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Multicarrier PWM techniques for three phase modular multilevel converter application in MRI systems

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ABSTRACT

This research paper presents about the performance analysis of three phase modular multilevel converter with level shifted (phase disposition pulse width modulation) and phase shifted pulse width modulation (PWM) method. This research not only discusses the significance of different modulation procedures in the context of modular multilevel converters but also carefully evaluates each of their unique performance characteristics. This research is based on the fundamental creation of pulses and patterns that can only be acquired by comparing sinusoidal reference signals with triangular carrier signal. Both levels shifted (phase disposition) and phase shifted PWM procedures are used to calculate the phase output voltage of a converter at 2N+1 level. The output waveform is crucially shaped by these modulation techniques, which also ensure effective energy conversion and lower harmonic content. On the basis of the output voltage waveform's quality, the comparative research is conducted and simulated results were presented.

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1. INTRODUCTION

High-power applications like DC electrical grids and offshore wind energy production have a lot of potential over modular multilevel converters because they require precise power flow control and high conversion efficiency to minimize their expenses for operation and environmental impact [1].Also the multilevel converter has high-quality AC signals with less voltage total harmonic distortion (THD) and less voltage stress on power devices. Utilizing output filters with less reactive components is achievable due to the exceptional quality of the output voltages. Higher voltages can be handled by this type of converters [1], [2] since the power switches are exposed to a lower voltage as a result; multilayer converters for medium and high voltage power applications have engrossed a lot of attention recently. Figure 1 depicts various applications of multilevel inverter [3], [4]. Modular multilevel converters (MMCs) are contemporary voltage source converters that can be used in various medium and higher voltage operations. Providing a power source for the gradient coils in magnetic resonance imaging (MRI) systems is one of the uses for multilayer inverters.

Basically, the multilevel topology has different topologies which are elucidated in Figure 2 as diode clamp, flying capacitor, neutral point, cascaded H bridge and modular multilevel topology. In the conventional power drive application to MRI system, the cascaded H bridge multilevel inverter is used. This paper proposed the modular multi-level converter for supplying power to gradient coils of MRI system. In recent years, the modular multilevel converter (MMC) topology has become one of the most alluring topologies for high voltage and high-power applications [5], [6]. The key features of this converter is modular design, capacity to scale to various power and voltage levels, reliability and redundancy, compatibility with standardized commercial semiconductor components, flexibility, high output voltage quality, high efficiency, and no additional capacitors on the DC link [7], [8].

Depending on the converter's intended use, MMC's DC Link is linked to high-voltage sources. The output of the converter is the upper and lower arm connection points, which are linked to the load. The MMC is a recent addition to the world of power electronics designed for efficiently converting high or medium voltage power without the need for transformers. It is necessary to learn about their control strategies in order in order to develop MMC. In earlier studies, many control approaches were addressed [6], [7]. In this article PS-PWM and PD-PWM, multicarrier PWM approaches were contributed.

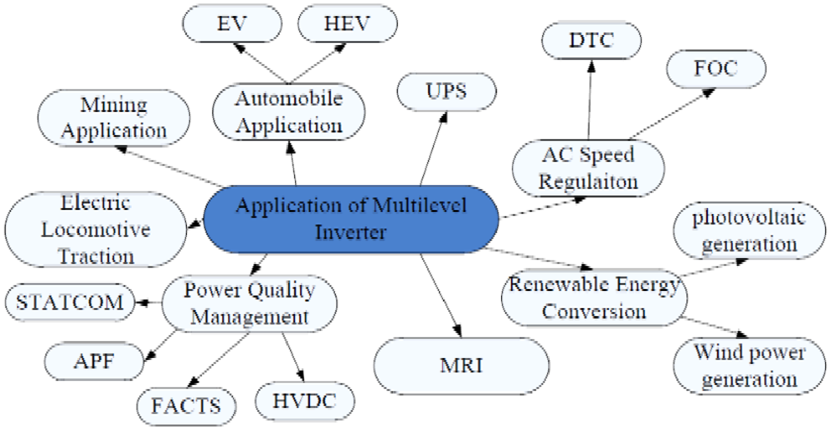


Figure 1. Application of multilevel inverter

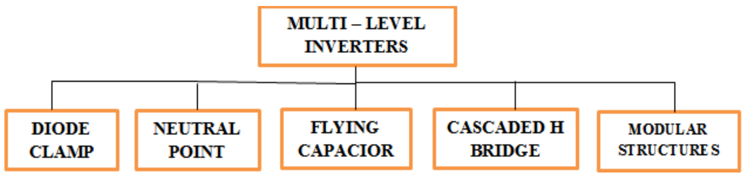


Figure 2. Classification of multilevel inverters

2. MODULAR MULTILEVEL CONVERTER

This converter technique primarily makes use of several cells or smaller modules that are stacked together to form an arm. Figure 3 depicts the fundamental composition of a standard MMC in which the Figure 3(a) describes about the structure of half bridge sub modules and also the Figure 3(b) illustrates about the three phase MMC circuit. Other cell configurations are also feasible. The most typical cell is a half bridge or a full bridge made up of semiconductor devices and one capacitor in [8].

In every phase or leg of the conventional MMC, the two arms are labeled as the upper and lower arms. The top arm is joined to the positive DC bus, while the lower arm is allied to the negative DC bus. To prevent the fault current and the circulation current caused by the momentary voltage difference between the cells from passing through the arms, an inductor is attached in series with both arms. The converter must operate steadily; hence voltage balancing of cell capacitors is necessary.

2.1. Principle of operation

The arms sub-modules are regulated in a method that either inserts or bypasses the capacitor in the circuit. Because of the complementary nature of sub-module operation, when S_1switch is ON, and the S_2 switch is OFF, Sub module is said to be in the Turn ON-state. Rajan and Seyezhai [9] the switches are needed to be ON or OFF, together with the current polarity, to determine the sub modules conduction paths. The Figure 4 displays the different conduction paths with positive current polarity and negative current polarity. Depending upon the direction of the current, the sub module's capacitor can either be charged or discharged. Table 1 provides a summary of the switching states.

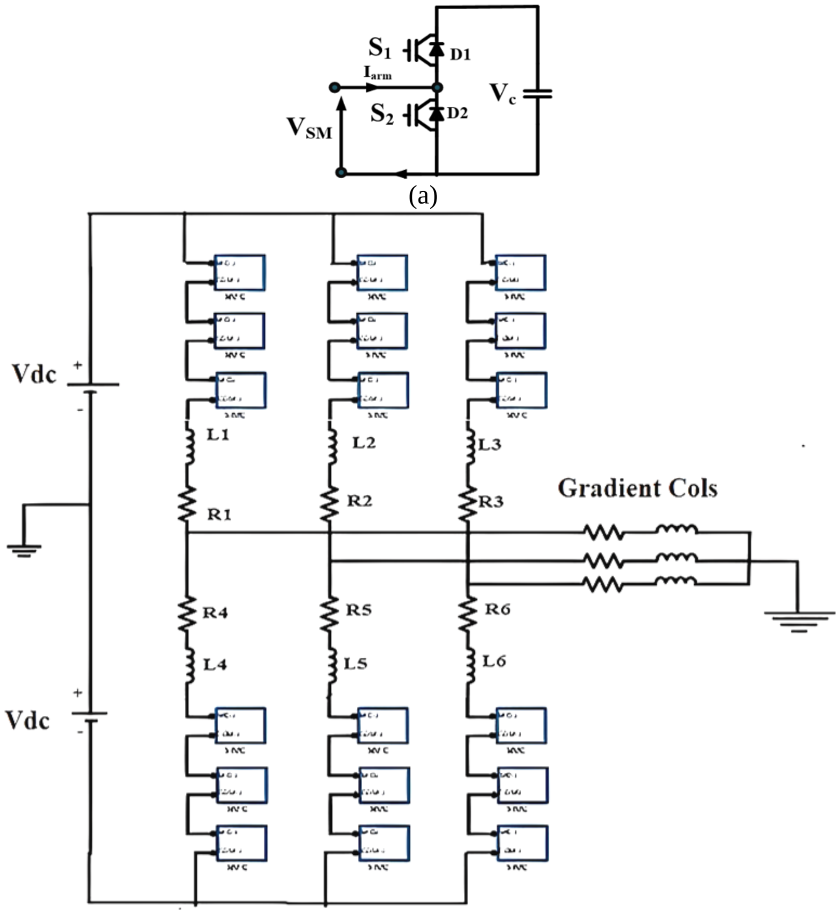


Figure 3. Standard MMC (a) structure of HBSM and (b) three phase MMC circuit

When an ample of sub modules are linked in series then the stepped output voltage waveforms near to the pure sinusoidal wave can be produced. Low level harmonic distortion may be found in the produced sine wave. The following equations are used for selecting the values for inductors and sub-module capacitors [10].

Arm Voltage = $V_{arm} = \sum_{i=0}^{n} V_{arm} + L_{arm}\frac{di_{arm}}{dt} + R_{arm}\, i_{arm}$ (1)

Circulating Current = $i_{circ} = \frac{1}{2L}\int_0^t u_k + I_{dc}$ (2)

Output Voltage = $u_{k-} u_o$ (3)

Circulating Current = $i_{circ} = \frac{i_p + i_n}{2}$

Reference voltage for the upper arm = V_{arm_ref} (t) = $\frac{V_{dc}}{2} - m\frac{V_{dc}}{2}\cos\ (\omega t)$ (4)

Arm Current = $i_{arm}(t) = \frac{I_{dc}}{3} + \frac{I_a}{2}\cos\,(\omega t - \varphi)$ (5)

Inductor = L ≥ $\frac{V_{dc}}{2\alpha_{max}}$ to limit circulating current (6)

Inductor = $L_0 = \frac{1}{(8\ \omega_0^2\, C_0\ U_{C)}}(\frac{P_s}{3I_2 f} + U_{dc})$ to limit fault current rate of rise (7)

Sub-module capacitor = $C_{SM} = \frac{P_s}{3\ K\ N\omega_0\varepsilon\ V_C^2}\left[1 - \left(\frac{k.cos\varphi}{2}\right)^2\right]^{\frac{3}{2}}$ (8)

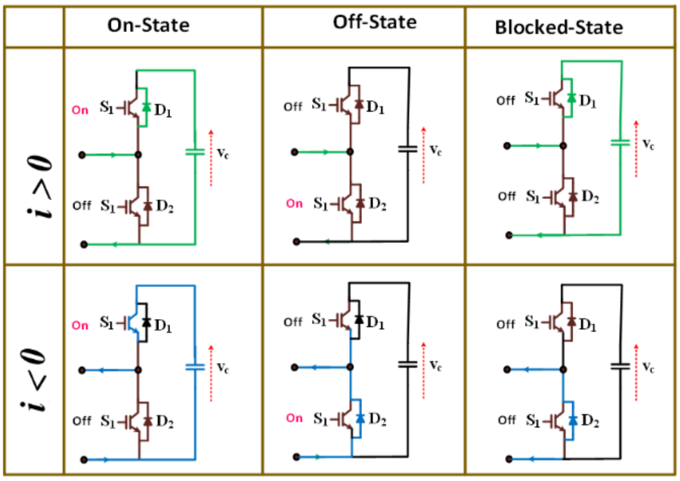


Figure 4. Sub module operation

Table 1. Switching state of 2-level half bridge MMC

Arm current	Switch 1	Switch 2	V_{in}	C_{sm}
I_{arm}>0	0	0	V_{cap}	Charge
	0	1	0	Stable
	1	0	V_{cap}	Charge
I_{arm}< 0	0	0	0	Stable
	1	1	0	Stable
	1	0	V_{cap}	Discharge
I_{arm} = x	1	1	Fault	Short circuit discharge

2.2. Modulation technique

To obtain the desired output voltage, a modulation technique's primary goal is to produce pulse width modulated gate signals for semiconductor switches in a converter. There are several types of modulation techniques are depicted as shown in Figure 5. Level-shifted modulation and triangle carrier-based phase-shifted modulation are the two types of modulation techniques utilized most frequently in MMCs. In [11], [12], triangular carrier signals and a single sinusoidal modulating signal is compared, any phase of the converter's upper and lower arm modulating signals is in sinusoidal and 180° times phase shifted. The quantity of identical triangular carrier signals needed depends upon the cells present in one arm.

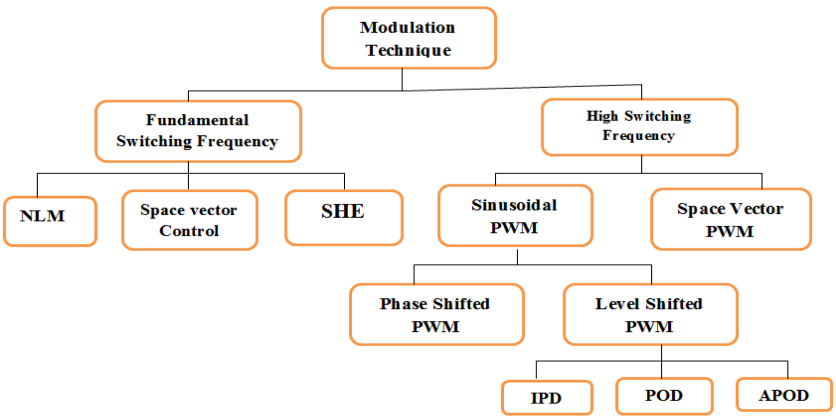


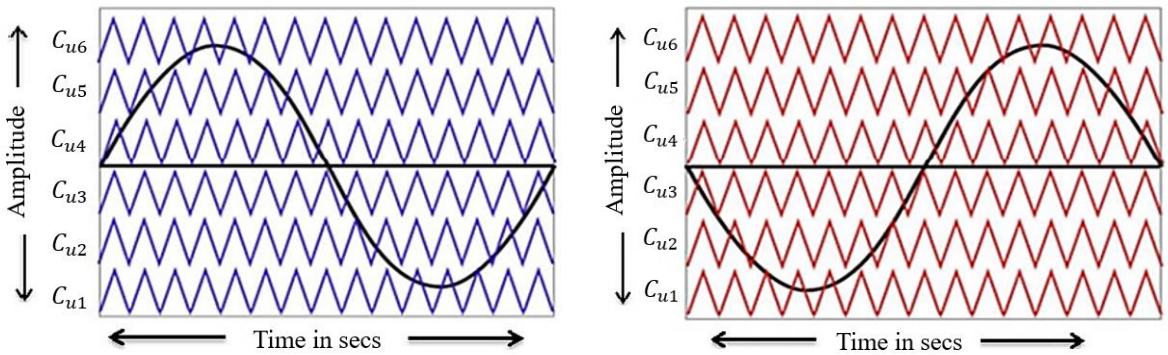
Figure 5. Classification of modulation technique

2.2.1. Level shifted PWM technique (LSPWM)

The triangular carriers are vertically spaced in the level-shifted modulation approach. It is possible to set the upper and lower arm's triangular carrier signals in phase alignment or phase opposition with one another. This leads to the two forms of level-shifted PWM approaches, namely in-phase disposition and phase opposite disposition. As illustrated in Figure 6, the level shifted triangular carrier signals used in the in-phase disposition (IPD) level shifted PWM approach are in phase with one another between the upper and arms [13]. The output voltage waveform can have N_{cell}+1 level using this modulation technique.

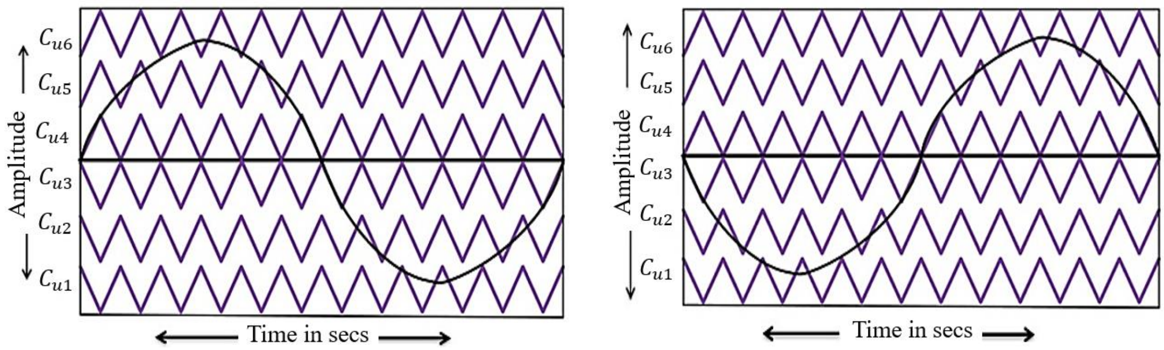
The level shifted triangular carriers are phase shifted by 180° among the upper and lower arms in the level shifted PWM technique with phase opposite disposition (POD) configuration, as shown in Figure 7. This method helps to increase the number of levels at the converter output voltage by using a phase shift between the carriers. Calais *et al*. [14], the converter's output voltage has N_{cell} +1 levels for every additional N_{cells} in either arm of the MMC.

According to APOD, carrier signals are alternately spaced 180° apart from one another as shown in Figure 8. The sidebands to the carrier frequency are displayed as the most important harmonics, same like the previous two carrier distribution methods. The PD, POD, and APOD control approaches in [15] all have the ability to generate signals with switching frequencies that are much lower than the carrier frequency.



(a) (b)

Figure 6. Phase disposition signals for N+1 level MMC (a) upper arm and (b) lower arm



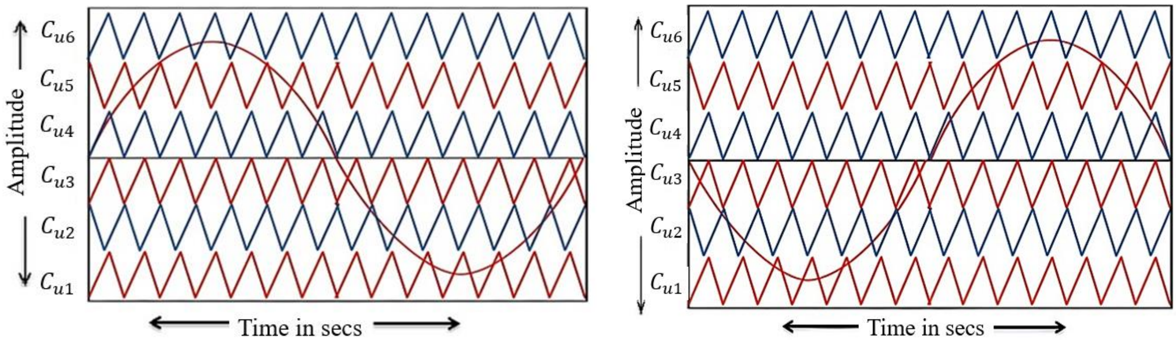
(a) (b)

Figure 7. Phase opposite disposition signals (a) upper arm and (b) lower arm

2.2.2. Phase shifted PWM

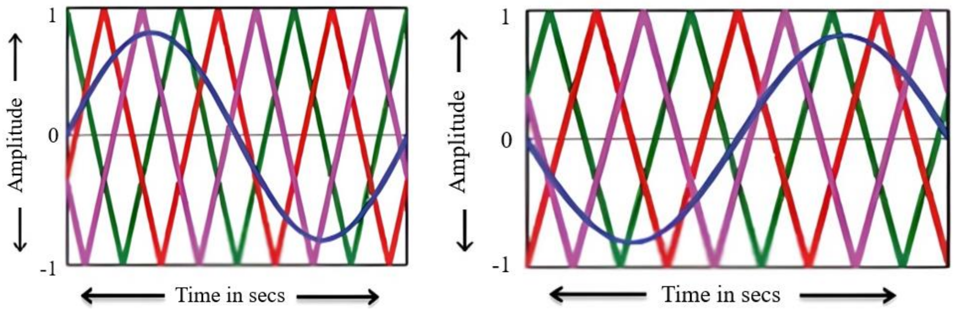
Phase-shifted PWM N carrier signals in MMC with N sub-modules per arm are compared with a reference signal. These N carrier signals all have the similar peak-to-peak values and frequency, but there is a phase difference among them. The number of levels in the inverter's output voltage can fluctuate due to a phase shift accompanied by the carriers, which is an intriguing observation. Following is the selection of the career phase transitions [16] phase variation between two nearby carriers in the same arm=360º. For N-levels, the phase difference between carriers in the upper and lower arm is equal to 0, but for 2N+1 levels, it is equal to 180º.

This 2N+1 modulation method yields output voltage waveforms with 2N+1 level. In contrast to the preceding version, the linked sub-modules for the identical phase leg here accept values between N-1 and N+1. There are exactly the same number of sub-modules N in the voltage waveform levels produced by the method N+1 and the case 2N+1 in [17], [18]. For the various levels shown in the output voltage waveform, the extra combinations offer the intermediate levels. Only one of the two arms' sub-module counts varies at any switching moment. This approach allows for the consideration of both level-shifted and phase-shifted carriers, with the phase shift between carriers being of particular significance [19]–[24]. The waveform of the 2N+1 phase shifted modulation with positive and negative carriers is exposed in Figure 9 for the MMC simulated for the number of sub-modules N=3.The intersection of the carrier and reference signal, which is produced by this carrier configuration, determines the switching actions for the upper and lowers half arms of the same converter arm. This carrier configuration generates a voltage waveform with seven levels.



(a) (b)

Figure 8. Alternate phase opposite disposition signals (a) upper arm and (b) lower arm



(a) (b)

Figure 9. Phase shifted signals for 2N+1 level MMC (a) upper arm and (b) lower arm

3. RESULTS AND DISCUSSION

Modular multilevel inverters (MMIs) are a specific type of multilevel inverter renowned for their ability to deliver superior power quality, minimize total harmonic distortion (THD), and maintain high efficiency when employed in high-voltage scenarios. When examining simulation outcomes for MMCs, they are typically assessed based on several key aspects: the quality of the output voltage waveform, power losses, and the switching frequency. Concerning the output voltage waveform quality, MMCs consistently yield an exceptionally high-quality AC voltage waveform characterized by minimal THD. This remarkable waveform quality results from the synthesis of the output voltage waveform through the integration of multiple levels of DC voltage sources. This approach enables greater precision and accuracy in voltage synthesis. During simulation analysis, one can quantitatively assess the THD of the output waveform, ensuring it remains well within the prescribed limits for the MRI system applications. Using MATLAB/Simulink, a three phase MMC is simulated which is depicted in the Figure 10. Its performance is examined for RL load in order to evaluate the various modulation strategies.

3.1. Seven level phase disposition level shifted PWM

For 2N+1 with Seven level MMC, three sub modules in upper and lower arm consists with three carrier signals and sinusoidal reference signal which was compared and gating pulses were generated for both the arms. The simulated output voltage waveforms of three phases level shifted 2N+1 MMC is given in the Figure 11 the THD analysis is given with Figure 12.

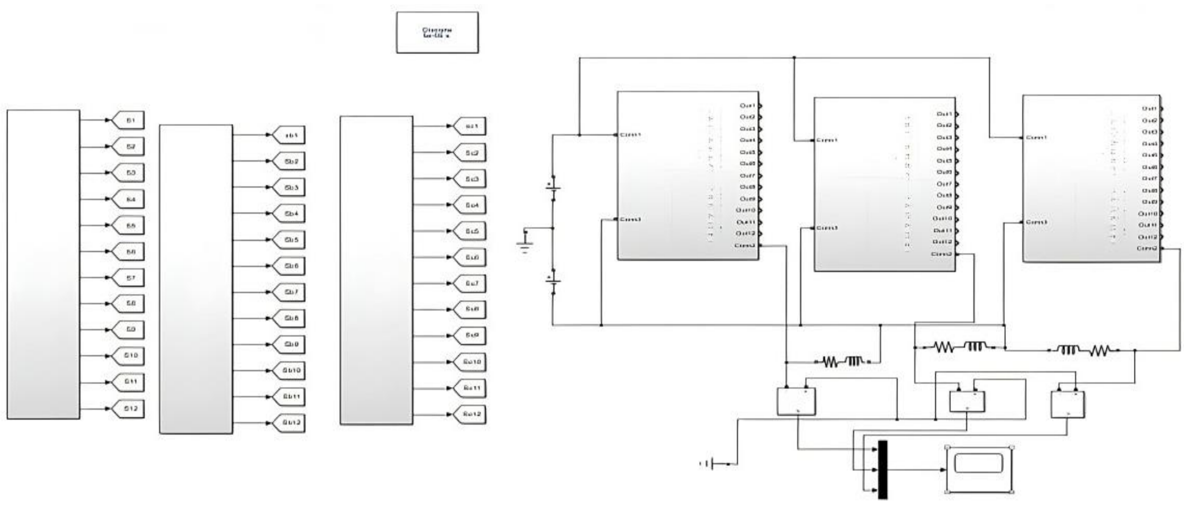


Figure 10. Simulation diagram of three phases MMC

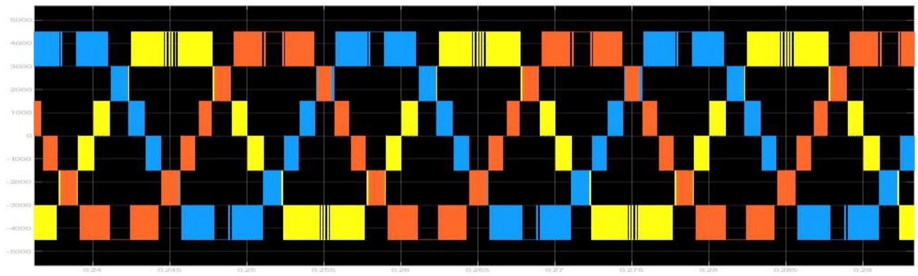


Figure 11. Output phase voltage waveforms of level shifted 2N+1 MMC

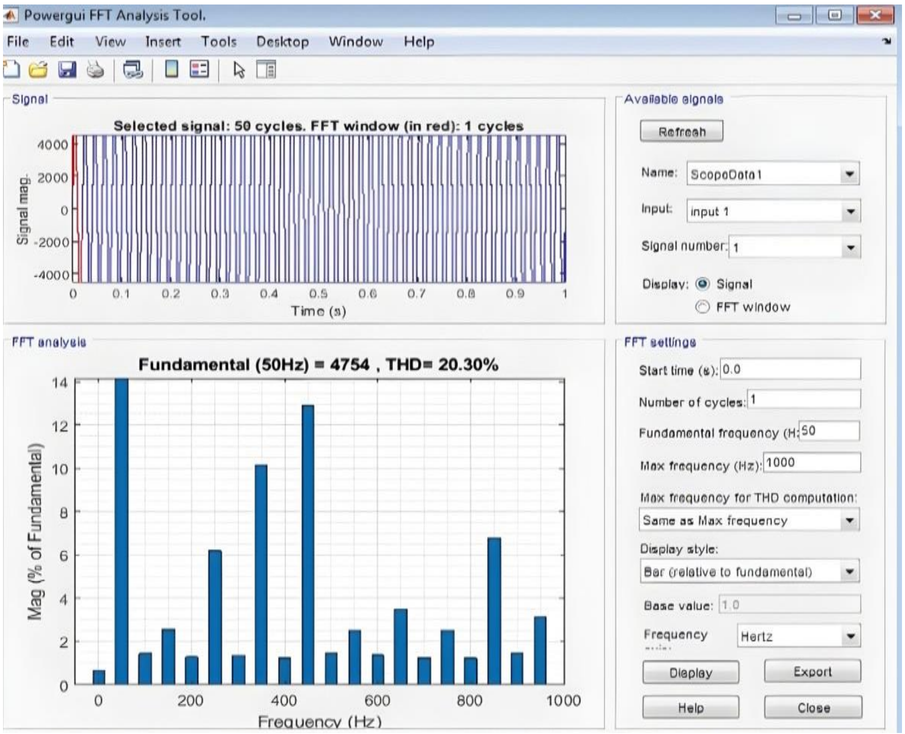


Figure 12.THD analysis of level shifted 2N+1 MMC

3.2. Seven level phases shifted PWM

The MATLAB simulation showcases a comprehensive analysis of a seven-level phase-shifted modular multilevel converter (MMC), depicting critical components such as the carrier signal, PWM pulses, and the resulting output voltage and current respectively. Additionally, Figure 13 provides insights into the system's performance. The study extends to a detailed THD analysis, presented in Figure 14, offering a comprehensive evaluation of the converter's harmonic content and overall efficiency.

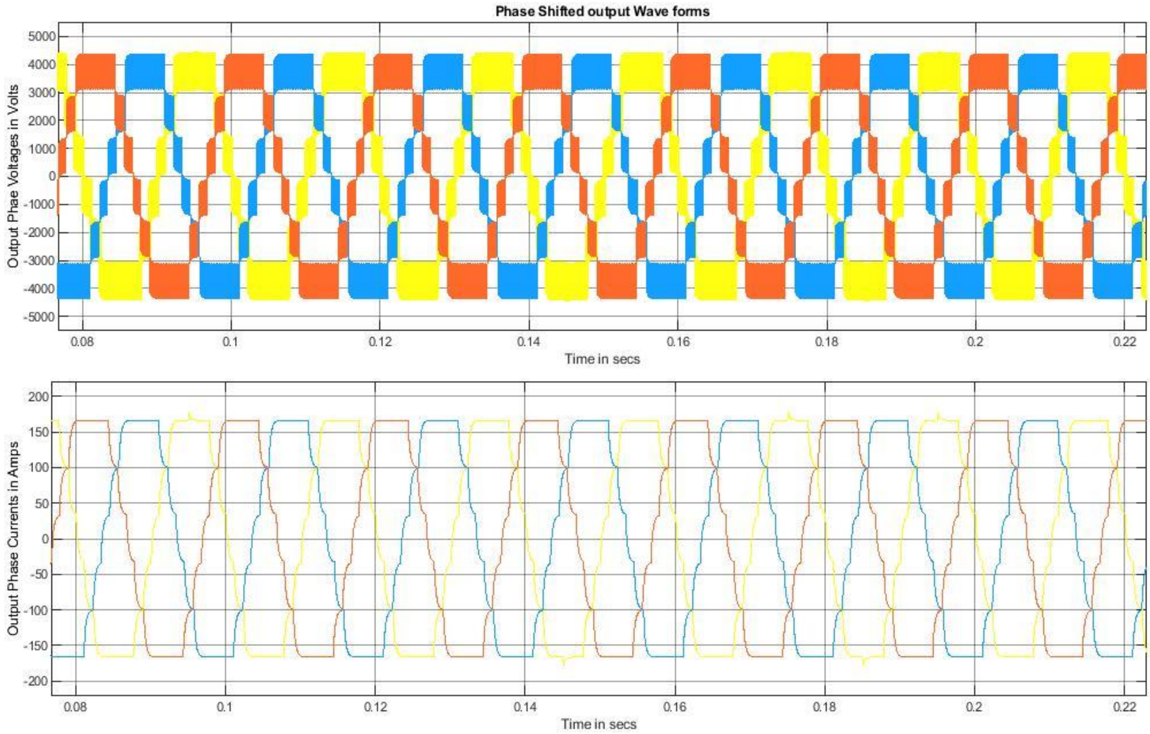


Figure 13. Output phase voltage and phase current waveforms phase

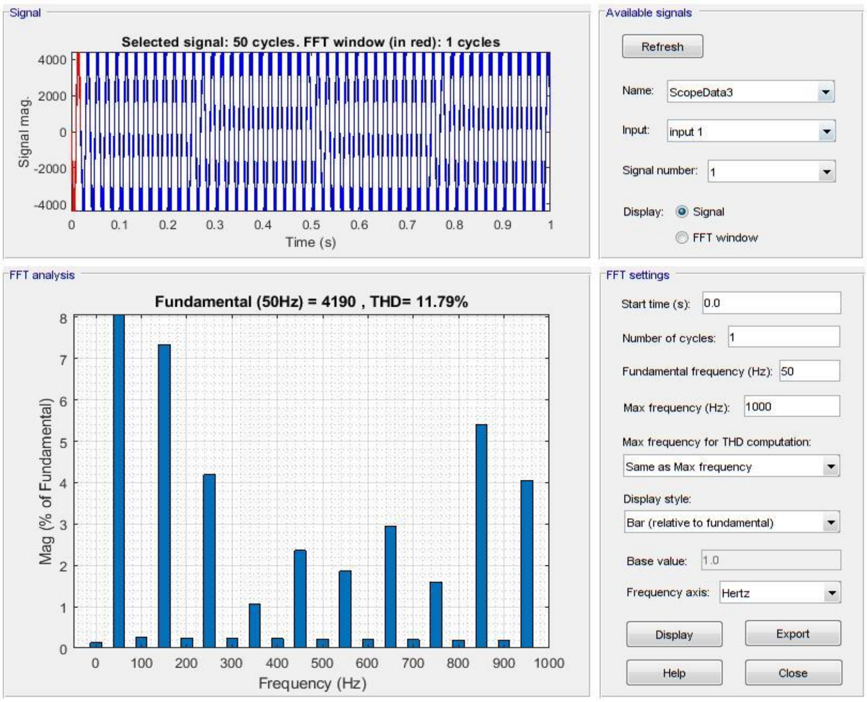


Figure 14. THD analysis of phase shifted output voltage waveform

Table 2. Comparison of THD performance analysis ofthree phase MMC

PWM method	THD Level in %
Level shifted (PD-PWN)	20.30
Phase shifted	11.79

4. CONCLUSION

This research focuses on the development and comparison of various PWM techniques for the modular multilevel converter (MMC) with the same number of sub-modules. The study utilizes MATLAB/ Simulink for simulating a 3-phase MMC employing both phase-shifted PWM (PS-PWM) and Level-Shifted PWM (PD-PWM) approaches, along with multicarrier PWM techniques, while considering an RL load. The primary objective is to assess and compare these methods based on the 2N+1 phase voltage levels they produce and the resulting total voltage harmonic distortion (THD). The comparative analysis of the simulation results indicates that all 2N+1 level methods using Phase-Shifted PWM exhibit lower THD compared to Level-Shifted PWM (PD-PWM), as illustrated in Table 2. PD-PWM introduces dead time in the phase output voltage, which is eliminated in PSPWM. Therefore, Phase-Shifted PWM demonstrates superior performance in the MMC. It can be concluded that the utilization of the 2N+1 modulation technique to generate numerous voltage levels in the MMC's output waveform enhances its operational characteristics, making this modulation approach more attractive.

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