direct current (HVDC) transmission, renewable energy integration, and grid-tied applications. Nevertheless, conventional modulation methods for MMCs, such as carrier-based pulse width modulation (PWM) or space vector modulation (SVM), may face constraints such as heightened harmonic distortion, diminished dynamic responsiveness, and intricate implementation at higher switching frequencies. There is a requirement for contemporary modulation method *i.e.* phase opposition disposition modulation method that specifically target these constraints, guaranteeing optimized performance, increased harmonic characteristics, and effective regulation at both high and low frequencies.

2. PROPOSED METHOD

2.1. Phase opposition disposition modulation technique

The phase opposition disposition (POD) modulation technique is a method of controlling the switching of power electronics in MMCs to achieve high-quality output waveforms with reduced harmonic distortion [27].

2.2. Working principle of POD modulation in MMCs

At each moment in time, the POD technique generates PWM signals by comparing the reference wave with a single carrier which is illustrated in Figure 1. The basic cycle is separated into six parts in order to produce the singular carrier for modulation. The reference signal is compared to the carrier signals. Sub-modules are introduced when the reference signal exceeds the carrier signal. When the reference signal is lower than the carrier signal, the sub-modules are skipped. In PWM, the carrier signals for the upper and lower arms undergo inversion to maintain a consistent sum of voltages in both arms. This technique effectively minimizes voltage ripple and harmonic distortion [28].

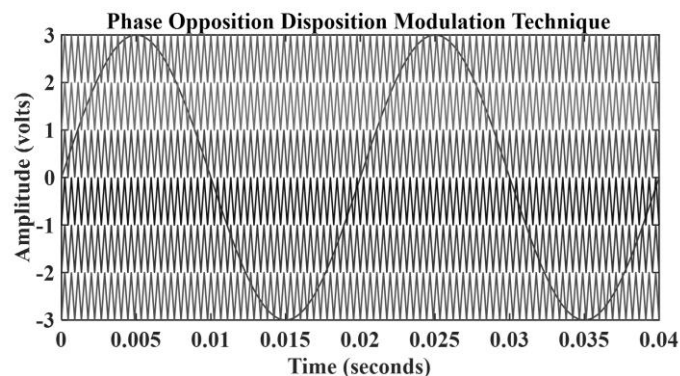


Figure 1. Signal representation of phase opposition disposition

2.2.1. Three modes of working

Three modes of working are as follows:

- Sub module arrangement: An MMC consists of multiple sub modules (SMs) in each phase leg. Each SM can generate a voltage of either V_{dc} (sub module inserted) or 0 (sub module bypassed). The sum of the voltages of all inserted sub modules determines the output voltage of the MMC [29].
- Carrier disposition: the carrier signals are disposed such that those above the zero reference (positive carriers) are in phase, while those below the zero reference (negative carriers) are 180 degrees out of phase with the positive carriers. This arrangement helps in reducing specific harmonic components in the output voltage [30], [31].
- PWM generation: the sinusoidal reference signal is compared with each of the carriers to generate the gating signals for the sub modules. When the reference signal is greater than a carrier, the corresponding sub module is inserted into the circuit; otherwise, it is bypassed [32].

Figure 2 depicts reference signal: This block generates the desired sinusoidal waveform that the MMC aims to produce at the output.

- Comparator: Compares the reference signal with the carrier signals. Separate comparators are used for the upper and lower arms.
- Sub-module control logic: Based on the comparator's output, this logic decides whether each sub-module should be inserted or bypassed.
- Upper and lower arms: Each arm has its carrier signal; the upper arm's carrier is a triangular waveform, while the lower arm's carrier is an inverted triangular waveform (phase opposition).
- Sub-modules: These are controlled based on the logic signals to synthesize the desired output voltage.

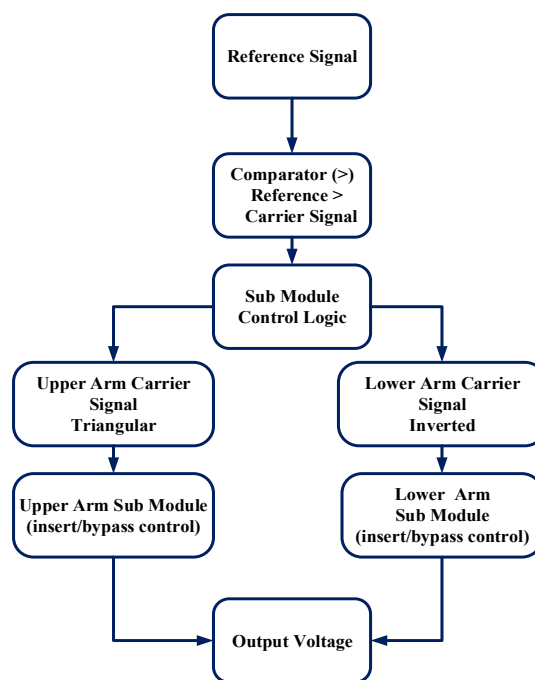


Figure 2. Block diagram representation of phase opposition disposition

2.3. Working operation of modular multi converter

The MMC operates by dynamically inserting and bypassing sub-modules in each arm to synthesize the desired output voltage and current. The use of advanced modulation techniques like POD helps to achieve high-quality output with reduced harmonic distortion. The modular nature of MMCs allows for scalability, redundancy, and ease of maintenance, making them ideal for high-power applications [33].

2.3.1. Working principle

The MMC operates by inserting or bypassing sub-modules in each arm to synthesize the desired output voltage and current. Figure 3 illustrated an MMC typically consists of three phases (for a three-phase system), and each phase has an upper and a lower arm, each containing sub-modules connected in series.

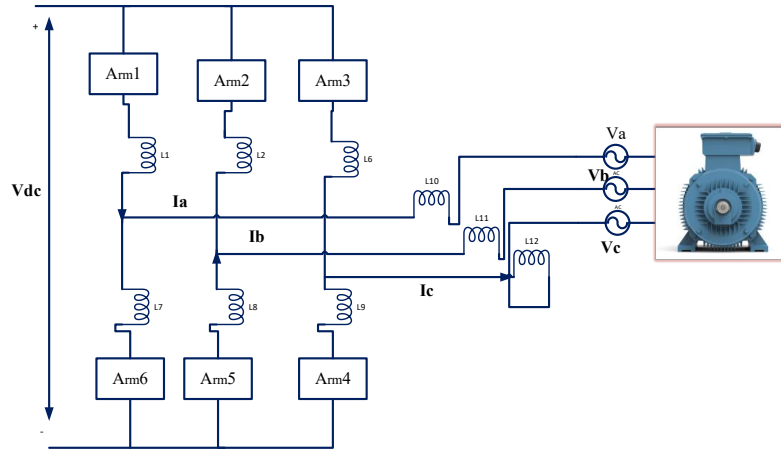


Figure 3. Basic structure of an MMC

2.4. Mathematical modelling and operation

Figure 4 depicts the MMC, which consists of sub-modules per arm, with upper and lower arms in each phase. Each sub-module contains a capacitor that stores voltage. The capacitor voltage is controlled to maintain a desired reference voltage. There is arm inductance in each phase that contributes to filtering the output current.

Figure 4 depicts MMC mathematical modelling with POD in which Triangle pulses has presented in this article. Let consider V_{in} , I_{in} , R_{in} , L_{in} , are input DC voltage, current, resistance and Inductances. And upper and lower voltages are V_{u1} , V_{u2} , V_{u3} and V_{l1} , V_{l2} , V_{l3} . And upper and lower arm currents are I_{u1} , I_{u2} , I_{u3} and I_{l1} , I_{l2} , I_{l3} .

$$\text{The upper arm voltage is } V_{ui} = S_{ui} * V_{ui}^{cr} \quad (1)$$

$$\text{The lower arm voltage is } V_{li} = S_{li} * V_{li}^{cr} \quad (2)$$

Where V_{ui}^{cr} , V_{li}^{cr} are upper, lower capacitor voltages.

$$\text{The upper arm current is } I_{ui} = \frac{S_{ui}}{I_{ui}^{cr}} \quad (3)$$

$$\text{The lower arm current } I_{li} = \frac{S_{li}}{I_{li}^{cr}} \quad (4)$$

$$\text{Total capacitor current } I_i^{cr} = \frac{I_{ui} + I_{li}}{2} \quad (5)$$

$$\text{Total arm current } I_{ui} - I_{li} \quad (6)$$

From Figure 5 consider loop analysis (upper session)

$$V_{inu} = V_{Rrm} + V_{Lrm} + V_{ui} + V_a + V_{aux} \quad (7)$$

$$V_{inu} = (I_{ui} * R_{rm}) + \left(L_{rm} * \frac{dI_{ui}}{dt} \right) + V_{ui} + V_a + V_{aux} \quad (8)$$

From figure consider loop analysis (lower session)

$$V_{inl} = V_{Rrm} + V_{Lrm} + V_{li} + V_a + V_{aux} \quad (9)$$

$$V_{inl} = (I_{li} * R_{rm}) + \left(L_{rm} * \frac{dI_{li}}{dt} \right) + V_{li} + V_a + V_{aux} \quad (10)$$

Where V_{aux} is auxiliary voltage of diodes in arm sections of switches

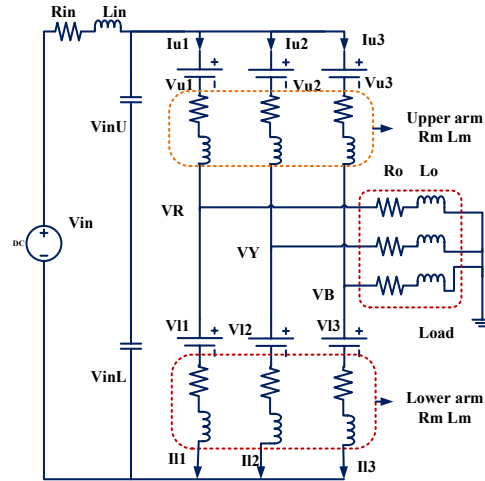


Figure 4. Structural diagram proposed topology

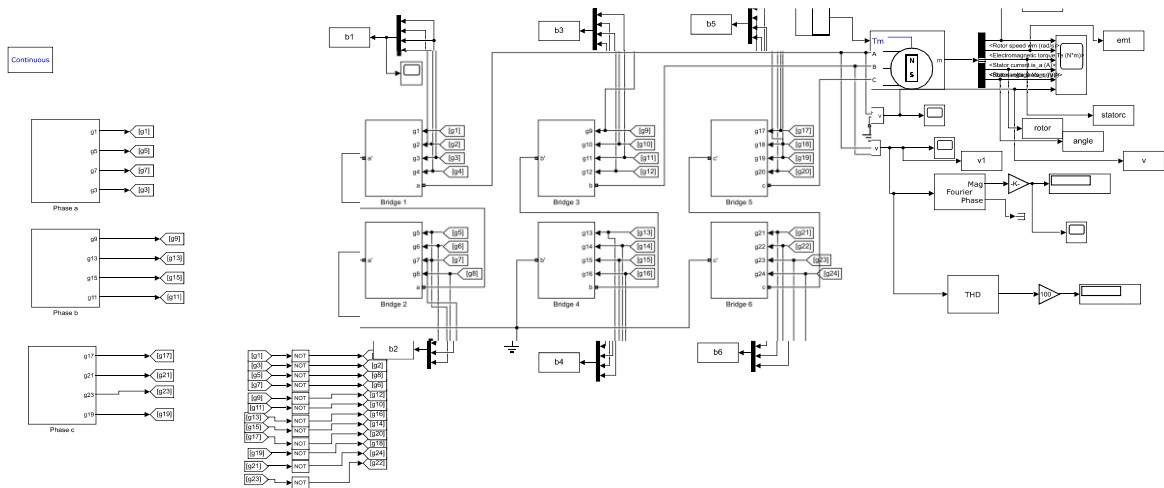


Figure 5. Simulink model for proposed topology

In the context of non-complementary switching, quasi-states effectively bypass one arm while simultaneously blocking the other arm fully. When the output voltage reaches $-V_{in}/2$ during the negative quasi-state, it bypasses the lower arm. This indicates the initiation of the main switches in the lower arm, as well as the cessation of the secondary switches. When both the primary and secondary switches are in the off position, they block the upper arm simultaneously. Thus, the lower arm serves as the conduit for the current during the output phase. However, the diodes in the upper arm's auxiliary switches can still conduct electricity if the DC connection's voltage exceeds the combined voltage of the capacitors in the upper arm's sub-modules. As a result, a charging current passes from the DC connection to the capacitors in the upper arm sub-modules.

$$\text{Therefore } \frac{V_{in}}{2} = V_{ui} + L_{rm} \frac{dI_{ui}}{dt} + V_R \quad (11)$$

$$\frac{V_{in}}{2} = V_{li} + L_{rm} \frac{dI_{li}}{dt} - V_R \quad (12)$$

From (11), (12)

$$V_R = \frac{V_{ui} + V_{li}}{2} \quad (13)$$

3. RESULTS AND DISCUSSION

In this article has been done design and analyze a POD-based seven-level MMC for efficient and reliable control of a permanent magnet synchronous motor (PMSM), with the aim of improving system performance in terms of power quality, harmonic reduction, and efficiency in high-performance industrial applications. This article focused on the control strategy (POD), the benefits of a seven-level MMC such as reduced harmonic distortion and better voltage control, and the optimization of the PMSM operation. Figure 5 depicts the Simulink model of POD based seven level MMC with PMSM and Table 1 represents the configuration and parameters requirements for the drive.

Table 1. The configuration and parameters requirements for the drive

No. of Phases	Three
Emf (back) Waveform	Sine wave
Rotor	Salient pole
Specify	Round rotor
Input (Mech)	Torque T_m
Stator ph. resistance	1.6 ohms
Flux linkage	0.1852

Figure 6 shows the variation of the electromagnetic torque (T_e) of an induction motor drive over a short period. Which represents

- Initial torque oscillations: At the beginning (0 to 0.01 seconds), the torque shows small oscillations. This might be due to initial transients as the motor starts up or reacts to a sudden load change.
- Increasing amplitude: As time progresses, the amplitude of the torque oscillations increases, reaching higher values towards the end of the observed period. This indicates a change in the operating conditions, possibly an increase in load or a response to control actions.
- Steady-state oscillations: Beyond 0.02 seconds, the oscillations in the torque become more pronounced and seem to stabilize in amplitude, suggesting the motor might be reaching a steady-state condition under periodic load variations.

Figure 6 depicts the electromagnetic torque (T_e) variations of an induction motor drive over a short period. The initial small oscillations followed by increasing and stabilizing torque ripples indicate the motor's dynamic response to control actions and load changes. Analyzing these torque variations is vital for optimizing motor performance and improving control strategies to achieve smooth and efficient operation.

Figure 7 depicts the rotor angle (θ_m) variations of an induction motor drive over a short period. The initial gradual increase followed by a steady increase with periodic oscillations indicates the motor's start-up phase and stable operation under control. Figure 8 depicts the rotor speed (ω_m) variations of an induction motor drive over a short period. The initial small oscillations followed by increasing amplitude and periodic oscillations indicate the motor's dynamic response during acceleration and under control.

Figure 9 depicts seven level inverter voltage line voltage and phase voltage given to induction motor drive with peak-to-peak 1000 V. The stepped nature of the waveform achieves higher power quality and lower harmonic distortion compared to traditional two-level inverters. By increasing the number of levels, the output waveform becomes smoother, closely resembling a sine wave.

Figure 10 depicts the proposed POD-based seven-level MMC combined with a PMSM demonstrates significant advancements in control performance, the proposed method achieves remarkably low total harmonic distortion (THD), reduced to less than 2%, which is a substantial improvement over traditional techniques such as space vector PWM (SVPWM) and carrier-based PWM (CBPWM), which exhibit THD levels of approximately 10-20%. This reduction in THD is primarily attributed to the multi-level topology and the phase-shifted pulse width modulation (POD-PWM) strategy, which effectively cancels harmonics and delivers smoother voltage outputs.

In terms of torque ripple, the proposed method excels with values below 1%-2%, significantly outperforming traditional approaches, which often exceed 10%-20%. This low ripple enhances motor smoothness and reduces vibrations, making the system ideal for high-performance applications such as electric vehicles and industrial automation. Compared to alternative advanced methods like Cascaded H-Bridge MMC, the POD-based seven-level MMC achieves similar torque ripple reduction while offering a simpler and more cost-effective design. Overall, the proposed system ensures exceptional performance in both THD and torque ripple metrics, delivering high precision, efficiency, and dynamic response. This makes the POD-based Seven-Level MMC with PMSM a superior choice for applications requiring stringent performance standards and operational reliability.

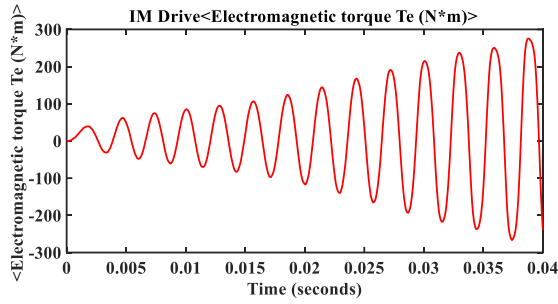


Figure 6. Representation of electromagnetic torque

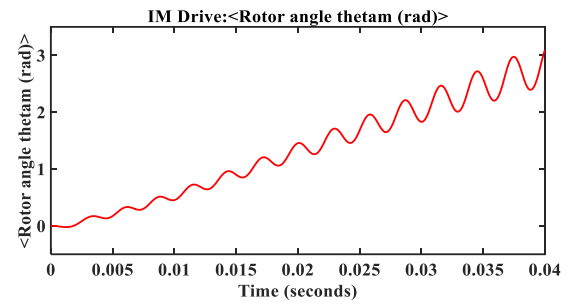


Figure 7. Representation of rotor angle

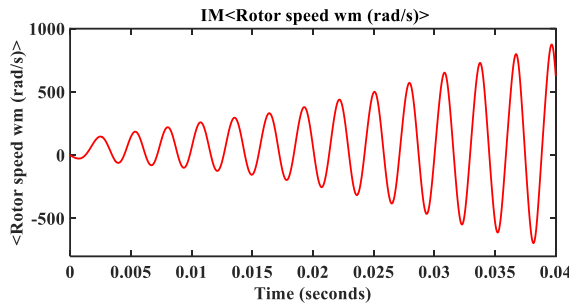


Figure 8. Representation of rotor speed

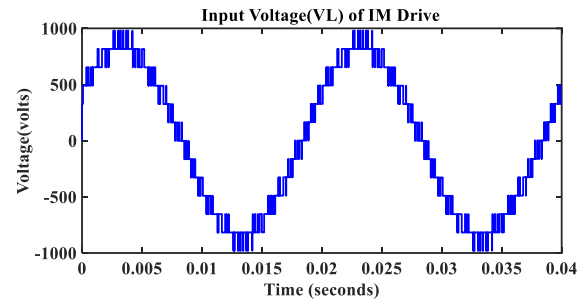


Figure 9. Representation of seven level inverter line voltage

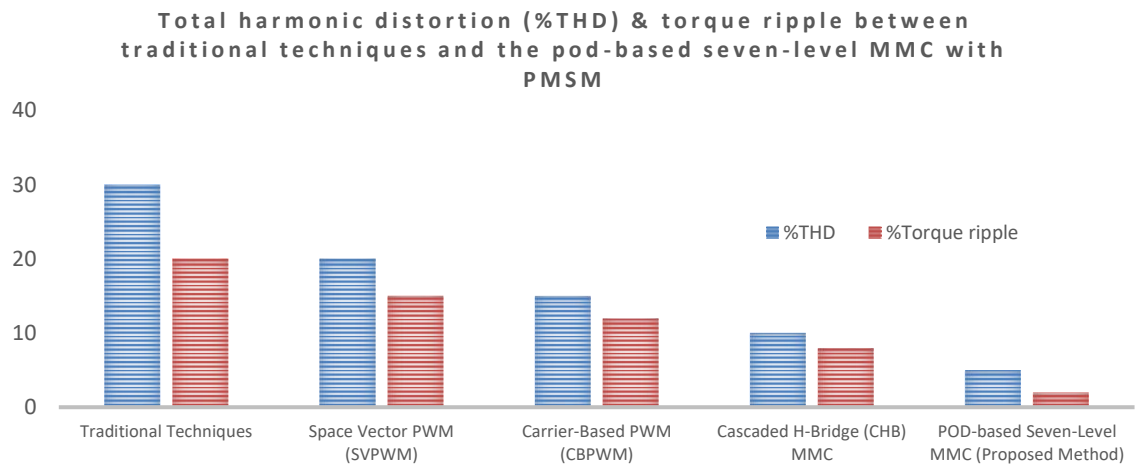


Figure 10. Comparative analysis

4. CONCLUSION

The POD modulation technique is a highly effective method for controlling MMCs, significantly enhancing their performance in high-voltage and high-power applications. By utilizing multiple phase-opposed carrier signals, POD modulation achieves low THD and high-quality output waveforms. This modulation strategy not only improves power quality but also ensures balanced switching actions, which are crucial for the longevity and reliability of the converter components. POD modulation's ability to reduce even-order harmonics and manage thermal and electrical stresses efficiently makes it particularly suitable for demanding applications such as renewable energy integration, HVDC transmission, industrial motor drives, and electric vehicle systems. The technique's inherent scalability and flexibility further contribute to its importance, allowing MMCs to be easily adapted to various power levels and system requirements. The POD modulation technique is an essential advancement in the control of MMCs, providing a robust solution for modern power electronics challenges. Its implementation leads to improved efficiency, reliability, and

performance of power conversion systems, aligning with the growing need for sustainable and efficient energy solutions in today's technological landscape.

The future scope of phase opposition disposition in modular multilevel converters is extensive, driven by advancements in power electronics, renewable energy integration, electric vehicles, HVDC systems, and smart grid technologies. The continued research and development in these areas will further enhance the capabilities and applications of POD, making it a critical component in the evolving landscape of electrical power systems.

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