Enhanced Trapezoidal Modulation in MMC: Comparative Analysis with Traditional Modulation Methods

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Citation | Hussain. S, Ulah. A, Ansari. J, "Enhanced Trapezoidal Modulation in MMC: Comparative Analysis with Traditional Modulation Methods", IJIST, Vol. 07 Special Issue. pp 232-243, May 2025
Received | April 09, 2025 **Revised |** May 11, 2025 **Accepted |** May 13, 2025 **Published |** May 15, 2025.

HVDC transmission and renewable energy systems extensively use Modular Multilevel Converters (MMC) because they provide outstanding scalability and modular architectural features. The performance quality of MMCs depends predominantly on which modulation technique engineers implement. This work studies Nearest Level Modulation (NLM) and conventional Trapezoidal Modulation alongside an enhanced Trapezoidal Modulation method to identify the top choice for high-voltage power implementations. The main goal of this research is to optimize modulation techniques for improving MMC harmonic performance and switching efficiency. Each modulation strategy is simulated through MATLAB/Simulink-based testing under identical operating situations. Product testing indicates NLM shows lower switching losses as well as superior power distribution efficiency but the updated Trapezoidal Modulation design combines reduced THD performance with simple implementation methods. The method's innovative aspect depends on the modified trapezoidal waveform synthesis from a fundamental-frequency triangular signal enabling simplified implementation as well as lower THD and avoiding the need for high switching frequencies used in conventional approaches. The research delivers critical knowledge about MMC modulation selection which systems designers and manufacturers can use to optimize converter operation based on specific applications.

Keywords: Modular Multilevel Converter (MMC), Nearest Level Modulation (NLM), Trapezoidal Modulation (TRP), Total Harmonic Distortion (THD), Switching Losses

Introduction:

High-voltage power systems depend on Modular Multilevel Converters (MMCs) because these converters bring scalability together with fault-tolerant capabilities and modular constructions [1]. A modular multilevel converter contains individual submodules which assemble into phase legs and can exist in three different evaluation arrangements [2]. MMCs operate through their unique structure to support high voltage operations without causing significant stress on components thus enabling their use in high-voltage direct current (HVDC) transmissions and motors and renewable energy integration [3]. High power quality along with conversion efficiency stands as a major challenge for Modular Multilevel Converters despite their existing advantages because modulation techniques establish the overall MMC performance profile [4]. The research aims to develop improved modulation techniques which enhance power quality together with loss reduction and simplify practical high-voltage application implementation [5].

Research into MMC modulation techniques has focused heavily in recent years and NLM alongside TRP represent the leading choices [6]. Using NLM yields enhanced switching capabilities and improved efficiency yet this modulation strategy entails complex operations alongside difficulties in maintaining submodule voltage equilibrium [7]. While Trapezoidal Modulation presents advantages of straightforward implementation it leads to elevated levels of total harmonic distortion (THD) and switching losses as compared to Nearest Level Modulation (NLM) [8]. Multiple studies suggest modifications of these techniques aimed at solving their existing shortcomings [9]. Present approaches fall short because they maintain limited performance-complexity equilibrium or provide modularized solutions for particular use cases [10]. The presented study enhances Trapezoidal Modulation by resolving traditional TRP limitations to provide a workable alternative for practical Multi-Master-control applications [11].

The paper evaluates the performance of different power converter topologies starting with Traditional Trapezoidal Modulation followed by Nearest Level Modulation (NLM) and it concludes with the Proposed Trapezoidal Modulation. The research identifies a method for minimizing THD while keeping system complexity at reasonable levels. The proposed modified trapezoidal waveform generation topology stands out because it decreases THD levels better than NLM and traditional TRP through its fundamental frequency triangular base signals and efficient design keeping implementation complexity low. Because traditional modulation methods face limitations from efficiency in TRP while also requiring complexity for NLM implementations there is a need for balanced modulation solutions [12]. An improved Trapezoidal Modulation technique has been developed to deliver better power quality together and straightforward implementation capabilities [13]. The proposed approach works to enhance MMC performance at high voltages by implementing solutions to deal with voltage unbalance and harmonic distortion problems [14]. The study compares improved Trapezoidal Modulation against traditional NLM to offer researchers both practical strategies for MMC system modulation selection [15].

Methodology:

MMC Overview:

The Modular Multilevel Converter (MMC) is a class of power converter appreciated for its high voltage scaling, modularity and efficiency [1], [2]. The MMC is built with several submodules (SMs), and they often take half-bridge or full-bridge configurations [3]. The half-bridge submodule of a Modular Multilevel Converter comprises two insulated-gate bipolar transistors along with one capacitor to produce either zero output or output at +Vdc/2. The full-bridge Modular Multilevel Converter submodule employs four IGBTs with a capacitor to generate output levels of -Vdc/2 and +Vdc/2 besides the zero state. For our study we selected the half-bridge topology as its uses half the number of switches compared to full-bridge. Every

SM consists of capacitors for energy storage with switch power devices [4]. Since the converter has three phase legs, each leg is further divided into two parts, an upper arm and a lower arm. These arms function simultaneously generating staircase output voltage similar to the sinusoidal waveform voltage. This modular approach allows MMCs to deal with very high voltage since the voltage load is spread out with sub modules hence minimizing the stress that the several components undergo [5], [6].

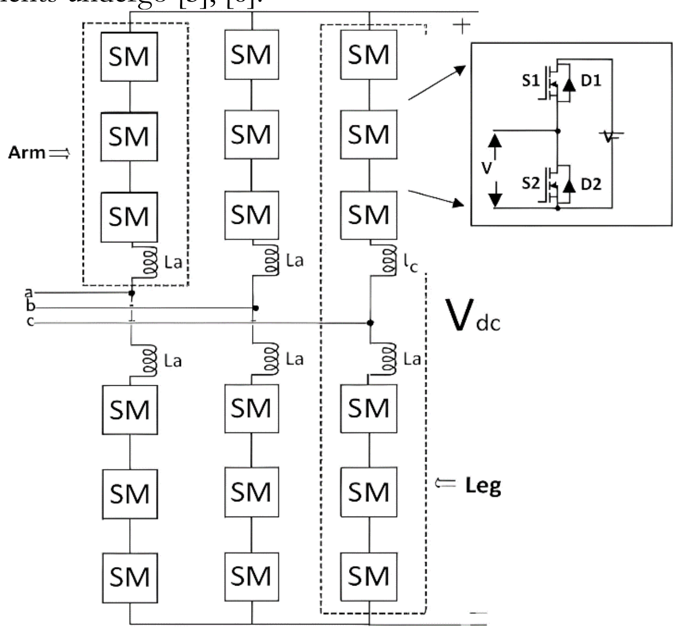


Figure 1. Three Phase MMC Architecture [16]

NLM Principle:

NLM functions by quantizing the reference waveform into respective voltage levels corresponding to the number of submodules in the MMC [17]. Each of the submodules provides a voltage increment and the modulation can enable or disable to approximate to the reference waveform [18]. This stepwise output further approximates the sine wave as number of levels rises and hence results in better waveform and lower percentage of harmonic distortion [19]. Equation 1 is used for Generating NLM signal of 100 Hz for Gate signal [20], [21].

$$V_{ref} = Vm \sin(wt)$$
$$V_i = i * \frac{V_{dc}}{n-1}$$
$$V_{nearest}(t) = argmin|V_{ref} - V_i|$$
$$V_{out} = V_{nearest}(t)$$

The sampling of reference waveforms in NLM occurs at a high rate for selecting the nearest voltage level from the n available discrete levels. Quantization, that is V_i, allows the conversion of the DC voltage into i_{th} voltage level. Then the rounding algorithm is applied to select the nearest valued at a certain discrete level and output voltage is taken. In NLM, capacitor voltages in the submodules have to be continuously monitored in real-time fashion to address the issue of voltage balance. The system performs a selection of which submodules must be active based on a fixed search table or an algorithm [22]. While the principal of NLM already implies presence of certain harmonic content, the distortion is significant and decreases as the levels grow, which makes its use for the management of MMC reasonable [17].

Trapezoidal Modulation Principle:

Commonly another technique used in MMCs is Trapezoidal Modulation because of its simple structure and foreseeable operation result [15]. The main characteristics of this method are based on the use of a reference signal with sinewave envelope and a straight trapezoidal segment. To find precise times when the submodule needs to switch, the MMC's output voltage levels are compared to the reference signal [23]. Equation 2 used for generating switching signal using trapezoidal modulation

$$Vref\ \ (t) = A \cdot Trap(t)$$

$$S(t)\ = \begin{cases} 1, & Vref(t) \geq Vtri(t) \\ 0, & Vref(t) < Vtri(t) \end{cases}$$

Further regulating the submodules in such a way, the Trapezoidal Modulation provides a staircase-like voltage waveform, which partially or fully matches the trapezoidal reference signal [17]. Compared to the square-wave modulation, the smoother transition in the trapezoidal waveform enhances harmonic performance as well as keeping the system simple [23].

Trapezoidal Modulation though occupies lesser bandwidth than bank modulation may have more harmonic distortion compared to techniques such as Nearest Level Modulation (NLM) [15]. High frequency switching is usually necessary for good quality of power and this results into high switching losses.

Nevertheless, Trapezoidal Modulation is still advantageous for applications of MMCs when low cost, simple control scheme, and fairly acceptable power quality are necessary. These include cases within medium voltage drive and industrial application where low THD and fine waveform regulation is not important.

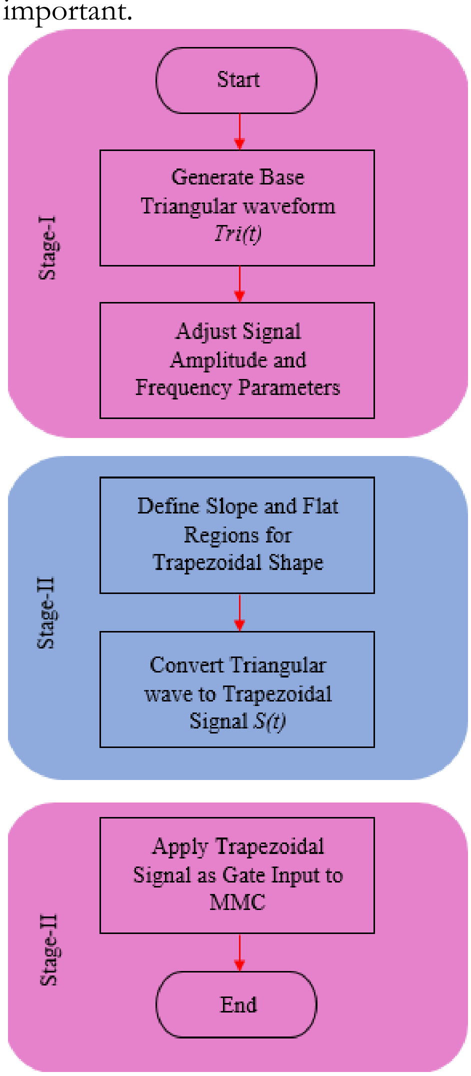


Figure 2. Proposed Trapezoidal Modulation Flowchart

Proposed Trapezoidal Principle:

The proposed trapezoidal modulation technique works at the second harmonic of fundamental frequency instead of using conventional high-frequency carrier signals. The system works without PWM comparisons because it directly applies a modified trapezoidal waveform to the gate signal. The flat-topped trapezoidal signal emerges through triangular waveform saturation which provides exact control over the duration of current conduction. Equation 3 Proposes Technique to Generate the Gate Signal

$$Trapezoid(t) = \begin{cases} 1, & if \;\; A \cdot Triangle(t) > 1 \\ -1, & if \;\; A \cdot Triangle(t) < -1 \\ & A \cdot Triangle(t) \end{cases}$$

The design produces an easier modulation structure which delivers enhanced harmonic performance. The modulation technique reduces Total Harmonic Distortion (THD) because it shapes waveforms to fit the desired output that remains synchronized with the band of fundamental frequencies. The method presents a simple new solution which matches well with high-power MMC applications while maintaining computational efficiency.

Results:

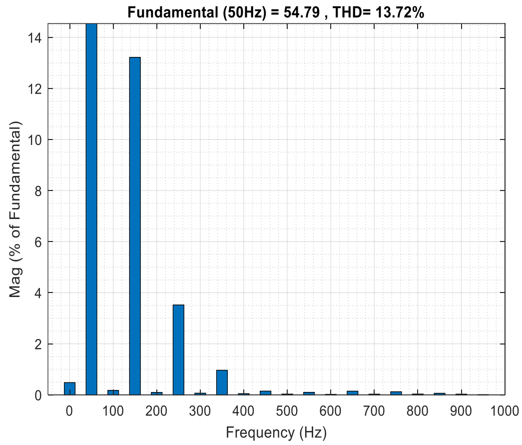
Harmonic Distortion:

THD comparisons of Nearest Level Modulation (NLM) and Trapezoidal Modulation for full scale MMC confirms that the MMC is more efficient at higher level of NLM with Trapezoidal Modulation. The proposed trapezoidal modulation technique provides a THD value of 9.11% during 21-level operation thus delivering better results than Trapezoidal Modulation's 10.91% and NLM's 13.72% because of its lower THD value. The number of levels used in the system directly affects the level of waveform distortion in the process. The THD measurement shows NLM produces 13.28% with 31 levels before Trapezoidal Modulation reduces it to 10.51% and the Proposed Trapezoidal Modulation makes it reach 5.76%. The THD value for NLM at 41 levels reaches 12.93% whereas Trapezoidal Modulation controls it to 8.82% and the Proposed Trapezoidal Modulation reaches a minimum THD of 5.53%.

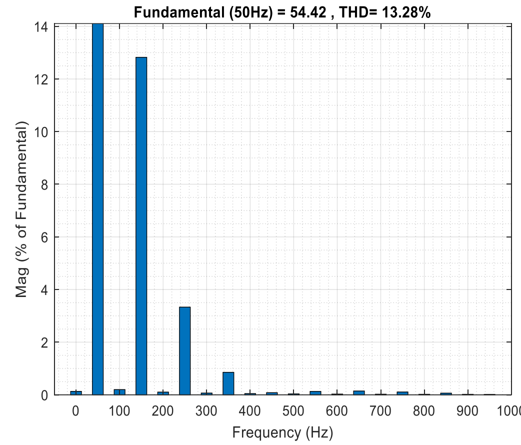
This indicates that THD is on an average reduced more by the proposed Trapezoidal Modulation than by NLM and previously used TRP in each of the tested levels as the following result table affirms. This can be attributed to its provision of crisper waveforms in the least harmonic components possible. However, as using discrete voltage levels, the examined loop currents of NLM contain higher harmonics, especially at lower modulation levels. Trapezoidal Modulation has lower THD as compared with the Nearest Level Modulation, thereby guaranteeing better power quality and a lesser load put on the equipment. Consequently, the findings point to the applicability of Trapezoidal Modulations in enhancing the predicament of harmonic performance of MMC systems.

Table 1. THD of NLM and Trapezoidal Modulations at different SM levels

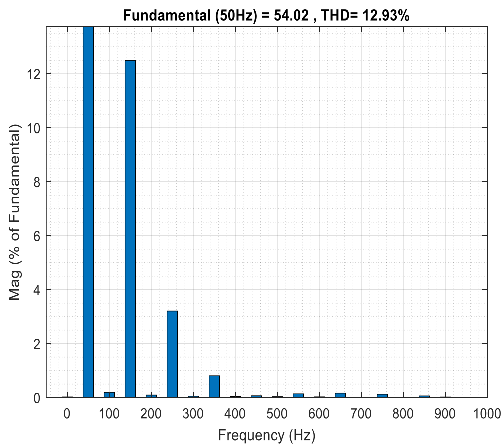
THD of Applied Modulation Techniques at different Submodule Levels			
Levels	**NLM**	**Trapezoidal Modulation**	**Proposed Trapezoidal Modulation**
21	(a) 13.72%	(d) 10.91%	(g) 9.11%
31	(b) 13.28%	(e) 10.51%	(h) 5.76%
41	(c) 12.93%	(f) 8.82%	(i) 5.53%


Fundamental (50Hz) = 54.79 , THD= 13.72%
Mag (% of Fundamental)
Frequency (Hz)

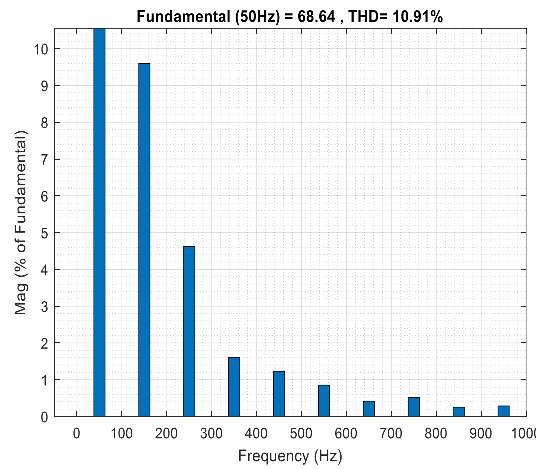
(a)


Fundamental (50Hz) = 54.42 , THD= 13.28%
Mag (% of Fundamental)
Frequency (Hz)

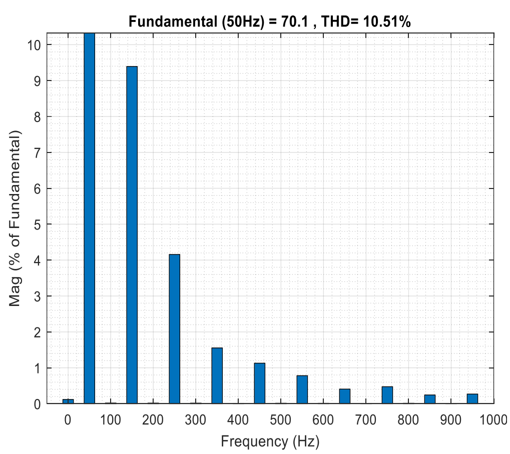
(b)


Fundamental (50Hz) = 54.02 , THD= 12.93%
Mag (% of Fundamental)
Frequency (Hz)

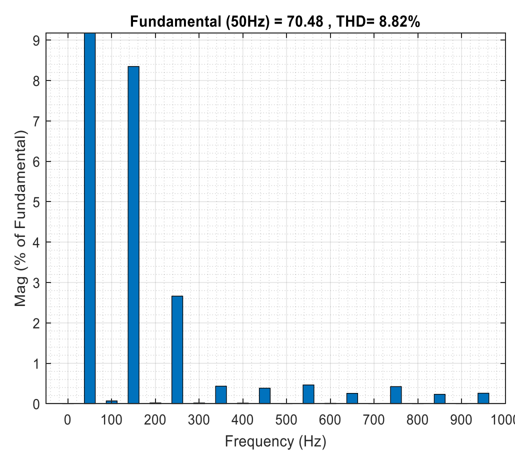
(c)


Fundamental (50Hz) = 68.64 , THD= 10.91%
Mag (% of Fundamental)
Frequency (Hz)

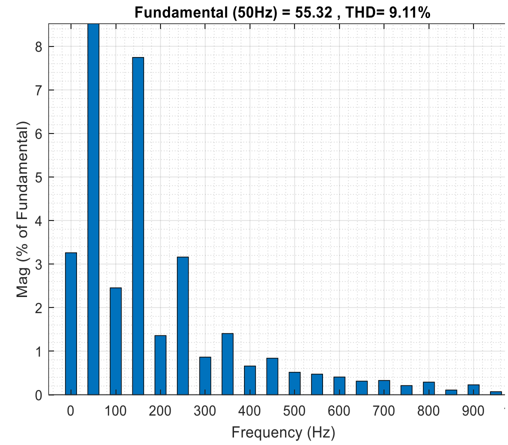
(d)


Fundamental (50Hz) = 70.1 , THD= 10.51%
Mag (% of Fundamental)
Frequency (Hz)

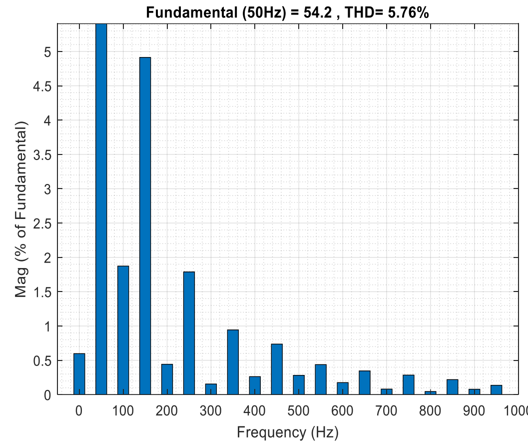
(e)


Fundamental (50Hz) = 70.48 , THD= 8.82%
Mag (% of Fundamental)
Frequency (Hz)

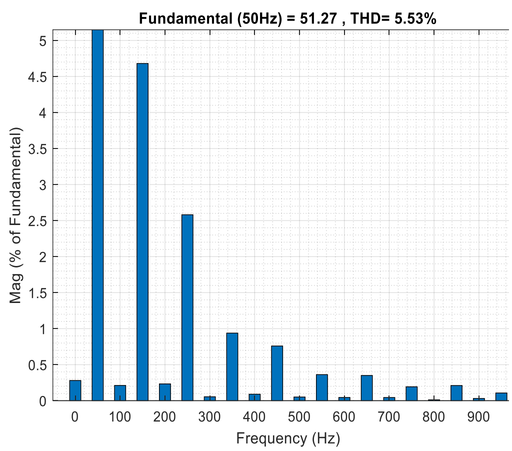
(f)



(g)



(h)



(i)

Figure 3. THD Results of Applied Modulation Schemes at Various levels

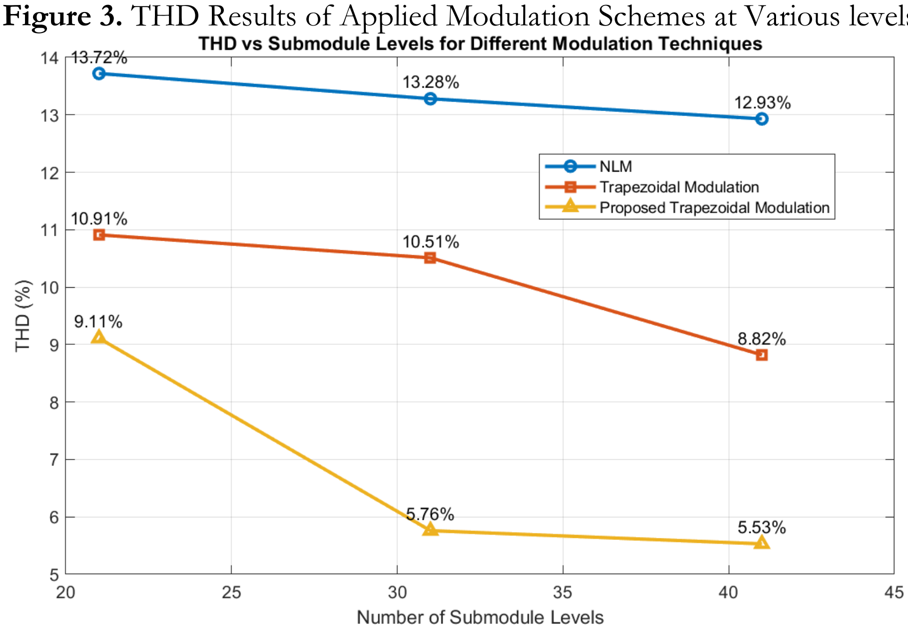
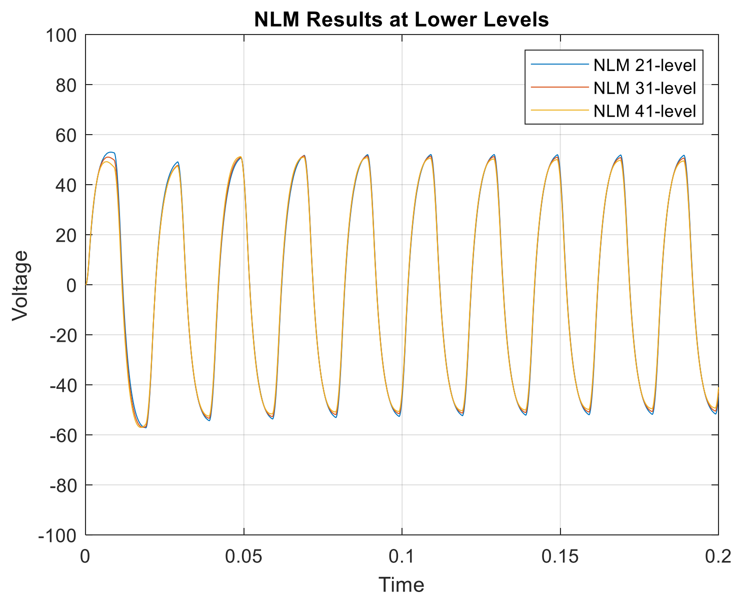


Figure 4. THD Trend Analysis of Used Modulation Techniques

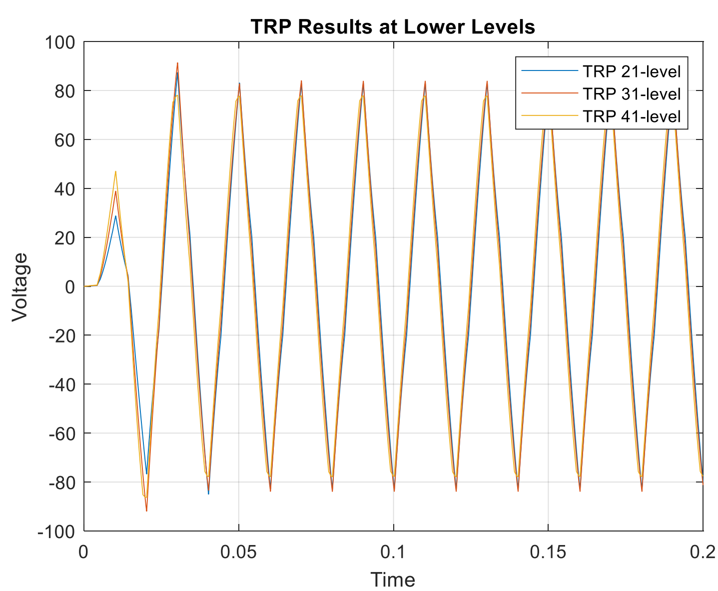
Switching Losses and Overall Efficiency:

The 50 Hz MMC inverter received 100V input while testing NLM and TRP Modulation throughout different channel levels from 21 to 31 and finally 41 for both upper and lower arms. The switching losses within NLM become substantial because the output voltage steps are distinct while operating at lower levels. The system efficiency decreased to 50% at 21 levels because of the excessive number of frequent switches. The efficiency of NLM modulation decreased even with higher level steps (31–41) because its discrete output pattern decreased the overall operational efficiency versus other modulation techniques for demanding applications.

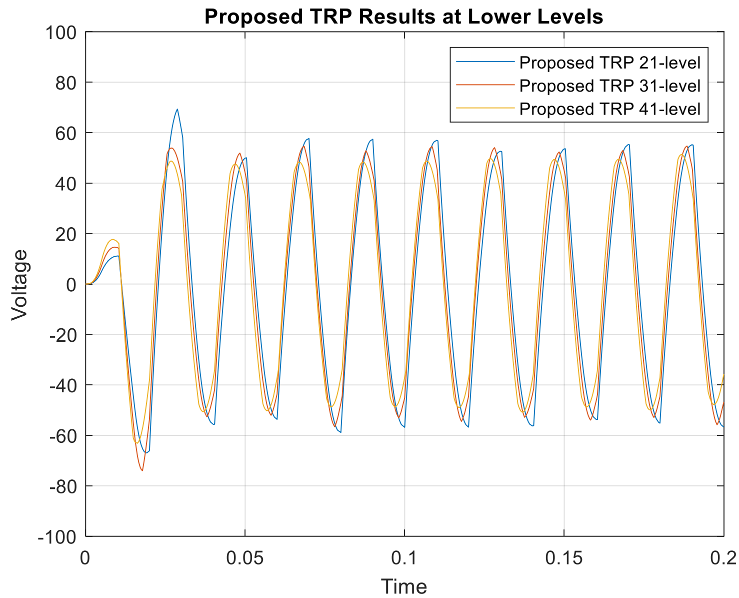
TRP modulation creates smooth voltage transitions that reduces the number of power switching events and lowers energy waste thus decreasing losses. The efficiency scores of TRP equal or surpass NLM while reaching the minimum THD requirement at 21 modulation levels. The efficiency of TRP improved continuously as the number of control levels increased. The reduced THD performance of TRP methods decreases stress placed on both filtering systems along with passive components. TRP shows better performance than NLM throughout all input levels even though both methods encounter operational difficulties when used at low input signals. TRP modulation proves suitable for MMC operations at 50 Hz frequencies because it creates a strong combination of quality-shaped waveforms alongside enhanced switching performance.



(a)



(b)



(c)

Figure 5. Voltage Measurements at the Load Side: (a) Voltage Results for Nearest Level Modulation at 21, 31 and 41 levels (b) Voltage Results for Trapezoidal Modulation at 21, 31 and 41 levels (c) Voltage Results for Proposed Trapezoidal Modulation at 21, 31 and 41 levels

Modulation Complexity:

The complexity level for modulation strategies in Modular Multilevel Converters (MMC) depends heavily on the modulation technique selection. The selection process for nearest output voltage using Nearest Level Modulation (NLM) demands sorting logic but becomes more complex when the number of submodules increases. Traditional Trapezoidal Modulation expands PWM techniques through a concept that compares a high-frequency triangular wave with fixed-shape trapezoidal waveforms to produce gate signals. The method requires high-frequency switching logic even though it does not perform sorting operations. The Proposed Trapezoidal Modulation uses fundamental frequency operation which applies predefined trapezoidal waveforms for generating gate signals. Because it eliminates frequency comparisons and decision algorithms at high frequencies it remains the simplest control method best suitable for digital control environments.

Discussion:

This research has conducted a comparison of three modulation methods for application on Modular Multilevel Converters (MMCs): Nearest Level Modulation (NLM), Traditional Trapezoidal Modulation (TRP) and the Proposed Trapezoidal Modulation. Key findings show that the proposed technique performs remarkably better than the other two in terms of Total Harmonic Distortion (THD), which minimum values are 5.53% at 41 levels, and far better than what 12.93% and 8.82% for NLM and Traditional Trapezoidal method. Further, the method proposed achieves this performance with the least control and switching complexity.

The major benefit of the proposed modulation is the working at fundamental frequency, which excludes the necessity of high frequency triangular carriers for primary PWM-type TRP. The simplification reduces the control burden, and the harmonic performance is better. By contrast, the effectiveness of NLM in reducing switching losses is offset by the increased THD and cumbersome sorting and balancing mechanism of voltages. Conventional (traditional) TRP lies between the two as far as complexity and performance are concerned yet it still lacks harmonic quality of the proposed method. Future work can look at combinations of hybrid schemes that can benefit from the harmonic properties of the proposed TRP and the adaptive switching abilities to optimize the control of high-power applications of MMC systems in real time.

Conclusion:

Trapezoidal Modulation (TRP) and Nearest Level Modulation (NLM) are being popularly employed in Modular Multilevel Converters (MMC) for increased efficiency and lower switching losses. Conventional TRP is economical but produces large harmonic distortion with the need for extra filtering. NLM has low switching losses but calls for sophisticated voltage balancing techniques for firm operation. The suggested Trapezoidal Modulation addresses MMC performance by supporting operation at the fundamental frequency range compared to conventional TRP operating at higher frequencies. This method minimizes harmonic distortion with lower switching losses in comparison to NLM, and it is thus an effective solution in terms of efficiency for high-power applications. By analyzing the equation of each modulation technique, we can mathematically understand the complexity of them.

Limitations and Recommendations:

Modulation techniques for Modular Multilevel Converters (MMC) must find an equilibrium between harmonic performance and switching loss levels. The switching losses of Nearest Level Modulation (NLM) decrease but the poor waveform resolution causes increased harmonic distortion. The Traditional Trapezoidal Modulation produces better harmonic performance than NLM although it requires elevated switching frequency that produces wider losses. The Proposed Improved Trapezoidal Modulation stands as the simplest among three modulation methods while it conducts operations at fundamental frequency to achieve superb THD performance. The improved method produces waveforms with enhanced quality through diminished harmonic content. This improved method introduces additional switching transitions but manages to sustain losses which decrease better than NLM. This method creates the most advantageous combination between processing simplicity and successful harmonic suppression. This proposed modulation approach works best among other alternatives for power electronic systems that need maximum efficiency with minimal harmonic distortion.

The study needs to research how mixing together elements from NLM and TRP can improve system functionality. The HIL testing approach serves as an essential requirement to validate practical operational effectiveness of the proposed approach. With HIL engineers can conduct real-time examinations to measure control delays along with system efficiency which provides vital information for adapting the implementation. The Proposed Improved Trapezoidal Modulation presents solid prospects for industrial applications because it delivers efficient performance along with low-THD and convenient implementation methods.

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