6TH International Conference and Workshop on Engineering and Technology Research (ICWETR) LAUFET 2025: 91-98

Examination of the Impact of Circulating Current on the Dynamics of Modular Multilevel Converter

[1]Kadandani N. B., [2]Abubakar I. and [3]Bukata B. B.

[1,2,3]*Department of Electrical Engineering, Bayero University, Kano, Nigeria*

https://www.laujet.com/

Keywords:

Modular multilevel converter (MMC), Circulating current, Arm current, Submodule (SM).

Corresponding Author:
nbkadandani.ele@buk.edu.ng

ABSTRACT

Modular multilevel converter (MMC) has been considered the preferred converter topology for high voltage applications such as high voltage direct current (HVDC) transmission systems due to its ability to produce output waveforms with reduced harmonic distortions, fault-tolerant capability, simple capacitor voltage balancing, modularity and scalability to different voltage and power levels. However, despite all these advantages, the converter has one peculiar structure of having a pair of arms in each phase leg which results in the flow of unavoidable circulating current through the converter arms. This paper examines the impact of the circulating current on the dynamics of the converter. Experimental results on a reduced order single-phase MMC prototype with three submodules (SMs) per arm show that the circulating current does not have any impact on the outer dynamics of the converter as demonstrated by the output current waveform which exhibits a smooth sinusoidal shape. However, both the upper and the lower arm current waveforms exhibit second-order harmonics. The presence of the double-line frequency component on the arm current waveforms shows that the circulating current does affect the inner dynamics of the converter. This impact can be translated to mean adding extra losses to the converter, increasing its components ratings and or increasing the amplitude of the capacitor voltage ripples.

INTRODUCTION

The modular multilevel converter (MMC) was first introduced in the year 2003 (Lesnicar and Marquardt, 2003). Since then, the converter has been the most attractive topology for medium to high voltage applications such as high voltage direct current transmission systems (HVDC) as experimentally demonstrated in (Kadandani, 2021b), medium voltage motor drives (Antonopoulos *et al.,* 2014), solid-state transformers (Kadandani *et al.*, 2021), and in traction systems (He *et al.,* 2019). Compared with the conventional two-level and three-level voltage source converters (VSCs), the MMC is now the most preferred VSC topology for industrial applications (Ismail and Kaliyaperumal, 2021). This is not surprising as the converter can produce output waveforms with reduced harmonic distortions, has fault-tolerant capability, simple capacitor voltage balancing, modularity and scalability to different voltage and power levels, reduced voltage stress of components, and excellent output characteristics (Geng *et al.,* 2022; Li *et al.,* 2016; Wang *et al.,* 2021a; Wang, *et al.,* 2021b; Zhou *et al.,* 2022). Different modulation techniques have been proposed for the converter. However, the work reported in (Kadandani, 2021c) highlighted all possible modulation techniques applicable to MMC in particular. Several works have also been reported in the literature regarding methods of balancing and or controlling the multi-variable parameters of MMC such as capacitor voltage balancing (Kadandani, 2023), submodule temperature regulation (Gonçalves *et al.,* 2018) and circulating current control (Kadandani, 2022a). Figure 1 shows the circuit schematic of a three-phase MMC. Each phase consists of a pair of arms that are connected

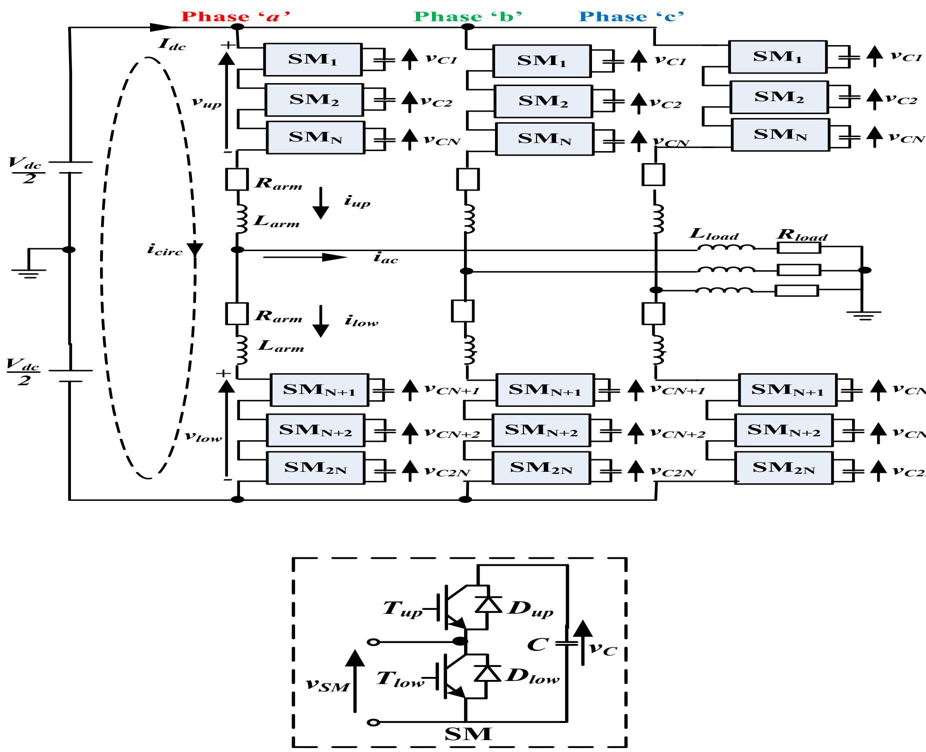


Figure 1: Three phase MMC, **(a)** circuit schematic, **(b)** sub-module chopper cell (Kadandani, 2021a)

in series between the DC terminals. Each arm consists of an arm inductor and several submodule (SM) chopper cells. Depending on the application and other configurations, the SM chopper cell can be realized in different topologies. Some of the possible circuit configurations of SM include; half bridge SM (HBSM), full bridge SM (FBSM), flying capacitor SM (FCSM), diode clamped SM (DCSM), T-Submodule 1 (TSM1) or T-Submodule 2 (TSM2) (Konstantinou *et al.,* 2015). However, HBSM is the most commonly used configuration due to its simplicity in terms of component count, lowest losses and easy control method. As such, it is simpler to construct than the other SM configurations. The N number of SMs that are serially connected in each arm of MMC generates N+1 voltage levels in its corresponding output phase voltage (Muthavarapu *et al.,* 2022).

V_{dc} is the input DC voltage, L_{arm} and R_{arm}, represent the respective inductance and resistance of an arm, i_{up} and i_{low} are respectively upper and lower currents flowing through the arm of the converter, v_{up} and v_{low} are the respective arm voltages, L_{load} and R_{load} represents an RL load, i_{ac} and v_{ac} are the output AC and voltage respectively, i_{SM} and v_{SM} are SM current and voltage respectively, C is the capacitance of the SM and v_C is the voltage across the SM capacitor, T_{up} and D_{up} are the upper insulated gate bipolar transistor (IGBT) and diode in the SM while T_{low} and D_{low} are the lower IGBT and diode in the SM, i_{circ} is the circulating current that flows within the arms of the converter without appearing at its output. The arm inductor plays a significant role in MMC design. It is the major determinant of the size of the converter. It also allows small mismatches in the arm voltages. Of interest to this research, focus is that the circulating current control can be used to limit the amplitude of the circulating current through the converter arm and possible fault current as well. The circulating current control has been considered as very vital in the application of MMC. It is anticipated that, if not properly controlled, the circulating current after causing extra conduction losses on the converter can also reduce its efficiency. The work reported in (Kadandani, 2022b) shows that circulating current control can also reduce thermal stress in MMC. Based on the foregoing, this paper intends to examine the impact of the circulating current on the dynamics of a laboratory prototype MMC. The remaining part of the paper is organized as follows: Section II entails methodology/experimental procedure. Results and discussion are presented in Section III. Finally, Section IV concludes the article.

METHODOLOGY/EXPERIMENTAL PROCEDURE

The experimental set-up was based on a scaled-down laboratory prototype single-phase MMC with three SMs per arm. The main prerequisites for the experimental setup are:

Power Supply: Four Farnell L30-5 "linear" 30V 5A power supply units (PSUs) for providing electrical interphase to the converter arms.

Digital signal processor (DSP): TMS320F28377D Dual-Core Delfino™ Microcontroller board.

Gate Drives: Two-way six gate drive circuit board for generating and sending the PWM signals to the SM/arm board capacitor voltage measurements.

Voltage Sensors: Seven LV 25-P voltage transducers for measuring all the six SM capacitor voltages across the converter leg and the output voltage at the AC terminal.

Current Sensors: Three CAS15-NP current transducers for measuring arm currents (upper and lower) and the output current.

Code Platform: Code Composer Studio (CCS) was used as the coding environment.

Graphical User Interphase (GUI): A MATLAB GUI is used with the control board both of which are linked via USB cable. It is meant to set up the GUI appearance and operate continuous communications with the target hardware (TMS320F28377D control board). Figure 2 shows a photograph of the set-up while Table 1 shows the values of the system parameters.

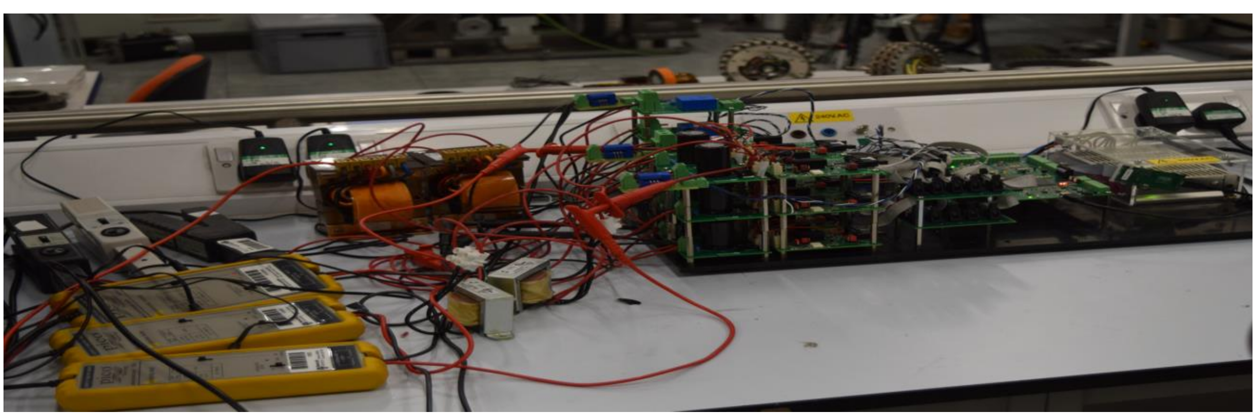


Figure 2: Photograph of the experimental test rig

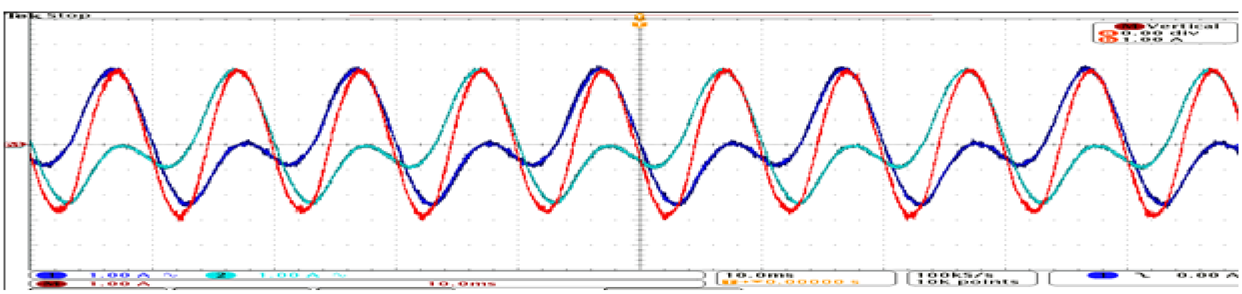
Table 1: Parameters of the Experimental Set-up

Parameter	Value
Number of submodule per arm	3
Submodule capacitance	2.2mF
Arm inductance	1mH
Load resistor	33Ω
Load inductor	1mH
DC link voltage	100V
Carrier frequency	4kHz
Modulation index	0.9

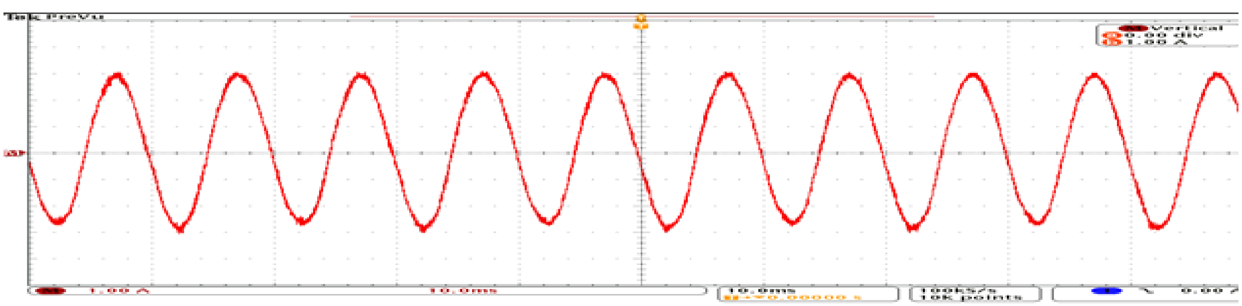
RESULT AND DISCUSSION

Circulating Current

Figure 3 shows how the circulating current was measured. In particular, Fig. 3(a) shows the circulating current amid arm currents of the converter, while Fig. 3(b) shows a twice value of the circulating current which was obtained from the measured arm currents using the sum math function in the digital storage oscilloscope. As such, the actual value of the circulating current is one-half of what is shown in the figure. It represents the current that flows between the input voltage source and the arms of each phase. In other words, the circulating current flows in each arm due to the occurrence of high-frequency DC component which flows during switching operations.



(a)



(b)

Figure 3: Impact of circulating current on the inner dynamics of the converter, (a) circulating current amid upper and lower arm current, (b) circulating current alone

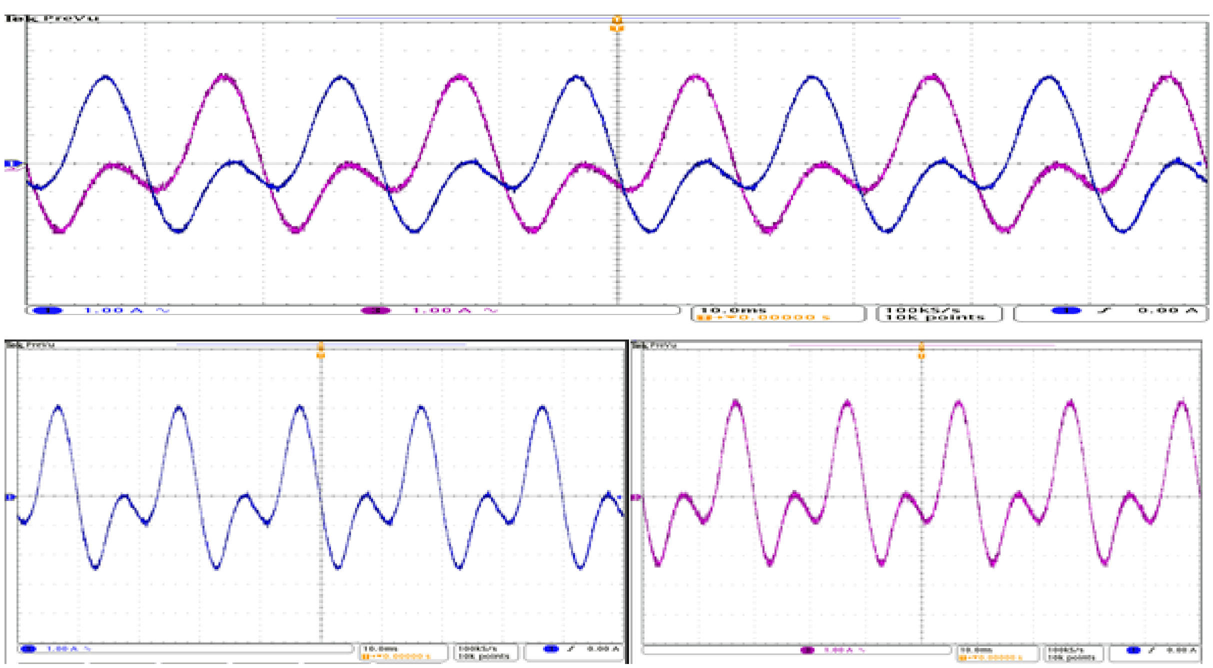
It can be seen that the circulating current contains a double line-frequency component which can also be seen on the arm currents and it adds undesirable losses, thermal stress and current stress to the MMC all of which can lead to reduced lifetime and reliability of the system. As such, the circulating current has to be controlled for efficiency improvement, loss and thermal stress minimisation.

Arm Currents and Voltages

Figure 4 shows the current waveforms in the upper and lower arm of the converter, while Figure 5 shows their voltage waveforms. It can be seen in Figure 4 that the upper and lower arm currents are symmetrical and have three components, a DC component, a fundamental component, and a twice the fundamental component. Both of the arm current shows some elements of circulating current which originate from two sources, namely; the voltage difference between the two arms of the converter, and the instantaneous voltage ripple of the SM capacitors. In other words, the circulating current is generated by inner voltage differences in each phase of the converter in the form of a negative sequence with a frequency that is twice that of the fundamental. As such, the circulating current does affect the peak value of the arm current which can result in an increase in switching and conduction losses of the converter.

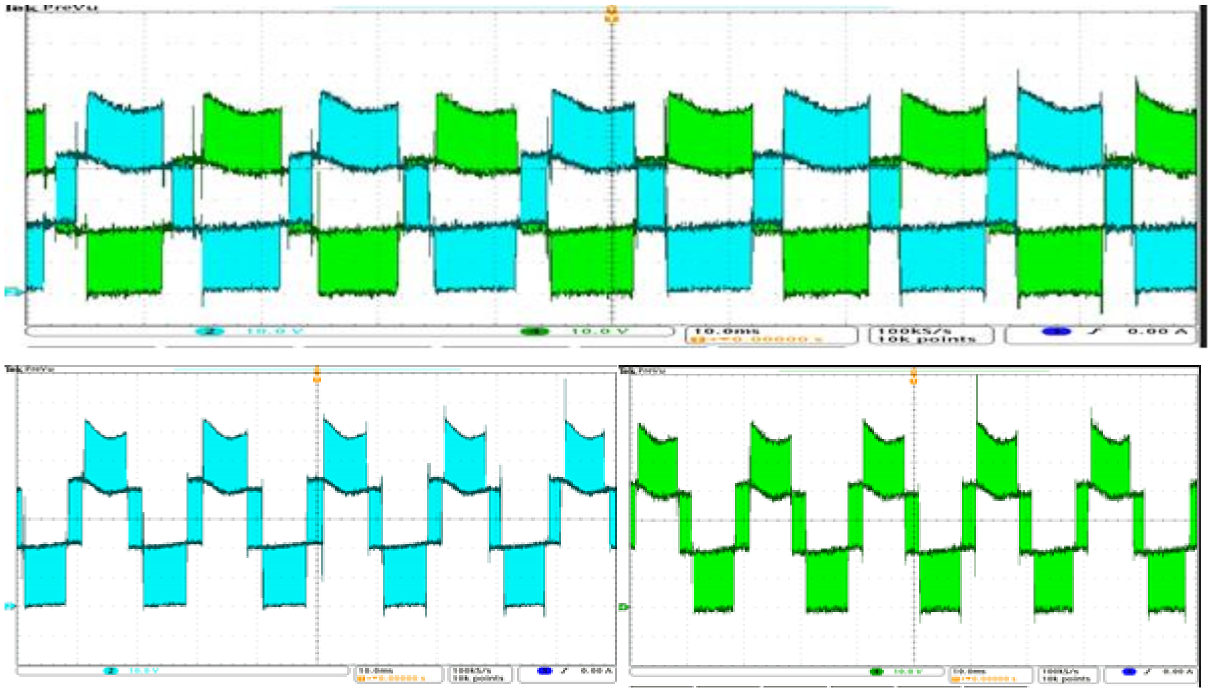
Output Current and Voltages

Figure 6 shows the output current and voltage waveforms of the converter. Both waveforms can be seen to have smooth sinusoidal waveforms. This implies that the circulating current is not detectable outside of the converter. In other words, the circulating current does not appear on the output AC, as such, it does not affect the outer dynamics of the converter However, its presence can cause significant wear and losses within the converter, as such a dedicated control is required to suppress it completely or minimize it to a minimum mode.



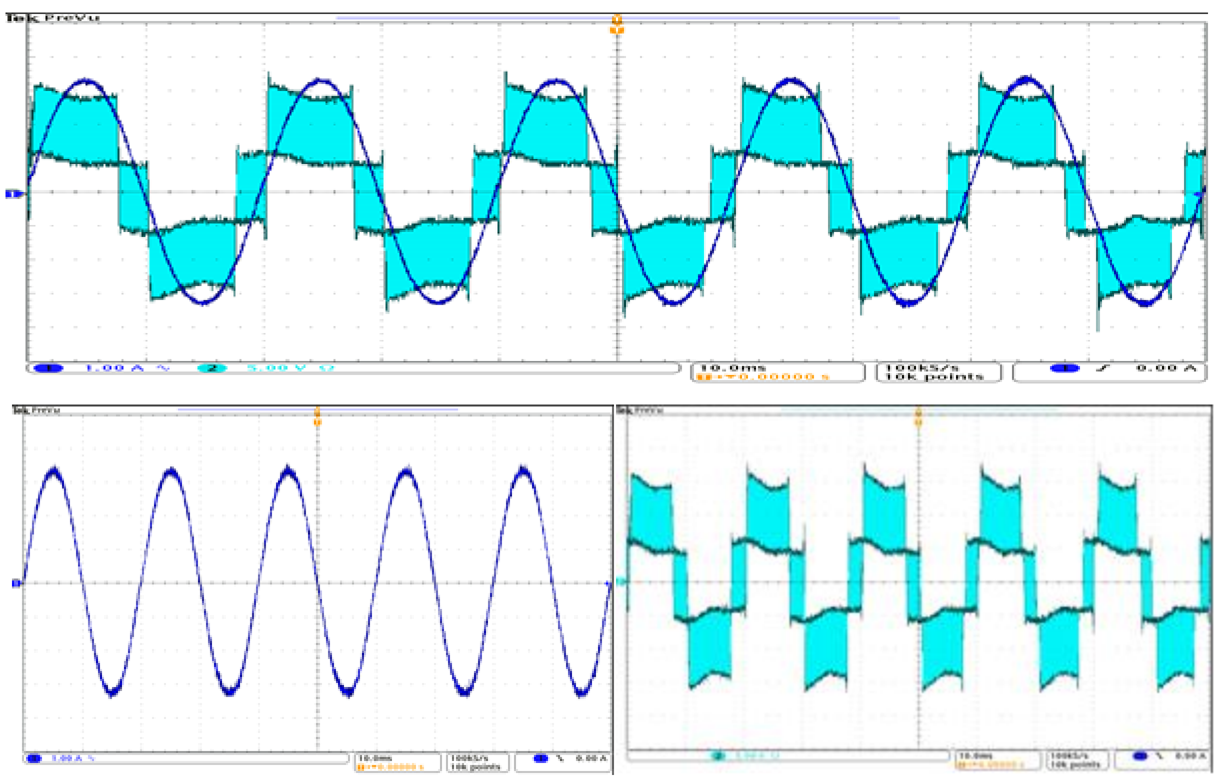
(a) **(b)**

Figure 4: Arm currents waveforms, **(a)** upper arm current, **(b)** lower arm current



(a) (b)

Figure 5: Arm voltage waveforms, **(a)** upper arm voltage, **(b)** lower arm voltage



(a) (b)

Figure 6: Output current and voltage waveforms, (a) output current, (b) output voltage

CONCLUSION

The paper has investigated the impact of circulating current control on the dynamics of MMC through an experiment on a laboratory prototype MMC with three SMs per arm. The results show that the circulating current has no impact on the outer dynamics of the converter but does affect its inner dynamics as demonstrated by the arm current waveforms which show the presence of second-order harmonics which are integral parts of A.C. circulating current. It is concluded that the circulating currents of each phase-leg of the MMC can have a significant impact on the rating value of the converter components, the amplitude of the capacitor's voltage ripples, and the power losses. The main impact of the circulating current on the converter is an additional source of losses. As such, the circulating current in MMC must be controlled for the converter to compete with other multilevel VSCs such as cascaded H-bridge converters.

REFERENCES

Antonopoulos, A., Ängquist, L., Norrga, S., Ilves, K., Harnefors, L. and Nee, H. (2014). Modular Multilevel Converter AC Motor Drives With Constant Torque From Zero to Nominal Speed *IEEE Transaction on Industry Applications, Vol. 50, No.* 3, 1982-1993.

Geng, Z., Han, M., Xia, C. and Kou, L. (2022). A Switching Times Reassignment-Based Voltage Balancing Strategy for Submodule Capacitors in Modular Multilevel HVDC Converters. *IEEE Transactions on Power Delivery, Vol. 37, No. 2*, 1215-1225. doi:10.1109/TPWRD.2021.3080298

Gonçalves, J., Rogers, D. J. and Liang, J. (2018). Submodule Temperature Regulation and Balancing in Modular Multilevel Converters. *IEEE Transactions on Industrial Electronics, Vol. 65, No. 9*, 7085-7094.

He, X., Peng, J., Han, P., Gao, S. and Wang, P. (2019). A Novel Advanced Traction Power Supply System Based on Modular Multilevel Converter. *IEEE Access, Vol. 7*, 165018 - 165028.

Ismail, H. M. and Kaliyaperumal, S. (2021). Enhanced Voltage Sorting Algorithm for Balancing the Capacitor Voltage in Modular Multilevel Converter. *IEEE Access, Vol. 9, 2021*, 167489-167502. doi:10.1109/ACCESS.2021.3134008

Kadandani, N. B. (2021a). Fatigue Analysis in Modular Multilevel Converter Using Rainflow Algorithm. *Bayero Journal of Engineering and Technology (BJET), Vol. 16, No. 2*, 37-47.

Kadandani, N. B. (2021b). Hardware Implementation of Modular Multilevel Converter Prototype for HVDC Transmission System. *Bayero Journal of Engineering and Technology (BJET), Vol. 16, No. 2*, 109 - 120.

Kadandani, N. B. (2021c). Switching Sequence and Modulation Techniques of Modular Multilevel Converter. *Proceedings of the 2nd International Symposium on Applied Science and Engineering (ISASE 2021), Atatürk University, Erzurum, Turkey*, pp. 70-73.

Kadandani, N. B. (2022a). Experimental Demonstration of the Influence of Circulating Current Control on Thermal Relief in Modular Multilevel Converter. *Zaria Journal of Electrical Engineering Technology (ZJEET), Vol. 11, No. 1*, 1-9.

Kadandani, N. B. (2022b). Thermal Stress Minimization in Modular Multilevel Converters Using Circulating Current Control with Submodule Temperature Regulation. *Zaria Journal of Electrical Engineering Technology (ZJEET), Vol. 11, No. 1*, 10-22.

Kadandani, N. B. (2023). Experimental Voltage Balancing Based Sorting Algorithm for Modular Multilevel Converters. *Bayero Journal of Engineering and Technology (BJET), Vol. 18, No. 2*, 19 – 27.

Kadandani, N. B., Dahidah, M. and Ethni, S. (2021). Design and Dveleopment of Modular Multilevel Converter for Solid State Transformer Application. *Bayero Journal of Engineering and Technology (BJET), Vol. 16, No. 1*, 31-41.

Konstantinou, G., Zhang, J., Ceballos, S., Pou, J. and Agelidis, V. G. (2015). Comparison and Evaluation of Sub-Module Configurations in Modular Multilevel Converters. *Proceedings of IEEE 11th International Conference on Power Electronics and Drive Systems*, 958-963.

Lesnicar, A. and Marquardt, R. (2003). An Innovative Modular Multilevel Converter Topology Suitable for a Wide Power Range. *Proceedings of IEEE Power Tech Conference, Bologna,, 3*, 1-6.

Li, X., Song, Q., Liu, W., Xu, S., Zhu, Z. and Li, X. (2016). Performance Analysis and Optimization of Circulating Current Control for Modular Multilevel Converter. *IEEE Transactions on Industrial Electronics, Vol. 63, No. 2*, 716-727. doi:10.1109/TIE.2015.2480748

Muthavarapu, A. K., Biswas, J. and Barai, M. (2022). An Efficient Sorting Algorithm for Capacitor Voltage Balance of Modular Multilevel Converter With Space Vector Pulsewidth Modulation. *IEEE Transactions on Power Electronics, Vol. 37, No. 8*, 9254-9265. doi:10.1109/TPEL.2022.3160665

Wang, W., Ma, K. and Cai, X. (2021a). Efficient Capacitor Voltage Balancing Method for Modular Multilevel Converter Under Carrier-Phase-Shift Pulsewidth Modulation. *IEEE Transactions on Power Electronics, Vol. 36, No. 2*, 1553-1562. doi:10.1109/TPEL.2020.3009272

Wang, W., Ma, K. and Caii, X. (2021b). Flexible Nearest Level Modulation for Modular Multilevel Converter. *IEEE Transactions on Power Electronics, Vol. 36, No. 12*, 13686-13696. doi:10.1109/TPEL.2021.3089706

Zhou, L., Chen, C., Xiong, J. and Zhang, K. (2022). A Robust Capacitor Voltage Balancing Method for CPS-PWM-Based Modular Multilevel Converters Accommodating Wide Power Range. *IEEE Transactions on Power Electronics, Vol. 37, No. 12*, 14306-14316. doi:10.1109/TPEL.2022.3192485