

Multicarrier PWM Control In Modular Multilevel Converter

Valentine Obiora
Centre for E-Mobility and Clean Growth
Coventry University
Coventry, United Kingdom
obiorav@uni.coventry.ac.uk

Wissam Jamal
Centre for E-Mobility and Clean Growth
Coventry University
Coventry, United Kingdom
<https://orcid.org/0000-0003-4969-3728>

Chitta Saha
School of Engineering and the Built Environment
Birmingham City University
Coventry, United Kingdom
<https://orcid.org/0000-0001-6831-846X>

Rajib Goswami
School of Future Transport Engineering
Coventry University
Coventry, United Kingdom
<https://orcid.org/0000-0003-0754-525X>

Mouadh Ezzine
Centre for E-Mobility and Clean Growth
Coventry University
Coventry, United Kingdom
ezzinem@uni.coventry.ac.uk

Reginald Ogu
Department of Computer Engineering
Federal University of Technology
Owerri, Nigeria
reginald.ogu@futo.edu.ng

Abstract— This paper explores the design and analysis of a Modular Multilevel Converter (MMC) with a focus on Multicarrier Pulse Width Modulation (PWM) and capacitor voltage balancing techniques. The study aimed to evaluate the impact of these techniques on power quality indices, specifically harmonics, within the converter. Using MATLAB/Simulink, a three-phase MMC was simulated to generate 3-level, 5-level, and 7-level voltages, assessing the effectiveness of the proposed voltage balancing and modulation methods. The results demonstrated that as the voltage levels increased, Total Harmonic Distortion (THD) decreased, confirming the efficacy of the proposed approach in improving power quality. Furthermore, the study connected a dynamic load, represented by a three-phase induction motor, to the MMC. The findings indicated that the modified Multicarrier PWM and voltage balancing techniques achieved the primary control objectives, ensuring system stability and effective motor performance. Despite these successes, the complexities inherent in MMC control suggest that further research could explore traditional control methods, such as optimal or nonlinear control, to enhance system reliability and performance.

Keywords—Level-shifted PWM, MMC, Power Quality, THD, Voltage balancing.

I. INTRODUCTION

A major concern in the global energy sector is the impending exhaustion of fossil fuels coupled with the environmental challenges posed by global warming. This has catalysed a paradigm shift towards renewable energy sources (REs), which now play an increasingly vital role in global electricity supply. [1]. According to [2], REs such as solar, wind, geothermal etc. supplied 28% of global electricity supply in the first quarter of 2023 with solar photovoltaics (PV) projected to increase the fastest.

Integrating solar PV into the power grid necessitates effective DC/AC conversion, making the design of interlinking converters a critical area of study. Traditional two-level inverters, while widely used in renewable energy integration, present several limitations such as high switching losses and limited scalability, which hinder their performance in high-power applications.

Existing literature discusses the traditional two-level inverter which is used in applications such as renewable energy integration, adjustable speed drives and high-voltage DC transmission[3]–[6]. [7] investigated and compared the control of a two level Z-source interlinking inverter using space vector pulse width modulation for photovoltaic fed renewable energy source. Also, [8] demonstrated the control of a two-level inverter fed Induction motor using Space vector PWM. Their work focused on analysing the advantages of the modulation technique on the induction motor control. However, despite its control simplicity and reduced costs, this converter suffers from snags such as large switching losses, large switching stress, high operating frequency, non-availability of high-power devices etc. [9], [10]. These limitations deteriorate the performance of the system.

The Multilevel Inverter (MLI) is an advanced power electronic converter that tends to overcome power quality and stability issues in electrical network because of the unstable output of Res [11]. This class of converters has received considerable scholarly attention in recent years due to their features of high-quality waveforms, scalability, fault-tolerant operation, redundancy in switching states etc. [12]. The literature on MLIs has highlighted several topologies such as the Neutral point clamped (NPC), flying capacitor (FC), cascaded half bridge (CHB), modular multilevel converters (MMC) to mention a few. A major demerit of this class of converters has to do with the enormous number of switching devices [13].

To address these challenges, the modular multilevel inverter (MLI) has emerged as a promising solution due to its ability to produce high-quality waveforms, scalable design, and fault-tolerant operation. Among various MLI topologies, the Modular Multilevel Converter (MMC) stands out for its practical application in high-voltage DC transmission and renewable energy integration. Despite its advantages, one of the key challenges in MMC operation is the complex task of capacitor voltage balancing within its submodules [15].

In a review study by [16], it was found that much of the research on modular multilevel inverter focused mainly on its mathematical modelling and less on capacitor voltage balancing. This is as a result of the complexity of the

balancing technique. [17] investigated the mathematical model of the MMC to design a converter control system. Also, [18] developed a simpler MMC model that preserved the dynamics while reducing the simulation time. However, the less studied concept of voltage balancing amongst the submodule capacitors is an important control concept for this class of multilevel converters.

Voltage balancing techniques have been studied by various authors such as [19] who proposed a novel arm balancing technique for efficient operation of the mmc under pulsed loads, [20] who proposed a new method of measuring capacitor voltage across the sub modules. [21] suggested MMC control can be further broken into two distinct control philosophies based on global arm control and individual control of submodule capacitors voltage using modulation techniques. However, [22] categorises these control objectives into primary and secondary control objectives with the former involving pulse width modulation control techniques to achieve the desired output voltage levels. [23] and [24] examined nearest level control (NLC) modulation to study voltage balancing for the mmc, [25] presented an analysis of capacitor voltage balancing using sinusoidal pulse width modulation (SPWM), NLC and Selective Harmonic elimination (SHE), [26] and [27] who performed comparative analysis of different voltage levels for the MMC using multicarrier pulse width modulation techniques.

This paper focuses on addressing this challenge by analysing the theoretical modelling and control strategies for MMCs, with a particular emphasis on a modified multicarrier pulse width modulation (PWM) technique. The study further applies this methodology to drive a three-phase induction motor, comparing its performance against a conventional two-level inverter.

This paper has been divided into four sections. The MMC structure, mathematical theory and control technique are discussed in section 2. Section 3 provides and discusses the findings from this study while the summarization of the main areas covered and suggestions for Improvement on future studies are presented in section 4.

II. METHODOLOGY

A. MMC Circuit and Design

The MMC structure is well documented in Literature. The configuration of the converter used in this paper is as shown in figure 2. In this converter topology, each phase is regarded as a leg and each leg consists of two arms namely the upper arm and the lower arm, respectively. In this study, each arm is made up of N submodules placed in a half bridge structure. The number of half bridge modules, required to generate a particular voltage level is calculated by the following equation [28]

$$N = m - 1 \quad (1)$$

where,

N=number of required submodules

m= voltage level.

The arm inductor and arm capacitance for the MMC circuit are respectively defined by [28]

$$L_{arm} = \frac{1}{C_{arm}\omega^2} \frac{2(h^2-1)+m_a^2h^2}{8h^2(h^2-1)} \quad (2)$$

$$C_{SM} = \frac{dv_{CU}}{dt} = n_u i_{armU}, C_{SM} = \frac{dv_{CL}}{dt} = n_l i_{armL}, \quad (3)$$

Where, ω is the angular frequency, C_{arm} the arm capacitance, h is the harmonic order, dv_{CU} and dv_{CL} denote the sums of the upper and lower arm voltages of the submodule capacitors i_{armL} and i_{armU} the lower and upper

arm currents respectively and modulation index denoted by m_a .

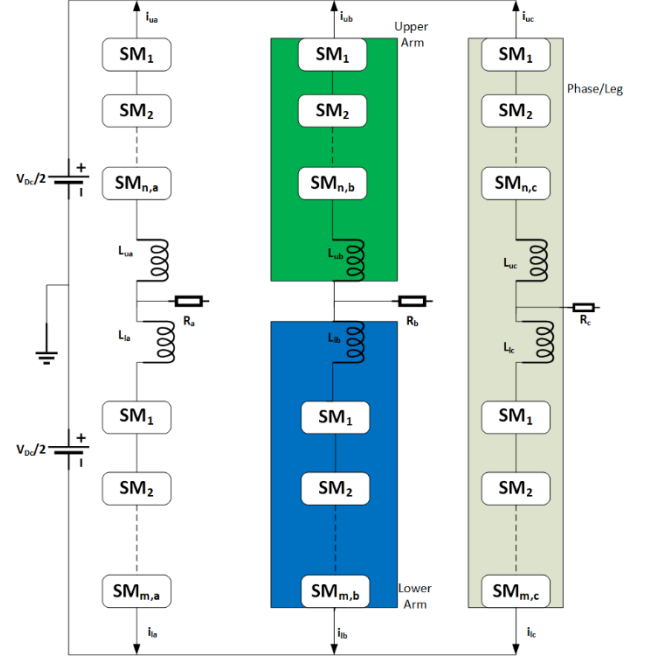


Fig 1: Three-phase half bridge submodule MMC topology

The circuit relationships for each phase leg of the MMC based on fig. 2 is derived using Kirchoff's voltage law around the upper and lower arm loops

$$\frac{v_{dc}}{2} - v_{x,u}(t) - v_{x,o}(t) = R_b i_{x,u}(t) + [L_k + L_b] \frac{di_{x,u}}{dt} + L_b \frac{di_{x,l}(t)}{dt} \quad (4)$$

$$\frac{v_{dc}}{2} - v_{x,l}(t) - v_{x,o}(t) = R_b i_{x,l}(t) + [L_k + L_b] \frac{di_{x,l}}{dt} + L_b \frac{di_{x,u}(t)}{dt} \quad (5)$$

Where $x \in \{a,b,c\}$. The differential and common node arm voltages and currents for each phase leg is defined as

$$v_{x,dm}(t) = \left[\frac{v_{x,u}(t) - v_{x,l}(t)}{2} \right] \quad (6)$$

$$v_{x,cm}(t) = \left[\frac{v_{x,u}(t) + v_{x,l}(t)}{2} \right] \quad (7)$$

$$i_{x,dm}(t) = \left[\frac{i_{x,u}(t) - i_{x,l}(t)}{2} \right] = i_{x,o}(t)/2 \quad (8)$$

$$i_{x,cm}(t) = \left[\frac{i_{x,u}(t) + i_{x,l}(t)}{2} \right] = i_{x,circ}(t) \quad (9)$$

The continuous time equations for $i_{x,dm}(t)$ and $i_{x,cm}(t)$ is thus derived by subtracting and then adding (4) and (5).

Further substitution of the appropriate common and differential node expressions from (6) to (9) yields

$$-v_{x,dm}(t) - v_{x,o}(t) = R_b i_{x,dm}(t) + L_k \frac{di_{x,dm}(t)}{dt} \quad (10)$$

$$\frac{v_{dc}}{2} - v_{x,cm}(t) = R_b i_{x,cm}(t) + [L_k + 2L_b] \frac{di_{x,cm}}{dt} \quad (11)$$

Taking the assumption that the arm inductors are coupled and the usual condition that the winding leakage and series resistance per winding are negligible, (10) and (11) can be reduced to

$$v_{x,o}(t) \approx -v_{x,dm}(t) \quad (12)$$

$$v_{x,cm}(t) \approx \frac{v_{dc}}{2} - 2L_b \frac{di_{x,cm}}{dt} \quad (13)$$

B. Multicarrier Modulation and Voltage Balancing Control

The staircase output waveform characteristic of multilevel inverters is generated using pulse width modulation (PWM) schemes. PWM is a widely used control strategy in electronic power converters to produce AC output voltage while minimizing harmonics without compromising the converter's output power. As previously discussed, various PWM techniques have been explored in the literature. [22] categorizes these techniques based on their switching functions into three main types: fundamental, low, and high switching PWM schemes. For Modular Multilevel Converters (MMCs), the Multicarrier PWM (M-PWM) technique is recommended due to its high switching capability. M-PWM is further categorized based on the carrier arrangement into Phase-Shifted PWM (PS-PWM) and Level-Shifted PWM (LS-PWM). In this study, the authors have modified the LS-PWM technique to achieve voltage balancing of the submodule capacitors using an open-loop control method.

The basic control objectives for a modular multilevel converter are primary and secondary objectives, respectively shown in figure 2. The reference (V_{ref}) and carrier signals (V_c) are necessary for generating the gating signals. In LS-PWM technique, the carrier signals for each half bridge submodule are identical but vertically shifted. There exist 6 triangular carrier signals, the height of each carrier waveform is given by dividing the modulation index of V_{ref} by the number of carriers.

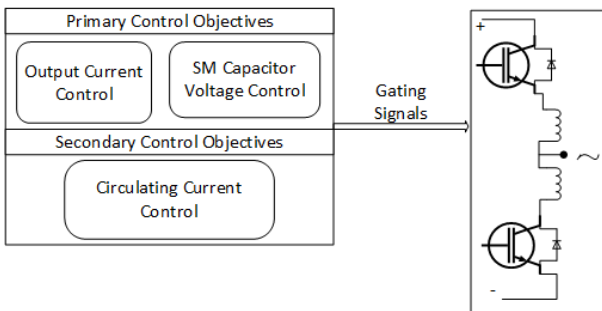


Fig 2. MMC control objectives [22]

Voltage balancing is crucial for ensuring that the voltages across the capacitors of the submodules remain stable, which is vital for the reliability of Modular Multilevel Converters (MMCs). The fundamental principle of voltage balancing techniques involves controlling the charging and discharging of the submodule capacitors based on the direction of the arm current, typically achieved through the use of sorting

algorithms. Previous studies, such as [22], [24], [29], and [30], have explored voltage balancing in MMCs using Phase-Shifted PWM (PS-PWM) and Nearest Level Control (NLC) techniques. In this paper, however, the authors utilize a Level-Shifted PWM (LS-PWM) technique, incorporating an adapted sorting algorithm, as illustrated in the flowchart in Figure 3.

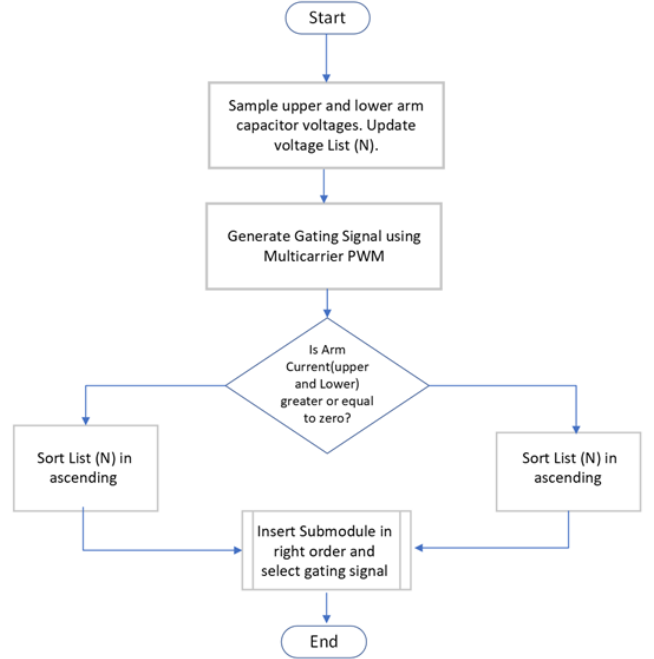


Fig 3: Capacitor voltage sorting algorithm flowchart

A sorting algorithm for a multilevel inverter requires three key variables to generate the desired PWM signals that drive the switching devices. While sorting algorithms are widely used to manage data sets in various applications, their specific application in the simulation or physical prototyping of MMCs is less frequently discussed in the literature. Few studies, such as [31], have addressed the use of sorting algorithms in this context.

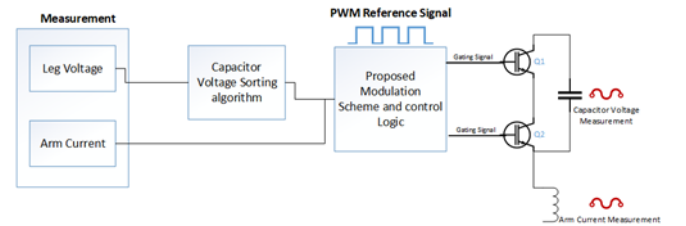


Fig 4: Block Diagram of proposed method

In this study, the bubble-sorting algorithm was employed, where the voltage of each submodule capacitor is stored in an array and sequentially compared with adjacent values, swapping them as necessary. The arm selection algorithm used is illustrated in Figure 3. In this process, capacitor voltages are acquired and stored in memory. Using signal processing through the "s-control" function, sorting is performed by comparing each submodule's capacitor voltage and arm inductor current with the modulating signal. This is done independently for both the upper and lower arms. The proposed control strategy implemented in this study is depicted in Figure 4.

III. RESULTS AND DISCUSSION

A single-phase modular multilevel converter is designed using MATLAB/Simulink generating 3-level, five-level, and

seven-level voltages to ascertain the proposed voltage balancing and modulation technique. The simulation parameters, detailed in Table I, were selected with a focus on evaluating the efficiency of the proposed method and converter type in Medium Voltage Direct Current (MVDC) and Low Voltage Direct Current (LVDC) applications, even though MMCs are typically used for High Voltage Direct Current (HVDC) systems. In this study, the Multicarrier PWM technique was utilised. The output current and voltage waveforms for the different voltage levels of the MMC were obtained for a dynamic load, as shown in Figures 5 and 6.

The results indicate that the output voltage for the 3-level converter switches between +VC, 0, and -VC, while the 5-level output transitions between +2VC, +VC, 0, -VC, and -2VC. Similarly, the 7-level output ranges between +3VC and -3VC, corresponding to the capacitor voltages during the switching cycle, consistent with existing MMC literature. Additionally, the Total Harmonic Distortion (THD) analysis reveals that as the voltage levels increase, the THD decreases. Specifically, a 2.46% THD was observed for the 3-level MMC, 1.19% for the 5-level converter, and 0.93% for the 7-level MMC, confirming that higher converter levels result in reduced harmonics.

Furthermore, the simulated 3-level MMC was connected to a dynamic load, specifically a 3-phase induction motor. The motor parameters are provided in Table II. According to the modulating signal, the motor was set to a speed of 1415 rpm, which it achieved within approximately 0.5 seconds. The speed and torque characteristics for the 3-level MMC and a conventional Voltage Source Converter (VSC) are presented in Figure 8. The comparison shows that the MMC outperformed the VSC, with the motor reaching stability in about 0.5 seconds, compared to 1.3 seconds for the VSC, which also failed to reach the set speed. Additionally, the torque comparison indicates that the MMC effectively maintained the set torque when driving the induction motor, as shown in Figure 10b.

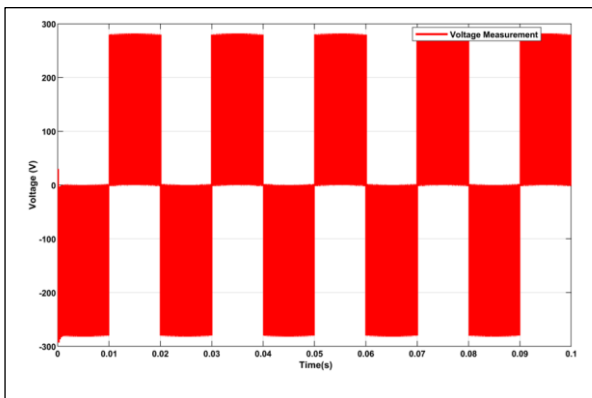


Figure 5. (a) 3Level MMC Line Voltage

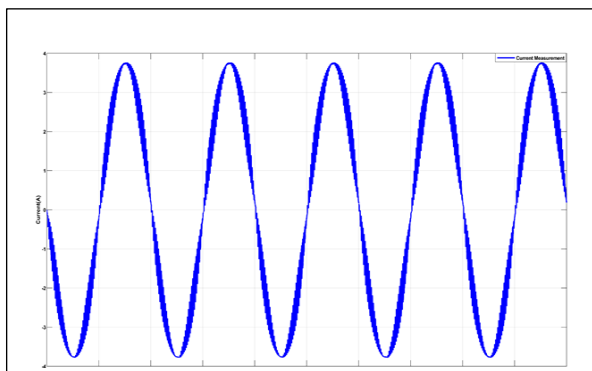


Figure 5. (b) 3 level MMC current waveform for Passive Load

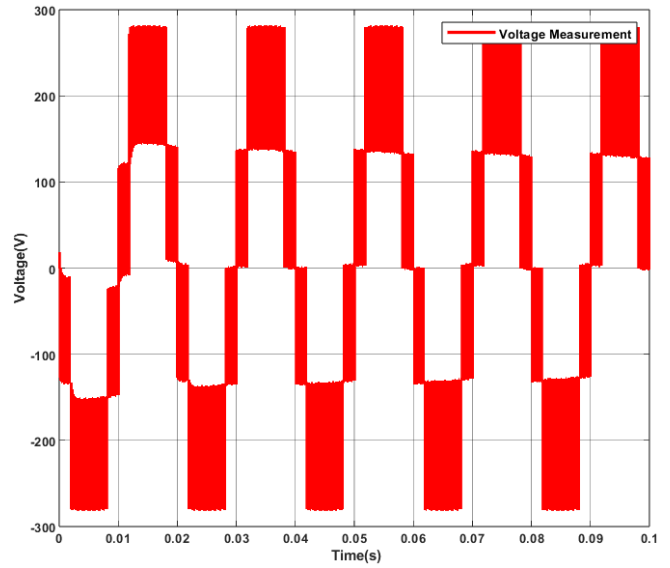


Figure 6(a). 5-Level MMC Voltage

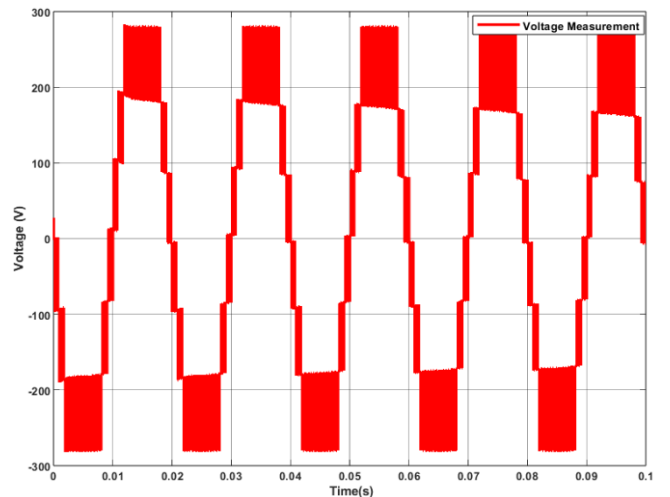


Figure 6(b). 7Level MMC Phase Voltage

Table I. Simulation Parameters for MMC simulation

Parameters	Value
Dc Link Voltage (V_{dc})	560V
Submodule capacitance	100uF
Arm Inductance	2.5uH
Load	74Ω and 12.5mH
Frequency	50Hz

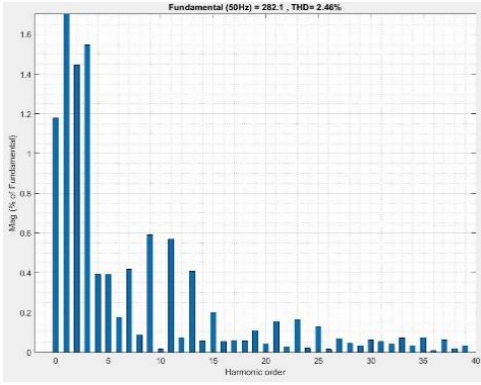
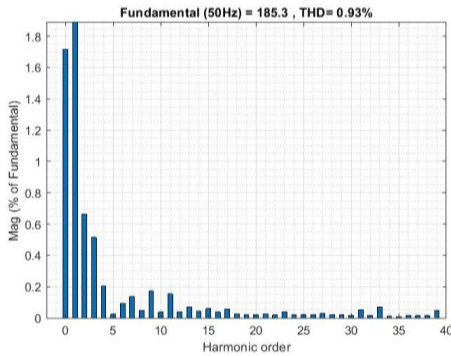


Figure 7. (a) THD for 3-Level MMC



(b) THD for 7-Level MMC

Table II: Parameters for Induction motor [32]

B	0.0028 N.m/rad/sec	Power	3HP
J	0.055 kg.m ²	Voltage rating	415V
M	0.1524H	Frequency	50Hz
Stator Ratings		Rotor Ratings	
R_s	1.88 Ω	R_r	2.72 Ω
L_{ls}	0.0125H	L_{lr}	0.0125H
L_s	0.1649H	L_r	0.1649H
Poles	4	Speed	1415 rpm

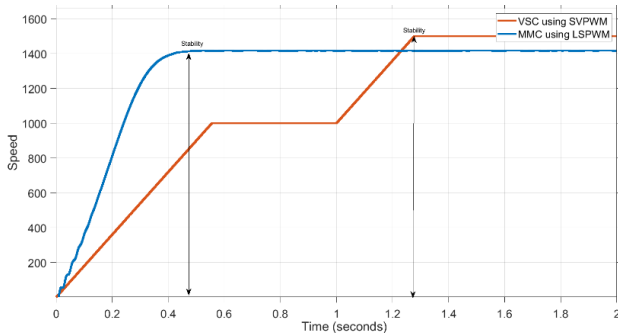
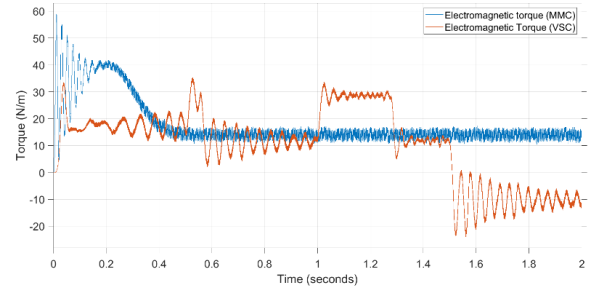


Figure 8 (a) Speed response of 3 level MMC connected Induction motor



(b) Torque response comparison plot between MMC and VSC connected Induction motor

IV. CONCLUSION

This study contributes to the expanding body of research on Modular Multilevel Converters (MMCs), which were first introduced in academic literature in 2003. The paper analyses the circuit of an MMC to examine the impact of Multicarrier Pulse Width Modulation (PWM) and capacitor voltage balancing on power quality indices, particularly harmonics. The analysis also included the connection of a dynamic load to the converter, with results indicating that the modified Multicarrier PWM and voltage balancing techniques effectively achieved the primary control objectives, leading to stability as demonstrated by the speed response of the dynamic load. However, given the inherent complexities in controlling MMCs, future research could explore the potential of traditional control techniques, such as optimal or nonlinear control methods, to further enhance system performance.

REFERENCES

- [1] V. Yaramasu, A. Dekka, and S. Kouro, Multilevel converters for renewable energy systems. Elsevier Inc., 2021.
- [2] IEA, "Global Energy Review 2020," 2020. doi: 10.1787/a60abbf2-en.
- [3] S. N. Manias, Inverters (DC-AC Converters). 2017.
- [4] A. Ordone, E. Unamuno, J. A. Barrena, and J. Paniagua, "Interlinking converters and their contribution to primary regulation: a review," Int. J. Electr. Power Energy Syst., vol. 111, no. February, pp. 44–57, 2019, doi: 10.1016/j.ijepes.2019.03.057.
- [5] E. Planas, J. Andreu, J. I. Gárate, I. Martínez De Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," Renew. Sustain. Energy Rev., vol. 43, pp. 726–749, 2015, doi: 10.1016/j.rser.2014.11.067.
- [6] S. Galami, "Power Electronics Converters for Microgrids with Smart Grid Functionality," Norwegian University of Science and Technology, 2014.
- [7] E. Catherine Amala Priya and G. T. Sundar Rajan, "Renewable Energy Source based Γ -Z source inverter interlinked to grid with Harmonics optimization Techniques," 2018, doi: 10.1109/ICIC.2018.8782323.
- [8] M. Abdellah and B. Kamal, "Experimental analysis of the space vector PWM control of two-level inverter to feeding an induction motor," Proc. 2017 Int. Conf. Electr. Inf. Technol. ICEIT 2017, vol. 2018-Janua, pp. 1–6, 2018, doi: 10.1109/EITech.2017.8255283.
- [9] A. Sudarsanan, R. Roopa, and S. Sanjana, "Comparison of Conventional & New Multilevel Inverter Topology," vol. 6, no. 2, pp. 330–334, 2015.
- [10] P. Chaturvedi, Conventional multilevel inverter: Topologies and control strategies. Elsevier Inc., 2018.
- [11] P. Sivaraman and P. Prem, "PR controller design and stability analysis of single stage T-source inverter based solar PV system," J. Chinese Inst. Eng. Trans. Chinese Inst. Eng. A, vol. 40, no. 3, pp. 235–245, 2017, doi: 10.1080/02533839.2017.1303337.
- [12] A. Salem, H. Van Khang, K. G. Robbersmyr, M. Norambuena, and J. Rodriguez, "Voltage Source Multilevel Inverters with Reduced Device Count: Topological Review and Novel Comparative Factors," IEEE Trans. Power Electron., vol. 36, no. 3, pp. 2720–2747, 2021, doi: 10.1109/TPEL.2020.3011908.
- [13] A. Sinha, K. Chandra Jana, and M. Kumar Das, "An inclusive review on different multi-level inverter topologies, their modulation and

- control strategies for a grid connected photo-voltaic system,” *Solar Energy*, vol. 170, no. June. Elsevier, pp. 633–657, 2018, doi: 10.1016/j.solener.2018.06.001.
- [14] C. Oates, “Modular multilevel converter design for VSC HVDC applications,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 3, no. 2, pp. 505–515, 2015, doi: 10.1109/JESTPE.2014.2348611.
- [15] R. Darus, G. Konstantinou, J. Pou, S. Ceballos, and V. G. Agelidis, “Comparison of phase-shifted and level-shifted PWM in the modular multilevel converter,” *2014 Int. Power Electron. Conf. IPEC-Hiroshima - ECCE Asia 2014*, pp. 3764–3770, 2014, doi: 10.1109/IPEC.2014.6870039.
- [16] A. Nami and H. Nademi, *Modular multilevel converter (MMC) and its control*, no. Mmc. Elsevier Inc., 2018.
- [17] E. N. Abildgaard and M. Molinas, “Modelling and control of the modular multilevel converter (MMC),” *Energy Procedia*, vol. 20, no. Mmc, pp. 227–236, 2012, doi: 10.1016/j.egypro.2012.03.023.
- [18] R. Vidal-Albalade, E. Belenguer, H. Beltran, and R. Blasco-Gimenez, “Efficient model for modular multi-level converter simulation,” *Math. Comput. Simul.*, vol. 130, pp. 167–180, 2016, doi: 10.1016/j.matcom.2015.10.001.
- [19] M. Jankovic, A. Costabeber, A. Watson, and J. C. Clare, “Arm-balancing control and experimental validation of a grid-connected mmc with pulsed DC load,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9180–9190, 2017, doi: 10.1109/TIE.2017.2711516.
- [20] O. S. M. Abushafa, S. M. Gadoue, M. S. A. Dahidah, D. J. Atkinson, and P. Missailidis, “Capacitor voltage estimation scheme with reduced number of sensors for modular multilevel converters,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 6, no. 4, pp. 2086–2097, 2018, doi: 10.1109/JESTPE.2018.2797245.
- [21] D. Siemaszko, “Fast sorting method for balancing capacitor voltages in modular multilevel converters,” *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 463–470, 2015, doi: 10.1109/TPEL.2014.2312101.
- [22] S. Du, A. Dekka, B. Wu, and N. R. Zargari, *Modular Multilevel converters: Analysis, Control and Applications*, First. John Wiley & Sons, 2018.
- [23] P. M. Meshram and V. B. Borghate, “A simplified nearest level control (NLC) voltage balancing method for modular multilevel converter (MMC),” *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 450–462, 2015, doi: 10.1109/TPEL.2014.2317705.
- [24] Y. Chen and X. Zhang, “Voltage Balancing Method on Expert System for 51-Level MMC in High Voltage Direct Current Transmission,” *Math. Probl. Eng.*, vol. 2016, 2016, doi: 10.1155/2016/2968484.
- [25] A. D. Bonde, P. M. Meshram, V. B. Borghate, and H. B. Gobburi, “Analysis of Capacitor Voltage Balancing Method of Modular Multilevel Converter (MMC) for the Application of SPWM, NLC & SHE-PWM Modulation Techniques,” no. Mmc, pp. 1–6, 2020, doi: 10.1109/stpec49749.2020.9297688.
- [26] R. Jaiswal, A. Agarwal, and R. Negi, “Performance Enhancement of Modular Multilevel Converter by using Modulation Technique,” *2019 IEEE 1st Int. Conf. Energy, Syst. Inf. Process. ICESIP 2019*, 2019, doi: 10.1109/ICESIP46348.2019.8938362.
- [27] Jatin, A. Agarwal, and V. K. Jadoun, “Comparative Analysis of 5 level, 7 level and 9 level Half-Bridge Modular Multilevel Converter,” *J. Phys. Conf. Ser.*, vol. 1478, no. 1, 2020, doi: 10.1088/1742-6596/1478/1/012012.
- [28] M. Zygmanowski, B. Grzesik, and R. Nalepa, “Capacitance and inductance selection of the modular multilevel converter,” *2013 15th Eur. Conf. Power Electron. Appl. EPE 2013*, no. September 2013, 2013, doi: 10.1109/EPE.2013.6634446.
- [29] A. M. Y. M. Ghias, J. Pou, M. Ciobotaru, and V. G. Agelidis, “Voltage balancing method for the multilevel flying capacitor converter using phase-shifted PWM,” *PECon 2012 - 2012 IEEE Int. Conf. Power Energy*, no. 1, pp. 274–279, 2012, doi: 10.1109/PECon.2012.6450221.
- [30] J. Ananthu and V. Srikanth, “Voltage balancing of modular multilevel converter for an induction motor drive,” *2017 Int. Conf. Intell. Comput. Instrum. Control Technol. ICICICT 2017*, vol. 2018-Janua, pp. 699–703, 2018, doi: 10.1109/ICICICT1.2017.8342649.
- [31] T. Heath, P. R. Green, M. Barnes, and P. Coventry, “Capacitor balancing controller voltage sorting statistics in modular multilevel converters,” *Proc. - 2017 IEEE South. Power Electron. Conf. SPEC 2017*, vol. 2018-Janua, pp. 1–8, 2018, doi: 10.1109/SPEC.2017.8333550.
- [32] W. Jamal, G. V. Williams, P. Igc, P. A. Mawby, and S. Park, “A Compact Dynamic Model of Induction Machine For PSPICE Simulation,” *Simulation*, 2004.