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Analysis of Harmonic Distortion Reduction through Modular Multi-Level Inverter using Nearest Level Modulation (NLM) Control Strategy

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Abstract:

The research paper presents the novel control strategy of Modular Multilevel Converter (MMC) to reduce Total Harmonic Distortion (THD) losses by the implementation of Nearest Level Modulation (NLM) control technique. However, the MMC strategy reduces the THD in comparison with the conventional converters which results in improvement of power quality. In addition to this, the MMC has been designed with higher scalability with high voltage and power capacity. Sub-module is an integral part of MMC which is built up as an identical and controllable part of it. This type of converter is also known as a controllable voltage source (CVS) converter. Many researchers have conducted a detailed review regarding control methods and necessary operations applied to MMC-based systems which can be applied for High Voltage Direct Current (HVDC), particularly focusing to reduce the THD. Power converters use many modulation techniques, but the existing techniques contribute to major switching losses. However, in this paper authors discussed in detail about MMC up to 49 levels, by implementing the NLM technique, it is showed that the MMC offers simplicity and good controllability in the THD reductio. In this work, the reduction of THD by increasing the voltage levels in MMC is comprehensively analyzed. The simulation results obtained through Matlab/Simulink are used to analyze the effectiveness of the proposed control strategy for stable operation of MMC used in HVDC applications.

Keywords: *MMC; NLM; THD; Power Quality Analysis; HVDC; MATLAB/Simulink*

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1. Introduction

The Modular Multilevel Converter (MMC) belongs to the multilevel converters' family [1-3]. It has attracted substantial interest owing to its various unique features including multiple output voltage levels, higher flexibility, and modular design scalability, capacitor-less dc-link as well as transformer-less operations [3-4]. The MMC has become the futuristic and preferred choice for HVDC applications due to having high redundancy, least cost, lower size of the filter, and low power semiconductor losses. The circuit topology of MMC is shown in Fig. 1. The inverter is one of the types of power electronic converters which converts Direct Current (DC) power supply to Alternating Current (AC) waveform. Inverters are usually used in solar panels and other sorts of devices to use DC power into powering

some useful AC loads. The output of the inverter depends upon its type which is being used. It can be a square wave, quasi-square-wave, or sine-wave inverter. Even if a sine-wave inverter is being used, its output is not purely sinusoidal as it contains some harmonics. These harmonics are the components of a periodic wave that are multiple of the fundamental frequency and produce distortion in the output [4-5].

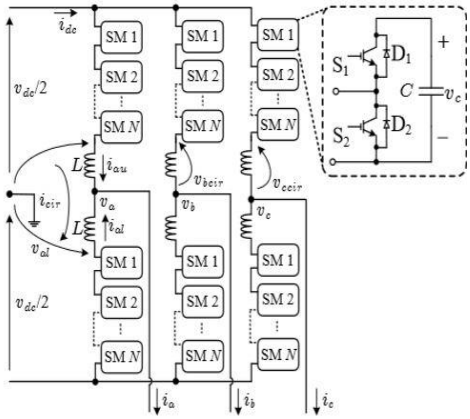


Fig. 1: Circuit Topology

These harmonic distortions can be minimized by using a suitable modulation technique or by using the suitable converter topology. Modular Multilevel Converters involves large number of levels with higher efficiency and lesser harmonic distortions [4] [5]. They can manage high voltage operations without involvement series-connecting switching devices. They provide lower common-mode voltages and higher power quality. They offer various advantages i.e. high modularity & scalability, transformer-less operation, lesser switching losses, and lower filtering cost [6].

2. Modular Multilevel Converter

It includes arms consisting of the upper and lower arm. Each arm has submodules (SM), and each is linked in the series [6] [7]. The upper arms and lower arms are connected to an inductor and a resistor to control fault current due to the potential difference that appeared in upper arms or lower arms [8]. The capacitor is placed in each submodule while each submodule consists of a half-bridge circuit to get a particular desired voltage level [9]. Also, each switch involves a diode in parallel to it intending to control the current flow. The working principle and generation of output levels of MMC can be understood by applying KVL to the basic structure of the circuit as shown in Fig. 2.

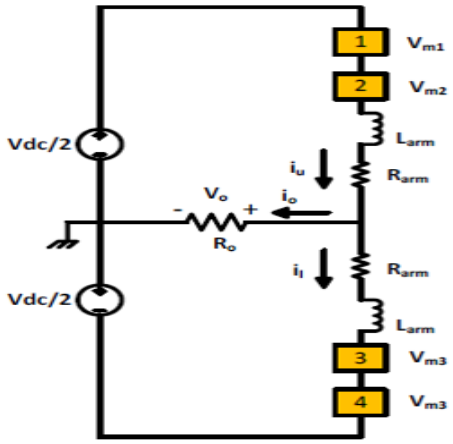


Fig. 2: Basic Structure of MMC

Where, V_{dc} is a supplied DC voltage, V_m [1-4] is a voltage across submodules and V_o is the output voltage. By neglecting arm inductance and assuming the capacitors as DC sources, KVL is applied on upper and lower arms rspectively.

For the upper arm:

$$Vo = \frac{Vdc}{2} - Vm1 - Vm2 \qquad (1)$$

For the lower arm:

$$Vo = -\frac{Vdc}{2} + Vm3 + Vm4 \qquad (2)$$

The voltage $Vo = V_{dc}/2$ can be calculated by bypassing two modules at the upper top and linking both modules in the lower loop. The potential of $V_o = -V_{dc}/2$ can be achieved by connecting both upper modules and bypassing two lower modules [10]. Similarly, to achieve zero levels, bypass one module from both the upper and lower loops. This can be achieved in four different ways. In this way, the output

voltage levels are generated corresponding to each loop. The submodule operation has three states; each is described in Table I.

TABLE I: Summary of the Operation of SMs

States	SM 1	SM 2	D1	D2	Capacitor
Blocking State	OFF	OFF	ON OFF	OFF ON	Inserted Not Inserted
Cut-in State	ON	OFF	-	-	Inserted
Cut-off State	OFF	ON	-	-	Not Inserted

2.1. Cell Structure

The literature proposes different types of submodule configurations. Following are the most well-known cell configurations:

Half-bridge submodule cell is the basic and the most common cell configuration in all SMs configurations due to its only two switching devices. If the upper switch S_1 is operating its conduction, SM is in the "ON" state. Interchangeably, if the lower switch S_2 is operating its conduction, SM remains in an "OFF" state. The output voltage of a cell is equal to SM capacitor voltage that depends on the switching operation of S_1 and S_2 as shown in Fig. 3.

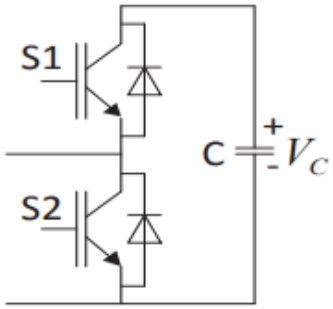


Fig. 3: Half-bridge SM Cell

Full-bridge submodule (FBSM) cell configuration contains four switching devices, and its output voltage is equal to the voltage of the capacitor, which depends on the switching operation of switching devices, as shown in Fig. 4.

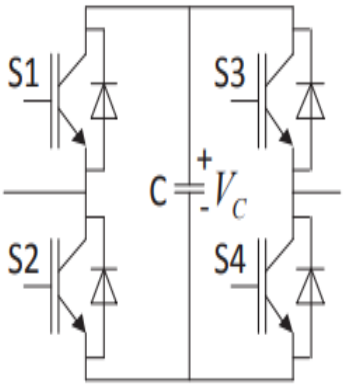


Fig. 4: Full-bridge SM Cell

Clamp-double SM (CDSM) configuration has two half-bridge SMs, one extra transistor with connected diodes, and additional diodes, as shown in Fig. 5. The switch S_5 remains always in the "ON" state, and this configuration operates like two series-connected half-bridge SMs.

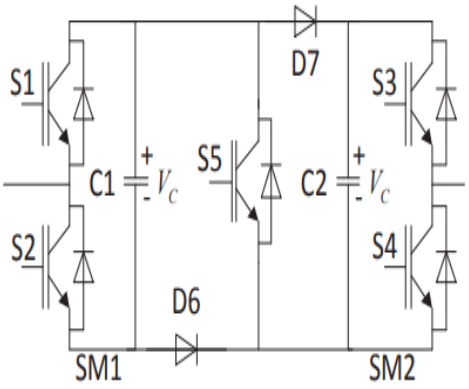


Fig. 5: Clamp-double SM Cell

Clamp-single SM (CSSM) consists of three switching devices with its parallel-connected diodes, a capacitor, and an extra diode, as shown in Fig. 6.

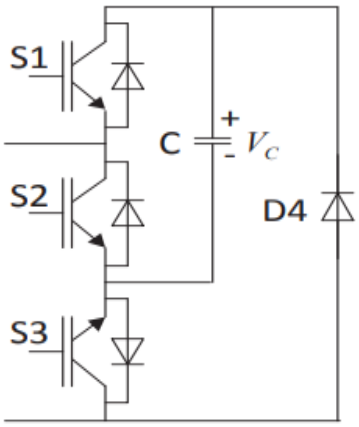


Fig. 6: Clamp-Single SM Cell

Apart from these SM topologies, many topologies of SMs are also present in literature [9] & [12]. In this paper, the most common and basic building block, Half-bridge configuration, is discussed in the rest of the section.

3. Modulation Technique

Modulation technique plays a vital role in the proper working, performance and efficiency f the converter. By using different PWM techniques, the levels of output can vary as per the desired requirement and application [11] [12]. The techniques of sinusoidal PWM are very common and used as control techniques, and they are additionally categorized into Level-Shifted and Phase-Shifted PWM techniques. Other variations of the level-shifted PWM techniques include In-Phase Deposition (IPD), Phase-Opposite Deposition (POD), and Alternate-Phase Opposite Deposition (APOD). These techniques use sine wave and different triangular waves, these are then compared to generate different levels of output voltages [13]. As there are many waves compared so this contributes to more switching losses.

The Nearest Level Modulation (NLM) technique is an alternative method for carrier-based modulation techniques that utilizes more waves [14]. It has the advantage of being simple for implementation. It was introduced mainly for large-drive multilevel systems, but it can also be used for MMC-based HVDC applications as it is more flexible and provides easy digital implementation when the converter is operating at a higher number of levels. It is used to avoid the triangular-carrier waves and directly computes the states of switching and duty cycles [15] [16]. The main idea behind this is to sample the reference at frequency F_S and then approximate it to the nearest level which results in the natural fundamental switching frequency with fewer switching losses.

For an MMC of N sub-modules per arm, NLM produces an N+1 output voltage level. If the converter operates at a higher frequency it will generate a better reference signal in terms of approximation. Now the reference waveform becomes a staircase, and the lower levels are used longer than the higher ones and hence this leads to the unbalance of capacitor voltage [17]. Therefore, NLM is not suitable for directly assigning to the sub-modules, instead, it requires a sorting algorithm before it is fed to the converter to ensure submodule energy balance. Fig. 7 shows the block diagram and the working of NLM. The block diagram shows that at first the reference voltage is normalized with the capacitor voltage of the submodule in the gain block then the round-function generates the closest integer number of the submodules to insert to approximate the reference voltage with the nearest voltage level [17] [18].

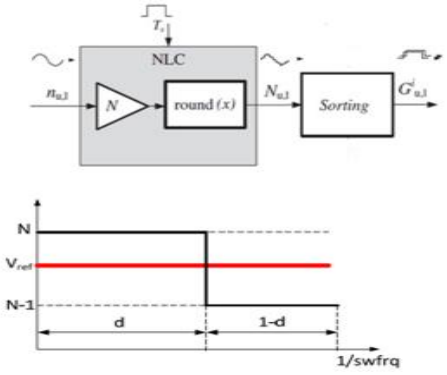


Fig. 7: Block Diagram & working Principle of NLM.

4. 49 Levels (H-Bridge) Modular Multilevel Converter

The MATLAB model of a three-phase circuit of MMC is shown in Fig. 8. RL load is connected at the grid side (AC side). The number of levels is varied to analyze the impact on the Total Harmonic Distortion (THD) and on the smoothness of output waveform. THD loss can be mitigated by inserting submodules in the converter [19]. Submodules are increased up to 49 output voltage levels. Hence, THD loss mitigation mainly contributes in power quality improvement [20]. The results are presented in the comparative analysis section for different levels including 22, 28, 33, 41, and 49 levels with RL load.

5. Results And Discussion

Comparative result analysis of multiple levels for (H-Bridge) MMC is done by using MATLAB/Simulink software (2018b). The output voltages and currents are compared concerning Total Harmonic Distortion for 22, 28, 31, 41, and 49 levels.

5.1. Case 1: 22 Levels

In this case, 22 level MMC, the output voltage & THD are shown in Fig. 9 & 10 respectively, and the output current & THD are shown in Fig. 11 & 12 respectively. At this stage, output voltage and current waveforms are not sinusoidal, they contain harmonics and the value of voltage harmonics is 2.58% with a fundamental frequency of 50 Hz. And the current THD is 0.94%.

5.2. Case 2: 49 Levels

In this case, MMC is increased up to 49, the output voltage and current waveforms become very smooth and closer to sinusoidal. The total harmonics distortion is reduced to a certain value. The output voltage and THD are shown in Fig. 13 & 14 respectively, and the output current & THD are shown in Fig. 15 & 16 respectively. The drastic reduction in voltage and current THD can be seen in the waveforms. Almost 56% of THD is reduced by an increasing number of levels. This also fulfils IEEE 519 standard about harmonics Current and Voltage limits.

The comparative result analysis has showed that 49 levels of MMC is having lesser THD in the output as compared with other MMC levels such as 22, 28, 31, and 41. As the number of levels increases, it means more submodules are being inserted and the converter produces a highly sinusoidal waveform at its output side. More levels contribute to decreasing instantaneous error, the converter generates the desired waveform, which is very close to the sinusoidal waveform. The summarized results of the comparative analysis are given in Table II and Fig 1.

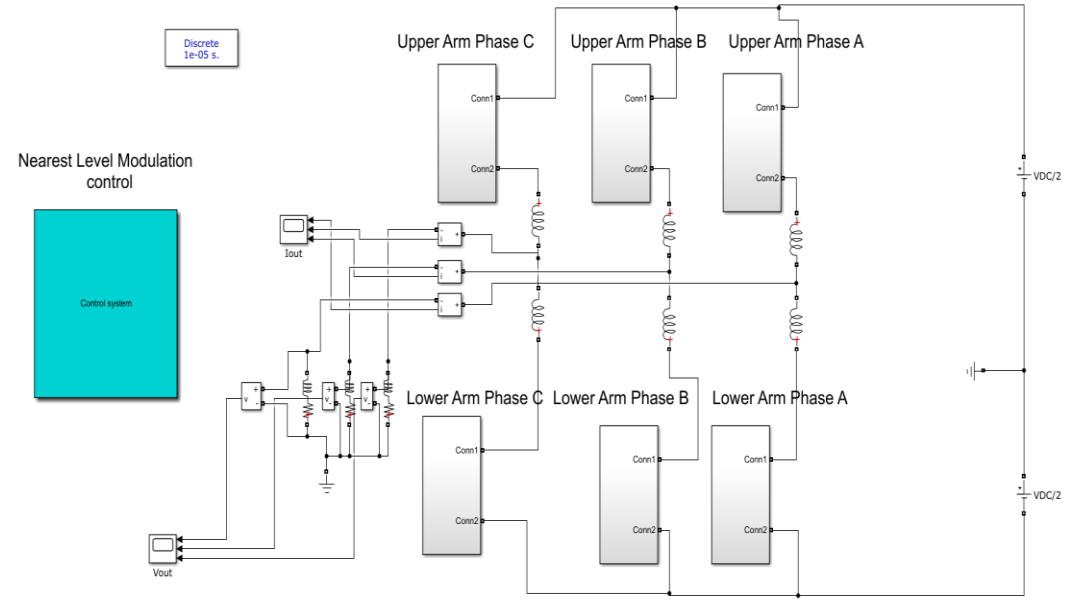


Fig. 8: Three-Phase MMC based Circuit Model

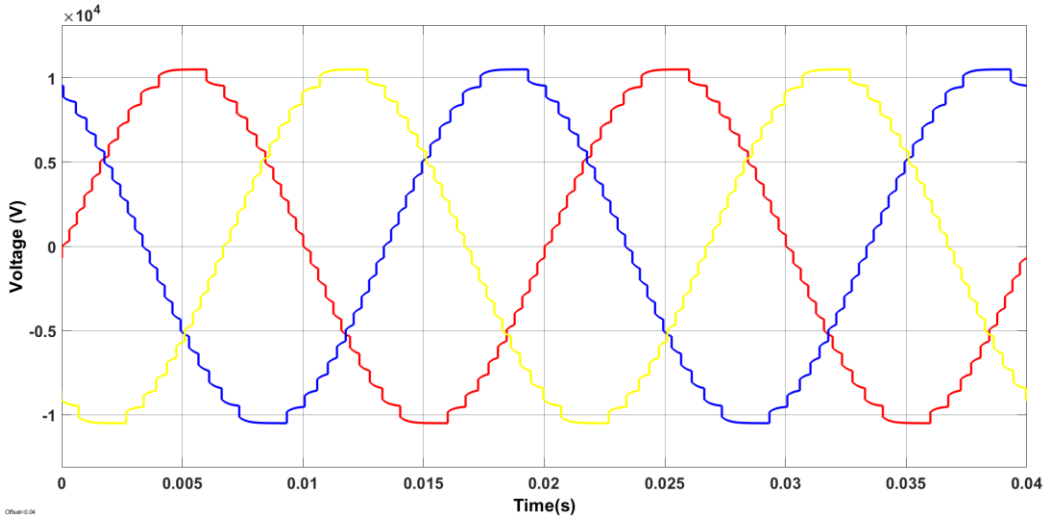


Fig. 9: Three-Phase Output Voltage for 22-Level MMC with RL load (2.58% THD)

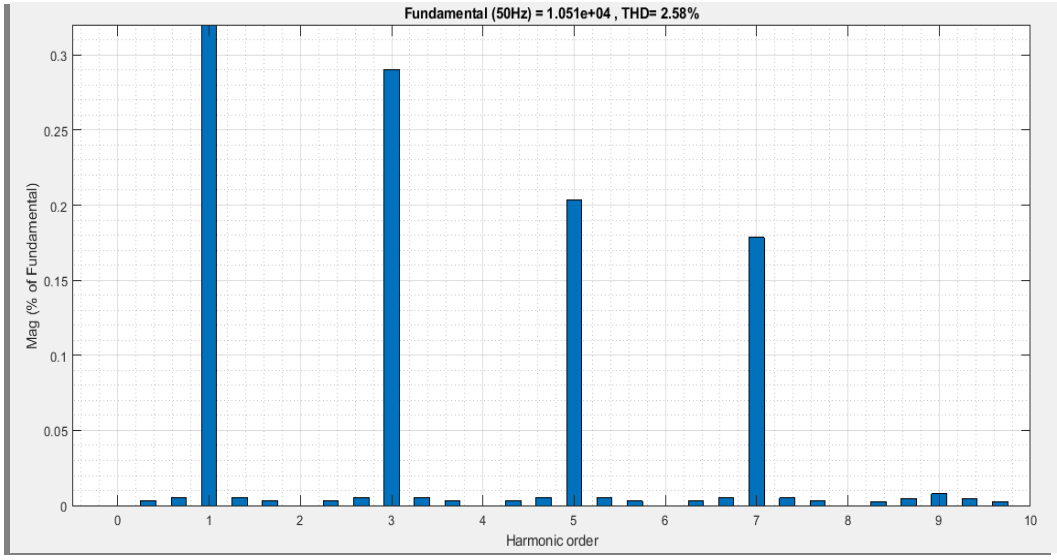


Fig. 10: Three-Phase Output Voltage THD for 22-Level MMC with RL load

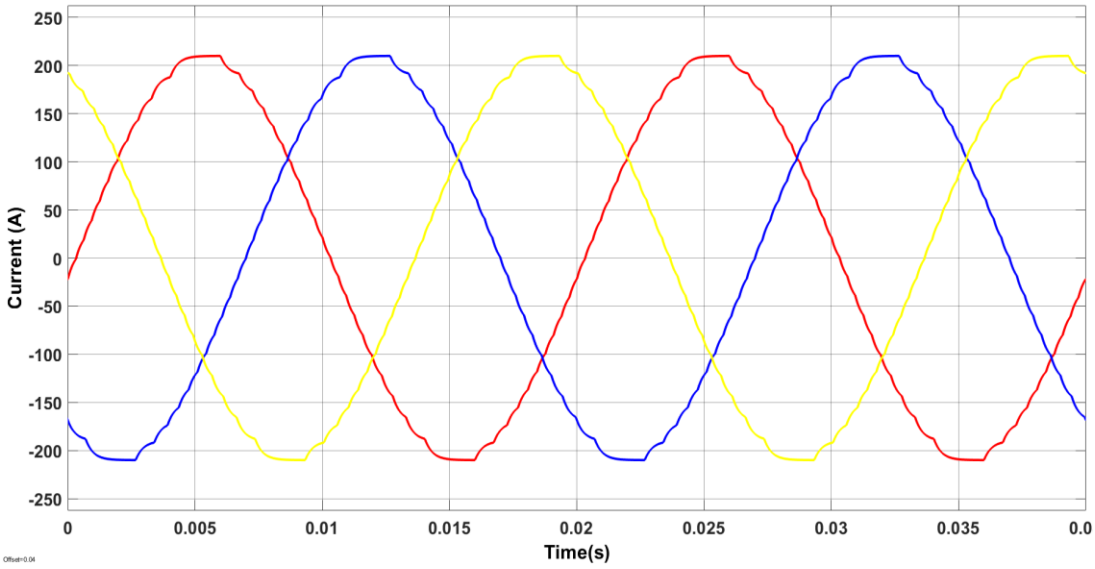


Fig. 11: Three-Phase Output Current for 22-Level MMC with RL load (0.94% THD)

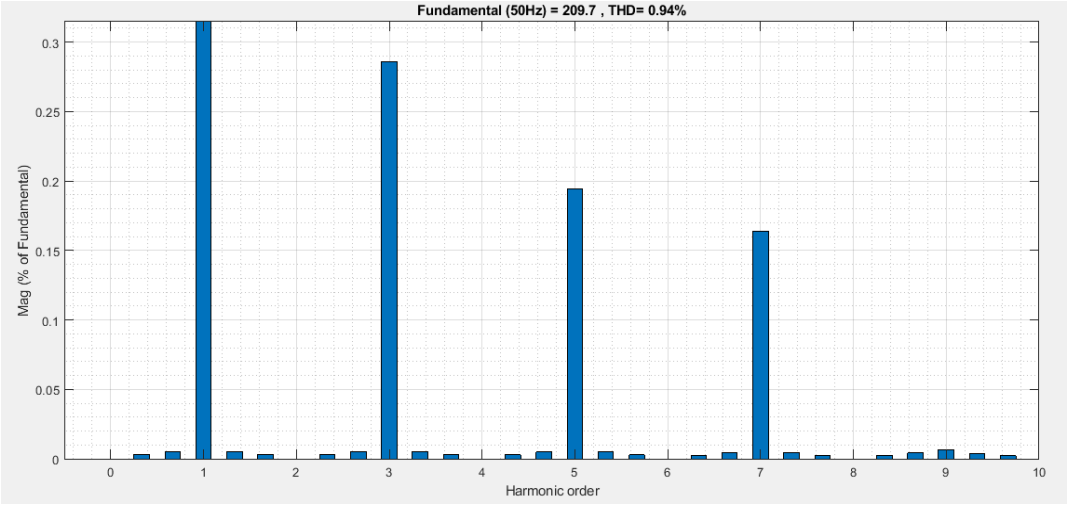


Fig. 12: Three-Phase Output Current THD for 22-Level MMC with RL load

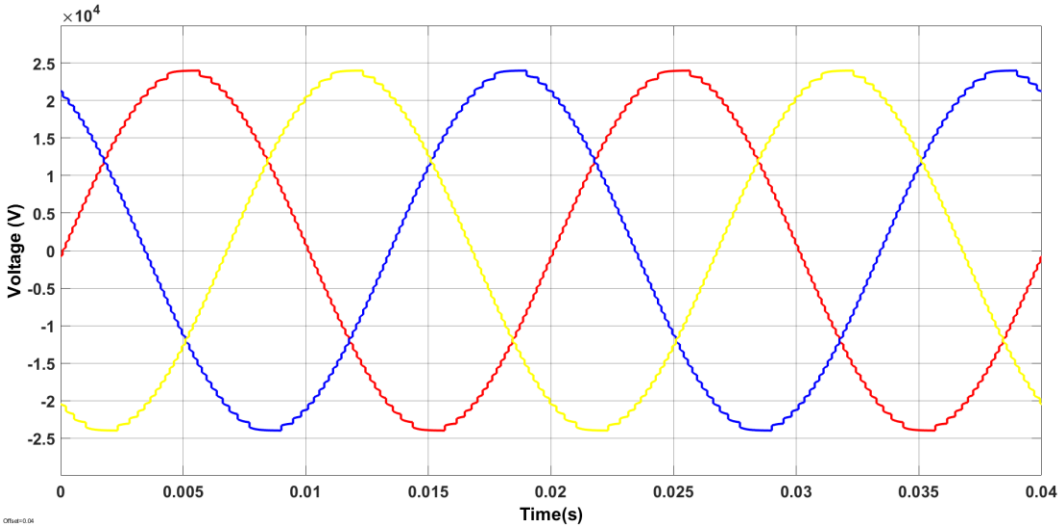


Fig. 13: Three-Phase Output Voltage for 49-Level MMC with RL load (1.13% THD)

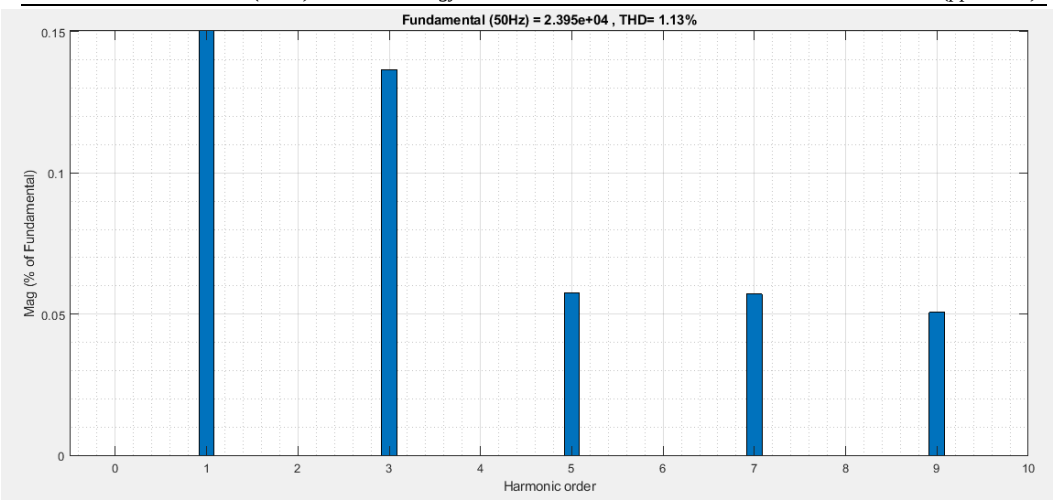


Fig. 14: Three-Phase Output Voltage THD for 49-Level MMC with RL load

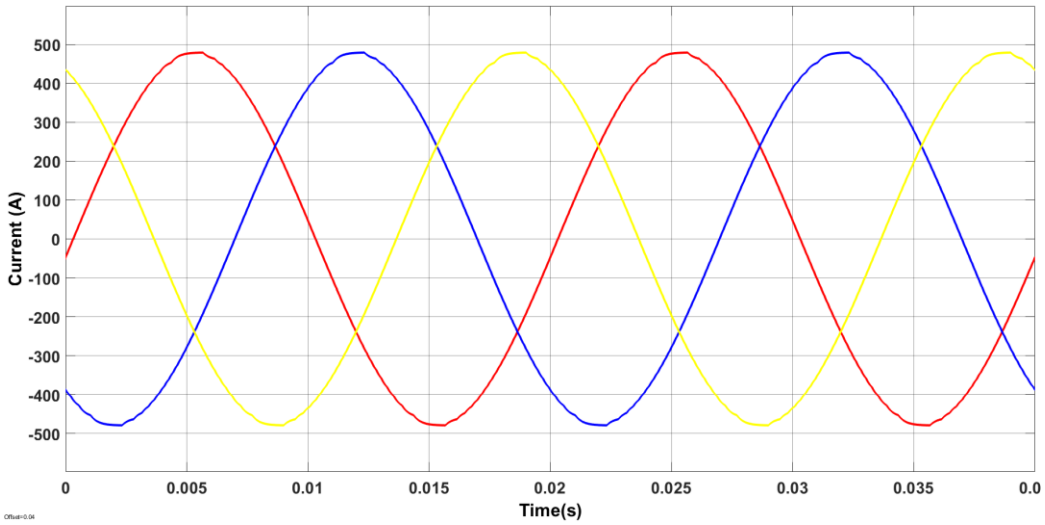


Fig. 15: Three-Phase Output Current for 49-Level MMC with RL load (0.27% THD)

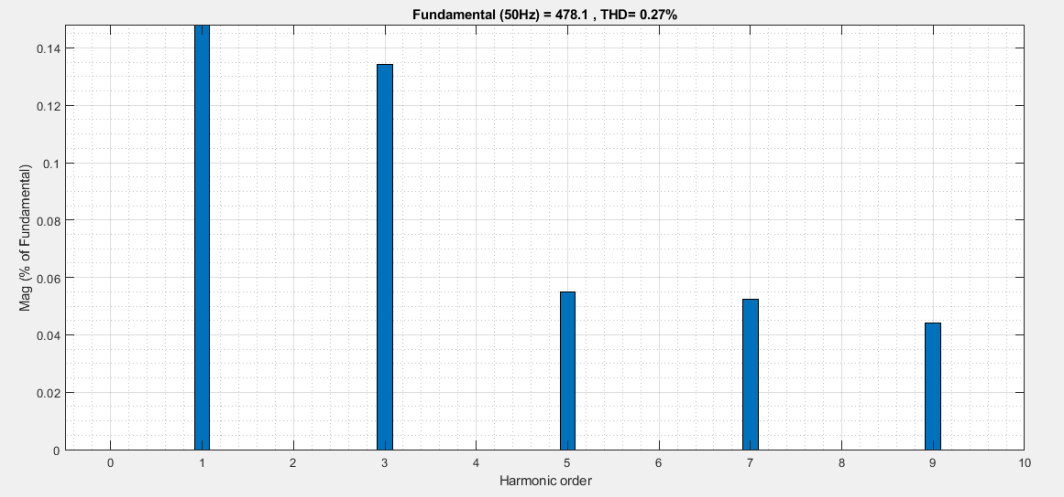
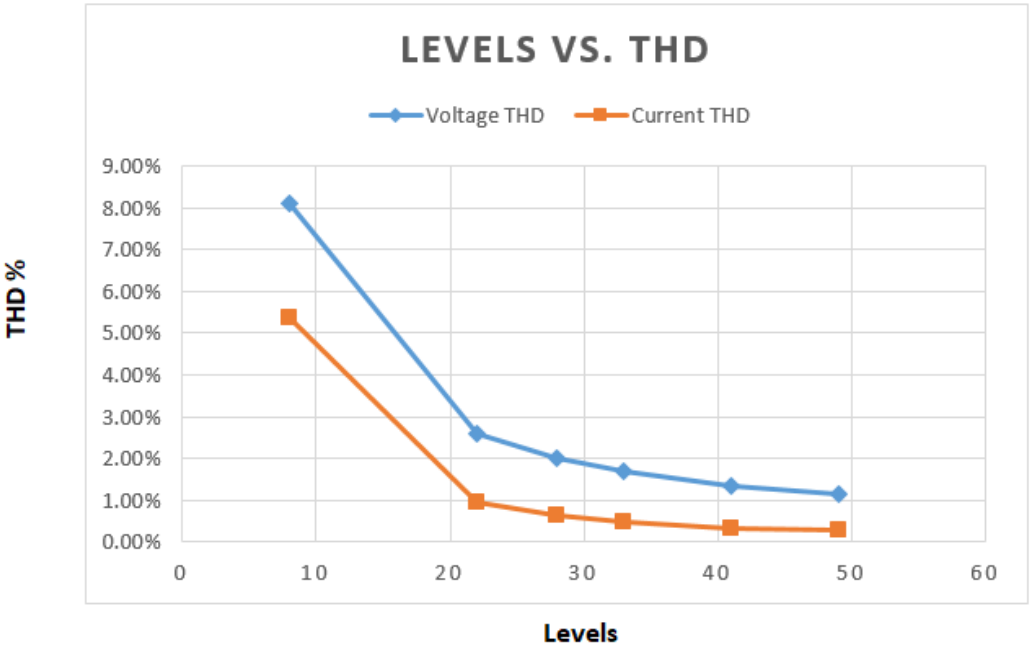


Fig. 16: Three-Phase Output Current THD for 49-Level MMC with RL load

TABLE II. Summarized results of the analysis of THD

Submodules (Upper/lower arm)	**Levels**	**Voltage THD**	**Current THD**
7	8	8.11%	5.36%
21	22	2.58%	0.94%
27	28	2%	0.64%
32	33	1.69%	0.49%
40	41	1.35%	0.34%
48	49	1.13%	0.27%



GRAPH I: Summarized results of the analysis of THD

6. Conclusion

It is concluded for obtained simulation results that Modular Multilevel Converter with H-bridge SM configuration produces less Total Harmonics Distortion (THD) when it is used with Nearest Level Modulation (NLM) control technique. It is further, analyzed that (MMC) through the NLM Modulation technique is found better in achieving very minimum THD as compared to the conventional inverters/ converters. However, in this work, the THD is reduced to 0.02% approximately with increased levels up to 49, which results in mitigation of harmonics distortion and improved voltage and current waveforms at the output side. MMC leads to various applications where the proposed MMC-based HVDC structure can be used to replace conventional power networks, particularly for HVDC systems.

AUTHOR CONTRIBUTION

All authors contributed equally to the work.

DATA AVAILABILITY STATEMENT

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

[1] Beheshti, N., Rezanejad, M., & Mehrasa, M. “Linearized control technique with Lyapunov function-based compensators for MMC-based HVDC system under load variation and fault condition”, International Journal of Electrical Power

& Energy Systems, Vol. 124, 106333. doi:10.1016/j.ijepes.2021.

[2] Mohammed Alharbi, Semih Isik "An Optimized SM Fault-Tolerant Control Method For MMC-based HVDC Applications",2019 IEEE Energy Conversion Congress and Exposition (ECCE), 28 November 2019.

[3] Hu P, Jiang D. "A level-increased nearest level modulation method for modular multilevel converters", IEEE transactions on Power Electronics. 2015 Apr; 30(4):1836-1842.

[4] M. Kumar, et.al" An Overview of Uninterruptible Power Supply System with Total Harmonic Analysis & Mitigation: An Experimental Investigation for Renewable Energy Applications ", International Journal of Computer Science and Network Security, Vol.18, issue 6, 2018.

[5] Wu D, Peng L. "Characteristics of nearest level modulation method with circulating current control for modular multilevel converter", IET Power Electronics. 2016 Feb 10;9(2):155-64.

[6] Soomro, Dur Muhammad, et al. "Optimal design of a single-phase APF based on PQ theory." International Journal of Power Electronics and Drive Systems 11.3 (2020): 1360.

[7] B.L Nayak, G. Venkataratnam " THD and Switching losses Analysis of Multi-Level Inverter Fed 3- Φ Induction Motor Drive", International Journal of Scientific and Engineering Research, Vol. 5, issue 1,pp 2067-2074"

[8] Soomro, Dur Muhammad, et al. "Mitigation of Voltage Sag Caused by Unbalanced Load by Using DFT Controlled DVR." 2019 IEEE International Conference on Innovative Research and Development (ICIRD). IEEE, 2019.

[9] Y.M Park, H.S Ryu, H.Y Lee, M.G Jung and S.H Lee "Design of Cascaded H-Bridge Multilevel Inverter based on Power Electronics building blocks and control for High Performance", Journal of Power Electronics, Vol. 10, No. 3, May 2010.

[10] S. Kouro, K. Gopakumar, J. Pou "Recent Advances and Industrial Applications of Multilevel Converters", IEEE transaction on Industrial Electronics, Vol. 57, No. 8, August 2010.

[11]Tahir, Sohaib, et al. "Robust digital deadbeat control design technique for 3 phase VSI with disturbance observer." IEICE Electronics Express (2017): 14-20170351.

[12] Tahir, Sohaib, et al. "Digital control techniques based on voltage source inverters in renewable energy applications: A review." Electronics 7.2 (2018): 18.

[13] B. Harish, U.R Kiran, B.M Lal and S.K Dash "Power Quality Improvement of DC-AC Converter by using Cascaded H-Bridge Multilevel Inverter", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 3, Issue. 2, Feb 2014.

[14] D. Subramanian, R. Rasheed "Modified Multilevel Inverter Topology for Driving a single-phase induction motor", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 2, Issue. 1, Dec 2013.

[15]Nadeem, Muhammad Haroon, et al. "Transient harmonic voltage based protection scheme for multi-terminal HVDC transmission networks." 2019 IEEE International Conference on Industrial Technology (ICIT). IEEE, 2019.

[16] Memon, Abdul Hakeem, et al. "Achieving High Input PF for CRM Buck-Buck/Boost PFC Converter." IEEE Access 6 (2018): 79082-79093.

[17]Ahmad, Muhammad, et al. "HVDC transmission an outlook and significance for Pakistani power sector." IOP Conference Series: Earth and Environmental Science. Vol. 133. No. 1. IOP Publishing, 2018.

[18] S. Ali, Z. Ling, K. Tian and Z. Huang, "Recent Advancements in Submodule Topologies and Applications of MMC," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2020.2990689.

[19] Fatemeh Shahnazian et.al., "Control of MMC-Based STATCOM as an Effective Interface between Energy Sources and the Power Grid", Electronics 2019, 8(11), 1264; https://doi.org/10.3390/electronics 8111264

[20] Memon, S.H., Kumar, M., Memon, A.H., Memon, Z.A. and Soomro, S.A., 2018. Total Harmonic Distortion (THD) Analysis of Grid Integrated Permanent Magnet Synchronous Generator (PMSG) With Full Scale Converter (FSC) Based Wind Farm''. IJCSNS, 18(12), p.232.