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Enhanced Hybrid MMC Integration into DC Microgrid for low voltage application

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ABSTRACT

The Modular Multilevel Converter (MMC) is a promising converter utilised in HVDC (High Voltage Direct Current) systems. MMC has numerous advantages over other converters, such as modular structure, output voltage and current scalability, superior power quality, and no required filter. Despite these benefits, it is less appealing for small-scale systems like Microgrid because of the many submodules (SMs). This work explores the integration of hybrid MMC into a DC Microgrid comprising various renewable and storage devices. Hybrid MMC consisting of half and full bridge SMs is driven using the proposed modified Nearest level modulation (MNLM) scheme, which enhances output levels to 3Nhalf+3Nfull+1 (Nhalf / Nfull is number of half / full bridge SMs) compared to conventional NLM, which generates N+1 levels. Thus, with MNLM applied to hybrid MMC, we get improved power quality, lower system cost, and require fewer SMs. Initially, the system is modelled and tested in MATLAB Simulink to acquire the offline simulation results. Subsequently, the real-time simulation is performed with the help of a hardware-in-loop simulation setup, which comprises an FPGA-based NI PXIe and Compact RIO for experimental verification of the proposed scheme.

1. Introduction

The world is moving toward sustainable energy solutions because of growing concerns about global warming caused by CO^2 gas emissions. Green energy sources, i.e., solar and wind, are widely used because of their long-term availability and environmental advantages [1]. DC microgrids are one of the most effective ways to integrate renewable energy sources locally in contemporary energy architectures. DC microgrids use direct current to provide advantages like lower conversion losses, more straightforward control schemes, and improved compatibility with contemporary DC loads like battery systems and electric cars [2-3].

DC microgrids offer a more direct and energy-efficient route than traditional AC microgrids, which have synchronisation problems and conversion inefficiencies when connecting to renewable sources. They are particularly well-suited for low-voltage residential and community-level applications where ease of integration, scalability, and modularity are essential [4-6].

Nevertheless, maintaining high power quality and system efficiency while integrating variable renewable energy sources is one of the key challenges in DC microgrids [7]. This calls for the use of sophisticated power electronic converters. Despite their widespread use, traditional converters like two-level or three-level inverters frequently have problems like poor harmonic performance, high switching losses, and limited scalability [8-9].

In this regard, Modular Multilevel Converters (MMCs) seem a viable alternative due to their excellent output waveform quality, minimal on/off losses, excellent scalability, and modular design [10-11]. Although MMCSs are mainly utilised in high-voltage applications like offshore wind integration and HVDC transmission, their appealing characteristics make them suitable for low-voltage applications like DC microgrids [12].

When employing the Nearest Level Modulation (NLM) technique with MMC, which produces N+1 AC output levels (N = number of submodules), the requirement for a large number of submodules to maintain power quality is a significant obstacle to the use of conventional MMC at the distribution level. This will increase circuit complexity, cost, and inefficiency [13].

To further enhance the MMC's performance at lower voltages, this study proposes a Modified Nearest-Level Modulation (MNLM) technique that is applied to a hybrid MMC (half and full bridge submodule-based MMC). MNLM minimises total harmonic distortion, improves power quality, and reduces the number of submodules needed without increasing cost or complexity. Because of MNLM, it works well in low-voltage applications.

This study explores the integration of the suggested Hybrid MMC using MNLM into a DC Microgrid for low-voltage renewable energy applications. The objective is to exhibit enhanced output voltage and current quality, decreased switching losses, and better utilisation of renewable energy sources. The findings will pave the way for more economical, scalable, and efficient power electronic solutions for contemporary DC microgrids.

2. Literature Survey

Modified NLM control has already been the topic of various research scholars for power quality improvement. For instance, in article [14], the author has presented a modified control scheme to raise the AC output levels to 2N+1 for power quality improvement using half-bridge SMs, where N is the number of SMs for low and high voltage applications. In [15], the modified NLM is proposed, which raises the levels to 4N+1 AC output levels. Power quality is much improved for HVDC applications, but a half-bridge cannot provide DC fault blocking capability. The author [16] proposed a modified control scheme using full-bridge SMs to enhance the quality of AC output current and voltage with 4N+1 levels for HVDC application. In article [17], the scholar has proposed a Novel enhanced MMC using a combination of half and full bridge SMs to generate 2Nhalf*Nfull+1 AC output levels, where Nhalf and Nfull are the number of half and full bridges, respectively, to improve power quality.

In [18], the author presented a novel NLM method only to generate 2N+1 AC output levels. Similarly, many other scholars in [19-22] have proposed various techniques to improve power quality by enhancing AC waveform levels, as shown in Table 1. In this work, the Modified control is presented, using half and whole bridge combination of SMs to achieve 3Nhalf+3Nfull+1 AC output levels, which provide better power quality, uses hybrid SMs to get the benefit of half and whole bridge combination and produces more output levels in comparison to previously discussed methods.

Table 1

Comparison with previous research

Ref No:	Control Scheme	Output Levels	Half bridge SM	Full bridge SM
[17]	MNLM	2N+1	Yes	No
[18]	MNLM	4N+1	Yes	No
[19]	MNLM	4N+1	No	Yes
[20]	EMMC	2HF+1	Yes	Yes
[21]	MNLM	2N+1	Yes	No
[22-25]	MNLM	2N+1	Yes	No

3. System Design and Modelling

Initially, the DC Microgrid was developed in MATLAB Simulink by integrating various energy sources, battery bank storage, and loads. The design begins with a Solar Photovoltaic (PV) system, configured using Maximum Power Point Tracking (MPPT) to get optimised energy from the solar system. The PV array consists of five modules in series and five in parallel, resulting in a power of 7.6 KW. Module parameters are carefully selected to achieve the desired rating and MMPT to ensure maximum efficiency under varying conditions. A DC-DC Boost converter was added at the PV system's output to generate a 300V DC voltage for the Microgrid. Next, a battery bank with a voltage rating of 100 volts and a charging capacity of 400 Ah was added to the system to enhance the energy storage of the Microgrid and provide a reliable backup.

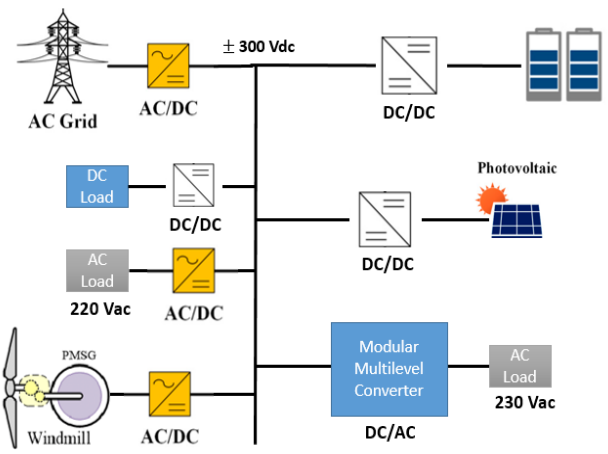

Fig. 1. DC Microgrid setup in MATLAB Simulink

A grid is also simulated using a three-phase source with a voltage of 380 V AC and a frequency of 50 Hz, allowing bidirectional power sharing between the Microgrid and the grid. Then, a wind turbine is added to the system with a power rating of 20 KW and a voltage of 380 volts. Then, using a DC-DC chopper, a DC load is directly attached to the Microgrid, and an AC load is connected with a DC-AC converter. Finally, the Modular Multilevel converter is modelled with a combination of half and full bridge topology and added into the model for analysis, as shown below in Figure 1. The overall system parameters are listed in Table 2 as shown below. The DC bus voltages at different nodes are shown in Figure 2.

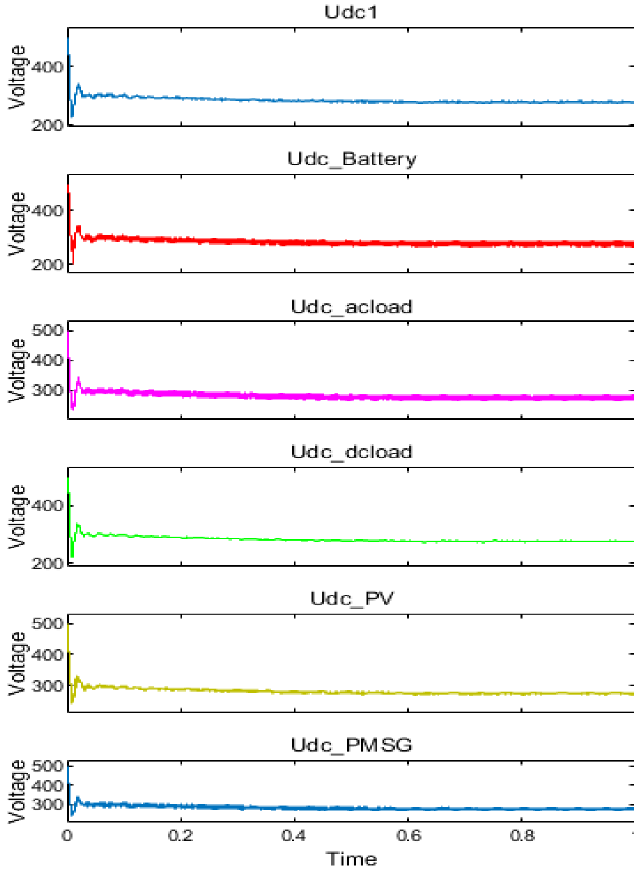

Fig. 2. DC Bus Voltage at different Nodes

Table 2

System parameters and values

S. No:	System Parameter Name	Value
1	DC Microgrid Voltage	300 volts
2	PV System Watts	7.6 kw
3	Battery Backup in Ah	400 Ah
4	Wind turbine kW	20 kw
5	AC Grid Voltage	380 volts
6	MMC SMs Voltage	60 volts
7	Arm Inductance	5 mh
8	MMC Output Voltage	230 volts

4. Hybrid MMC

The integration of full bridge (FB) and half bridge (HB) submodules (SMs) in MMC is a complex design intended to take advantage of both the SMs topology in the renewable energy applications, as shown below in Figure 3. Each phase leg of the MMC comprises a series connection of an equal number of half- and full-bridge SMs. Kirchhoff's Current and Voltage laws should be applied to both arms of a phase to analyse the hybrid MMC and derive its output current and voltage equations.

$$V_{k\_up} = -\sum_1^N V_{SM\_H} \pm \sum_1^N V_{SM\_F} + \frac{1}{2}V_{dc} - L_{arm}\frac{di\_up}{dt} \quad (1)$$

$$V_{l\_low} = \sum_1^M V_{SM\_H} \pm \sum_1^M V_{SM\_F} + \frac{1}{2}V_{dc} - L_{arm}\frac{di\_low}{dt} \quad (2)$$

The output voltages from equations (1) and (2) at any instant of operation of the MMC would be equal. The V_{k_up} is the upper arm, and V_{l_low} is the lower arm output voltages. The voltage of a full-bridge SM can either be positive, negative or zero, depending upon the switching pattern of the switches in the SM. However, the half-bridge SM will provide positive and zero voltages. The equation of the output current would be the difference in currents of the upper and lower arms, which can be written as shown in (3).

$$i_{out} = i_{up} - i_{low} \quad (3)$$

$$V_{out} = \frac{1}{2}[V_{dc} + (\sum_1^M V_{SM_H} \pm \sum_1^M V_{SM_F} - \sum_1^N V_{SM_H} \pm \sum_1^N V_{SM_F})] - L_{arm}\frac{di\_up}{dt} \quad (4)$$

Thus, using equations (1) and (2), the final equation could be written as in equation (4).

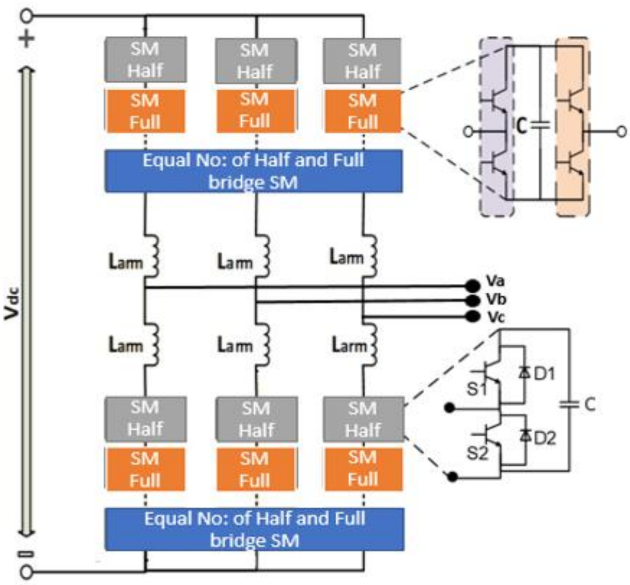

Fig. 3. Three-phase hybrid SMs based MMC system

5. Working principle of conventional NLM

Nearest-level modulation (NLM) was a new scheme proposed for the first time in 2010. It sets the trigger voltage closer to the modulation waveform's integer value. Compared with PWM techniques, the NLM technique is easier to use, uses a lower switching frequency, and requires less computing effort. With many SMs, the NLM approach performs better than PWM techniques [23].

However, when there are few SMs, the NLM approach produces comparatively large harmonics on the AC side to demonstrate the step-wise waveform of the modulation and related trigger. If there are 4 SMs in each arm, the output voltage has 5 levels. The reference waveforms for MMC with any no of SMs can be found using equations (5) and (6) as shown below.

$$N_{Upper} = Round_{0.5}\frac{V_{dc}}{2V_d}[1 + k\cos(\omega t)] \quad (5)$$

$$N_{Lower} = Round_{0.5}\frac{V_{dc}}{2V_d}[-k\cos(\omega t) + 1] \quad (6)$$

Vd denotes SM capacitor voltage. The round function is utilised to round values of the reference waveform to the closest integer, which can be calculated based on its decimal value. If the argument's decimal fraction is below 0.5, it will be rounded to the nearest integer that was previously accessible; if it is larger than 0.5, it will be rounded to the next integer that was previously available. The reference step for the lower and upper arm is shown in equation (7). The overall reference equation is shown in equation (8).

$$\begin{cases} V_{up}^{ref} = [(k - l - 1) + 0.5V_d] \\ V_{low}^{ref} = (l + 0.5)V_d \end{cases} \quad (7)$$

$$V_E^{ref} = (l - 0.5k + 0.5)V_d \quad (8)$$

6. Modified Nearest Level Modulation Technique

In all the phases of the three-phase MMC converter, the modified NLM method introduces a little shift either in the phase of the reference signal of the lower or upper MMC arm. It illustrates the suggested modified NLM approach, where the lower arm reference waveform exhibits a shift in its phase compared to the reference signal of the upper arm, as shown below in Figure 4. The reference and staircase waveform equations for the modified NLM algorithm are shown in (9) and (10), and for 3Nhalf+3Nfull+1 AC voltage levels.

$$V_{Lower}^{ref} = \frac{V_{dc}}{2}[1 + k\cos(wt + \gamma)] \quad (9)$$

$$V_{Lower}^{step} = round_{0.5}\frac{V_{dc}}{2}[1 + k\cos(wt + \gamma)] \quad (10)$$

Where γ is the phase shift required to be inserted in the reference and has been calculated based on the output current and voltage THD, the THD is measured and compared with the stored values. Then the optimum phase shift value is selected based on the lowest THD. If there is a change in load, then the value of the phase shift is selected again. Equal number of half-bridge and full-bridge SMs in the upper and lower arm are connected.

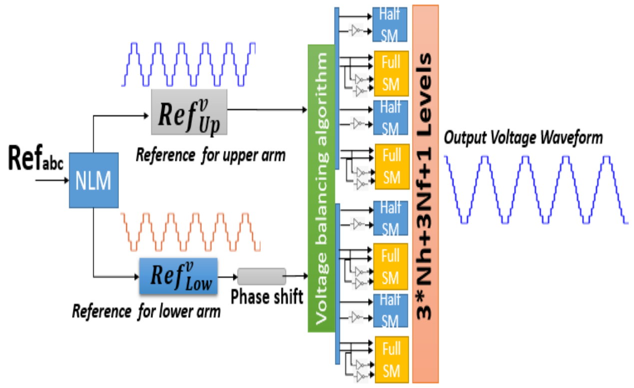

Fig. 4. Modified NLM scheme and applied switching signal

7. Simulation results and discussion

In the results section, a three-phase hybrid SM topology-based low-voltage MMC is thoroughly simulated and analysed in a DC Microgrid with solar, wind, grid, and battery energy systems to check the Microgrid's performance for various system states, such as changes in load demand and variable energy production.

The operational reliability of the Microgrid is confirmed by analysing important metrics like energy storage, power sharing, and voltage stability. Later, a three-phase hybrid MMC is incorporated in the model for efficient DC to AC conversion to feed the load. The NLM scheme is applied to a model with 4 SMs in the upper and lower arm (2 each half and full SM). As per the literature, 2N+1 AC output voltage and current levels, i.e. 9 levels, were obtained. The voltage THD measured was 16.21% and the current THD was 12.42%. Later, the Modified NLM scheme was developed and applied to the model. It was observed that, with 4 SMs, 13 levels were generated in the voltage and current waveforms. The THD of the voltage and currents is also reduced to 8.15% and 5.79% respectively. The combined results of conventional and modified NLM are shown in Figure 5 and 6 for voltage and current, respectively. The capacitor voltages of MMC also remain balanced after applying the Modified NLM method, as shown in Figure 7.

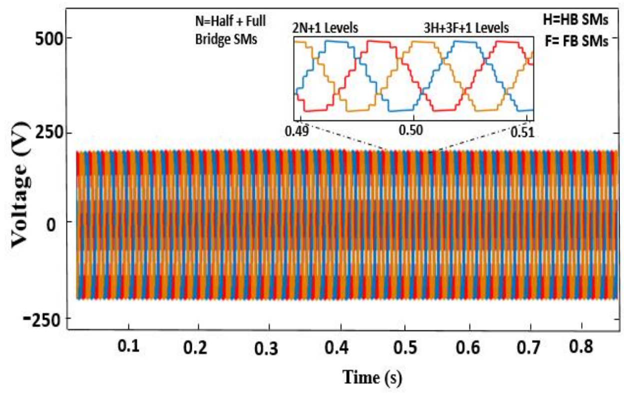

Fig. 5. 9 levels to 13 levels hybrid MMC Voltage waveform

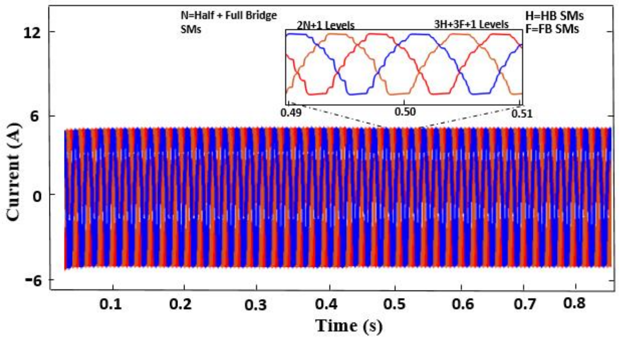

Fig. 6. 9 levels to 13 levels hybrid MMC current waveform

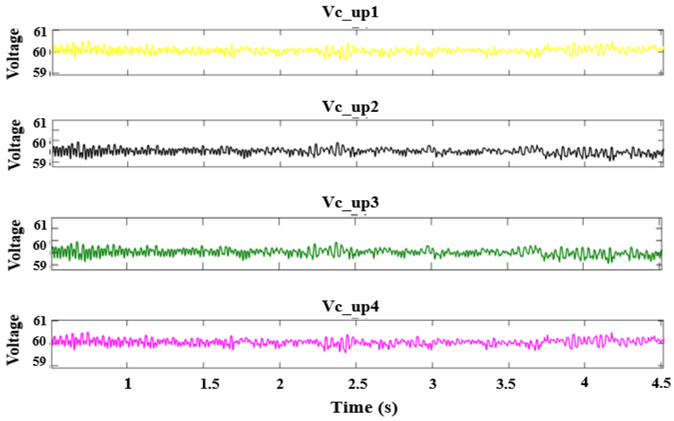

Fig. 7. SM capacitor voltages of phase A upper arm

Similarly, the hybrid MMC with 8 SMs in upper and lower arm (4 each half and full SM) is modelled and simulated using the Conventional and Modified NLM. With SMs using conventional NLM, 17 levels were obtained in the ac output voltage current waveform, and 25 levels were seen with Modified NLM. The THD of output voltage with conventional NLM was 9.43% and with Modified NLM was 4.67%. The THD of output current with conventional NLM was 6.32% and with Modified NLM was 3.12%. The voltage and current outputs are shown in Figures 8 and 9, respectively.

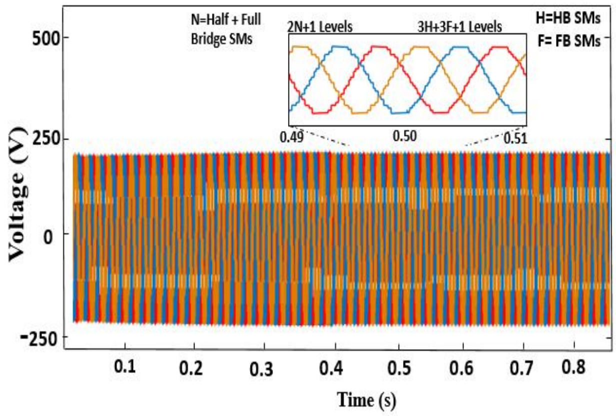

Fig. 8. 17 levels to 25 levels hybrid MMC Voltage waveform

The results obtained using MATLAB Simulink are further summarised in Table 3 for THD of voltage and current using 4 and 8 SMs in the hybrid MMC.

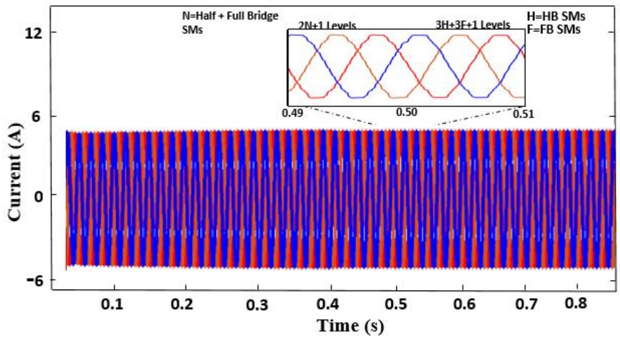

Fig. 9. 17 levels to 25 levels hybrid MMC current waveform

Table 3

Comparison of %THD of voltage and current for Conventional and Modified control in MATLAB Simulink

No: of SMS	Conventional NLM		Modified NLM	
	Voltage % THD	Current % THD	Voltage % THD	Current % THD
4	16.21	12.42	8.15	5.79
8	9.43	6.32	4.67	3.12

8. Hardware in loop (HIL) results and discussion

The results were obtained and analysed after completing the MATLAB Simulink simulation of the DC Microgrid and integrating the hybrid MMC into the DC Microgrid. The MATLAB Simulink results were the offline simulation results and were not enough to demonstrate the approach for Modified NLM control; therefore, the real simulation has to be carried out for actual demonstration of the control method, before proceeding to the hardware implementation of the system in future. The HIL setup consists of a real-time FPGA-based controller named Compact RIO (NI CRIO 9035), which is programmed using LabVIEW FPGA (graphical programming language). The digital simulator, NI PXIe-1085, is based on an FPGA on which the simulation will be built and loaded. A four-quadrant power amplifier will amplify low voltage and current generated by PXIe-1085 to derive the 220 Volt load, serve for communication between each device, and provide an HMI for monitoring and control purposes. The overall HIL system is shown below in Figure 10.

The DC Microgrid model was initially designed and tested in an HIL setup with the help of DC-DC, AC-DC, and DC-AC converters. Then, the hybrid MMC is added to the system by designing its circuit in MATLAB Simulink. Through LabVIEW programming, conventional and Modified NLM control schemes were implemented in an FPGA-based NI Compact RIO controller. The MMC model is loaded and deployed in the NI PXIe system using

OPAL RT software. The model and controller at this stage are ready to run on FPGA to depict the system's actual behaviour with conventional and modified schemes.

The results of the hybrid MMC with 4 SMs were taken and observed in LabVIEW software, as shown below in Figure 11 and 12 for voltage and current, respectively. The voltage %THD for conventional and modified NLM is 16.43% and 8.29% respectively. Whereas the current %THD was 12.58% and 5.89% for the conventional and modified schemes, respectively. Similarly, the number of SMs were raised to eight per arm. This configuration raised the levels from 17 to 25 using the conventional and modified NLM methods. The %THD of voltage was measured as 9.57% and 4.75%, whereas the current %THD was 6.46% and 3.24% for conventional and modified schemes. Further results are shown in Figure 13 and 14 for the voltage and current waveforms. The real-time results are also summarised in Table 4. Now as we are getting improved output voltage and current with fewer SMs using Modified NLM scheme compared to what we could have achieved by using conventional control scheme by using more number of SMs (including switches, capacitors and other equipment) we can conclude that system cost has reduced and complexity of MMC is also reduced.

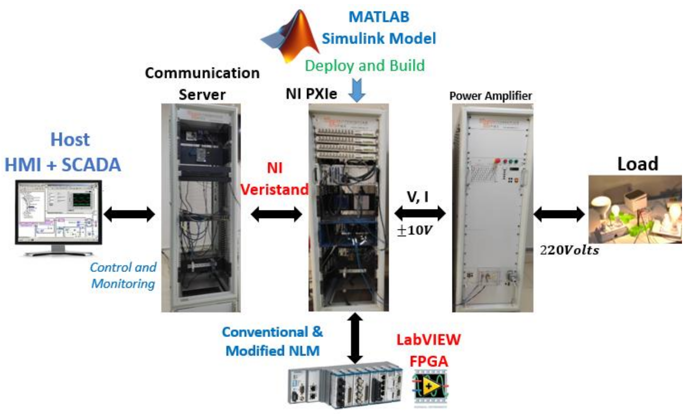

Fig. 10. Real-time HIL Setup

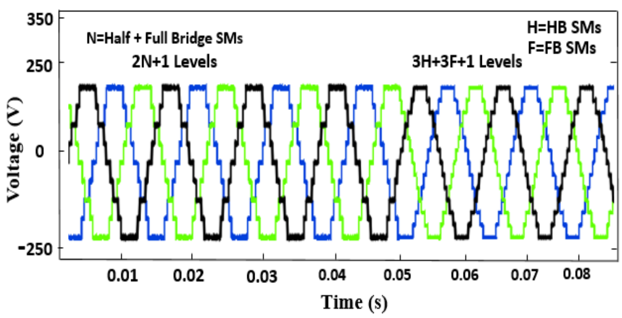

Fig. 11. 9 levels to 13 levels hybrid MMC Voltage waveform HIL results

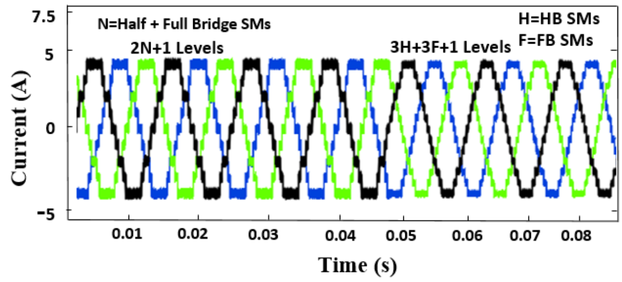

Fig. 12. 9 levels to 13 levels hybrid MMC Current waveform HIL results

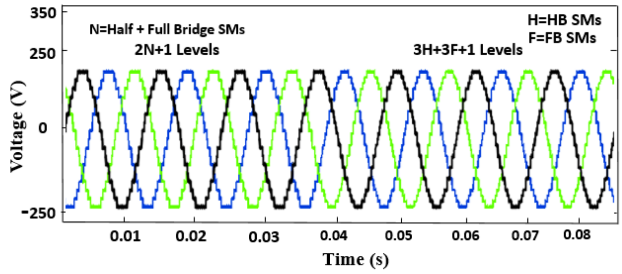

Fig. 13. 17 levels to 25 levels hybrid MMC Voltage waveform HIL results

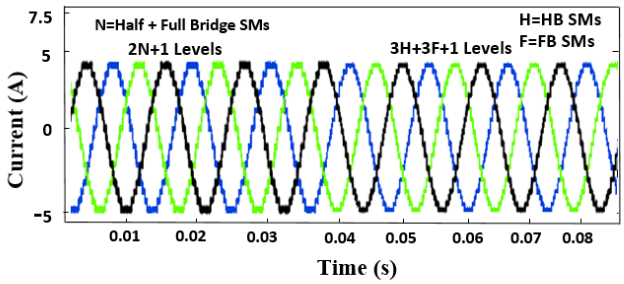

Fig. 14. 17 levels to 25 levels hybrid MMC current waveform HIL results

Table 4

Comparison of %THD of voltage and current for Conventional and Modified control in HIL setup

No: of SMS	Conventional NLM		Modified NLM	
	Voltage % THD	Current % THD	Voltage % THD	Current % THD
4	16.43	12.58	8.29	5.89
8	9.57	6.46	4.75	3.24

9. Conclusion

This study investigated the possibility of integrating a hybrid MMC into a small Microgrid system that uses grid, solar, battery, and wind energy. By reducing the number of SMs needed, the Modified NLM technique successfully addressed the conventional problem of managing many submodules in MMCs. By generating 3Nhalf+3Nfull+1 AC output voltage and current levels, this method enhances the power quality and raises converter efficiency. Combining the advantages of modularity, scalability, and superior power output, the MMC provides a practical and effective solution for Microgrid applications, as per simulation results performed in MATLAB Simulink. These results imply that the MMC is a promising substitute for conventional converter topologies in distributed energy systems and has great potential for optimising small-scale

Microgrid operations when utilising modulation techniques like MNLM.

By testing experimentally the hybrid MMC with Modified NLM through a hardware prototype to test the simulated results. Also, how the hybrid MMC behaves during the various operating conditions of the Microgrid like faults, sudden variation in loads, and renewable intermittency would be interesting in understanding the reliability of such a system. Future work can also study long-term SM voltage balancing, thermal stress as well as component ageing to make sure it can be practically deployed.

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