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# Performance investigation of modular multilevel inverter topologies for photovoltaic applications with minimal switches

***Introduction.*** *In recent years, a growing variety of technical applications have necessitated the employment of more powerful equipment. Power electronics and megawatt power levels are required in far too many medium voltage motor drives and utility applications. It is challenging to incorporate a medium voltage grid with only one power semiconductor that has been extensively modified. As a result, in high power and medium voltage settings, multiple power converter structure has been offered as a solution. A multilevel converter has high power ratings while also allowing for the utilization of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells may be readily connected to a multilevel inverter topology for enhanced outcomes. The* ***novelty*** *of the proposed work consists of a novel modular inverter structure for solar applications that uses fewer switches.* ***Purpose.*** *The proposed architecture is to decrease the number of switches and Total Harmonic Distortions. There is no need for passive filters, and the proposed design enhances power quality by creating distortion-free sinusoidal output voltage as the level count grows while also lowering power losses.* ***Methods.*** *The proposed topology is implemented with MATLAB / Simulink, using gating pulses and various pulse width modulation methodologies. Moreover, the proposed model also has been validated and compared to the hardware system.* ***Results****. Total harmonic distortion, number of power switches, output voltage and number of DC sources are compared with conventional topologies.* ***Practical value.*** *The proposed topology has been very supportive for implementing photovoltaic based multilevel inverter, which is connected to large demand in grid.* References 12, table 5, figures 23.

*Key words:* **fast Fourier transform, multilevel inverter, photovoltaic, pulse width modulation techniques, total harmonic distortion.**

***Вступ****. В останні роки зростаюча різноманітність технічних застосувань вимагає використання потужнішого обладнання. Силова електроніка і мегаватні рівні потужності потрібні в багатьох приводах двигунів середньої напруги і комунальних застосуваннях. Складно увімкнути мережу середньої напруги лише з одним сильно модифікованим напівпровідниковим приладом. В результаті, для установок високої потужності та середньої напруги як рішення було запропоновано структуру з кількома силовими перетворювачами. Багаторівневий перетворювач має високу номінальну потужність, а також дозволяє використовувати відновлювані джерела енергії. Відновлювані джерела енергії, такі як фотоелектричні, вітряні та паливні елементи можуть бути легко підключені до топології багаторівневого інвертора для покращення результатів.* ***Новизна*** *роботи полягає у новій модульній структурі інвертора для сонячних батарей, у якій використовується менше перемикачів.* ***Мета****. Пропонована архітектура призначена для зменшення кількості перемикачів та загальних гармонійних спотворень. Немає необхідності в пасивних фільтрах, а пропонована конструкція покращує якість електроенергії, створюючи синусоїдальну вихідну напругу без спотворень зі зростанням кількості рівнів, а також знижуючи втрати потужності.* ***Методи****. Пропонована топологія реалізована за допомогою MATLAB/Simulink з використанням стробуючих імпульсів та різних методологій широтно-імпульсної модуляції. Крім того, запропонована модель також була перевірена та порівняна з апаратною системою.* ***Результати****. Загальне гармонійне спотворення, кількість силових ключів, вихідна напруга та кількість джерел постійного струму порівнюються із звичайними топологіями.* ***Практична цінність****. Запропонована топологія дуже сприятлива для реалізації багаторівневого інвертора на основі фотоелектричних елементів, який пов'язаний із великим попитом у мережі.* Бібл. 12, табл. 5, рис. 23.

*Ключові слова:* **швидке перетворення Фур'є, багаторівневий інвертор, фотовольтаїка, широтно-імпульсна модуляція, повні гармонічні спотворення.**

**1. Introduction.** Multilevel inverter (MLI) topology has lately emerged as a critical option for high-power medium-voltage energy control. The most essential topologies, according to [1], are diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multi cell with distinct dc sources. Among the most significant controlling and modulation techniques developed for this series of inverters are asymmetric multilevel based sinusoidal pulse width modulation, multilevel selective harmonic elimination, and space-vector modulations [1].

The authors of [2] proposed a revolutionary multilevel pulse width modulation-based inverter design for the use of stand-alone solar systems. This system is made up of a pulse width modulation (PWM) inverter, a set of voltage level inverters, a staircase output voltage generator, and cascaded transformers. It creates higher voltage waves by generating a big voltage to the necessary levels using cascaded transformers with a franchise secondary. The engine's secondary turn-ratio has been set suitably [2].

According to [3], alternating phase opposed disposition PWM for diode-clamped inverters seems to have the same harmonic effectiveness as phase-shifted carrier PWM for cascaded inverters and composite PWM for hybrid inverters whenever the carrier frequencies have been chosen to achieve having similar number of inverter switch conversions within every cycle. Using knowledge, a PWM technique for cascaded and hybrid inverters are developed that provides the same harmonic advantages as phase disposition PWM for diode-clamped inverters [3].

**2. Literature review.** The most important and noteworthy applications of these converters, such as particular laminators, conveyors, and grid-connected photovoltaic regulators, are emphasized. The need for an effective front end on the input stage of inverters that feed regenerative applications, as well as the many circuit design options, is also discussed. Furthermore, fast growing industries also including high-voltage high-power devices and sensing applications, as well as some additional future development prospects, are being examined [4, 5].

The fundamental disadvantage of a traditional cascaded MLI is that when levels rise, additional semiconductor switches are required. This changes the size of the inverter and complicates the control strategy. The use of a MLI with fewer switches minimizes the size of the inverter and simplifies control [6]. The diode clamped, flying capacitor, and cascaded H-bridge inverters are the three principal MLI topologies used in commercial applications with different dc voltage sources.

Capacitor voltage balancing is an issue in flying capacitor and diode-clamped inverters, but it is handled in cascaded H-bridge inverters. The main problem of classic

cascaded is that additional semiconductor switches are required even as levels grow. As a result, many adjustments will be required to reduce the size and cost of the inverter [7]. The authors of [8] investigated a number of recent articles on problems such as the creation of inverted pulse width modulation method in cascaded H-bridged MLI systems.

According to [9], multilevel converters are essential in both moderate and high-power applications. Diode clamped, flying capacitor, and cascaded H-bridged are the three most common configurations for multi-level inverters. To accomplish medium voltage and high-performance characteristics, the modular design of cascaded-H bridged MLI characteristics and performance is adopted. Short and open circuit faults are two forms of power switching device failures that might occur in cascaded H-bridged multilevel inverter (CHB-MLI). Short circuit problems mostly damage, so protection from short circuit is required. Artificial neural network approaches for short circuit protection by using high potency fuses and de-saturation method.

The authors of [10] had analyzed open-circuit faults in power switches the device shutting down, and they can go undetected for a long time. This could cause secondary defects in the inverter or other drive components, culminating in the entire system being shut down and expensive repairs.

The authors of [11] had analyzed fault analysis in inverter and also faults an inverter device is used continuously under abnormal settings, further issues will arise, resulting in severe consequences. Furthermore, the MLI is composed of several switching devices and the entire system is complex in structure, and there are numerous nonlinear impacts. As a result, MLIs need some novel diagnostic strategies which could not deal with nonlinear detection issues but also diagnose and locate faults easily. The device voltage and current of a multilayer inverter might vary based on the part and location of the faults. Some research concentrates on the device output current or voltage to assess fault form and position more quickly and easily, and then used the sample to expand a number of fault diagnosis techniques. Owing to the dangerous effects of short circuit faults on converter circuits, this type of fault must be detected as soon as possible. It is necessary to remember that certain circuit drivers are already in a position to detect defective switches. Hence considering the value of medium voltage drives on the industry, robust detection mechanisms need to be discussed.

The authors of [12] had investigated green energy and helping in solving various challenges such as climate change and pollution, the implementation of renewable distributed energy resources in the operational distribution system has risen fast. Due to its qualities of rapid charging and discharging, regulating power quality, and meeting peak energy demand, integrating battery energy storage systems might be regarded one of several finest alternatives in providing answers to the listed difficulties.

The fundamental objectives of the proposed research effort are to develop a high-performance MLI which has less number of power semiconductor switches. By the reduction of number of switches, total harmonic distortion (THD) and power losses have been minimized. The proposed technique is validated with the help of experimental setup.

## 3. Multicarrier pulse width modulation techniques.

**3.1 Alternate phase opposition disposition.** This approach requires that one of those ($m$ – 1) carrier frequency signal be phase distorted from one another by 180 degrees alternatively for an $m$-level sequence pattern, as illustrated in Fig. 1 for various modulating signals. There are no harmonics at $f_c$ because the most important harmonics are focused as circuit distortion around the carrier frequency $f_c$.

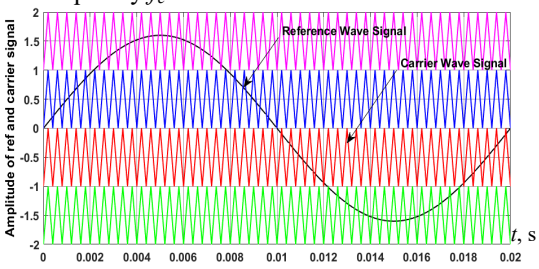

Fig. 1. Alternate phase opposition disposition multicarrier PWM

**3.2 Phase opposition disposition.** The carrier signal waveforms seem to be in phase around the outer minimal standard value, while the ones above and behind minimal have a 180 degree phase shift, as seen in Fig. 2 for different frequency components. In both the phase and line voltage waveforms, the highest harmonics are grouped around the carrier frequency signal $f_c$.

**3.3 Phase disposition.** As established in Fig. 3, when using the phase disposition modulation scheme, every one of the carrier signals is in phase.

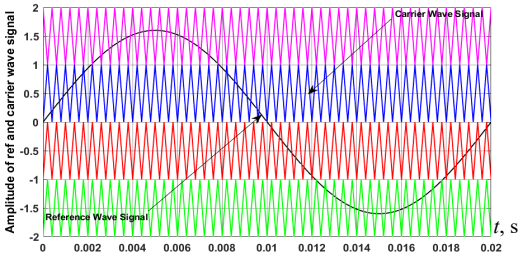

Fig. 2. Phase opposition disposition multicarrier PWM

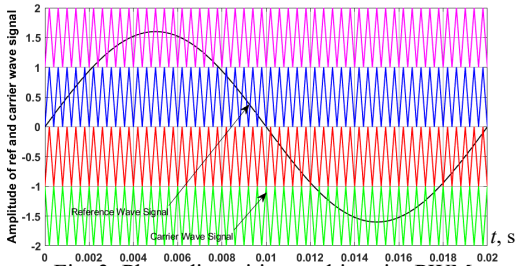

Fig. 3. Phase disposition multicarrier PWM

**4. Proposed topologies.** A three-phase low component power semiconductor switch based multilevel DC-link inverter scheme is used to address the limitations of standard topology. Simulation modelling and analysis are used to assess the dependability of a five-level inverter with an inductive load. H-bridge inverters link separated voltage levels and series switches to connect voltage sources to loads. As the number of levels increases, so does the circuit complexity. The proposed design operates in symmetrical mode to decrease the number of switches while maintaining the same number of output levels by maintaining the DC source amplitudes equal and the sinusoidal waveform. Figure 4 shows the photovoltaic (PV) connected modular recommended MLI I and II, with the configuration of the inverter being the focus of this whole study.

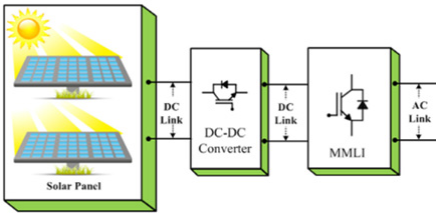

Fig. 4. Photovoltaic connected modular MLI

4.1 Proposed topology - **I.** The suggested five-level modular MLI, which provides a greater number of output voltage levels, is depicted in Fig. 5, $+2V_{dc}$, $+V_{dc}$, 0, $-V_{dc}$, and $-2V_{dc}$ are the five output levels. The PWM method is used in this inverter to generate high quality output. When four level shifted, triangular waveforms are compared to a single sine wave, four signals are created. The number of switches is decreased to 6($m$–2) in this suggested architecture, where m is represents the number of output voltage levels. The switching patterns of the proposed modular MLI are shown in Table 1. Table 2 lists the parameters which are used in the simulation analysis.

**4.2 Proposed topology - II.** A modified MLI topology is presented for three-phase systems to minimise the number of switches and alleviate the disadvantages of standard design. The functioning of a five-level inverter with a resistive load is evaluated via simulation. Isolated DC voltage sources and switches are linked in series. Switches are used by H-bridge inverters to link voltage sources to loads. By retaining the amplitudes of the DC sources constant, the suggested topology operates in symmetrical mode, reducing the number of switches while maintaining the same number of voltage output levels. The circuit complexity grows as the proportion of levels increases, culminating in a sinusoidal waveform.

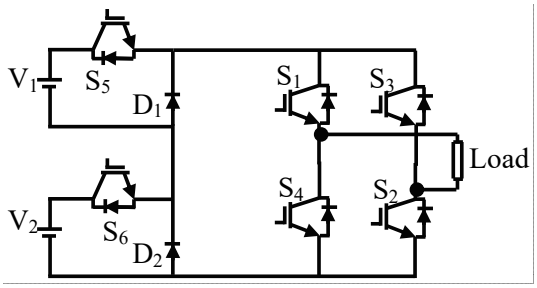

Fig. 5. Proposed modular MLI - I

Table 1

Switching patterns of proposed modular MLI - I

| Vo | S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|
| $+2V_{dc}$ | 1 | 1 | 0 | 0 | 1 | 1 |
| $+V_{dc}$ | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $-V_{dc}$ | 0 | 0 | 1 | 1 | 0 | 1 |
| $-2V_{dc}$ | 0 | 0 | 1 | 1 | 1 | 1 |

Table 2

Design parameters of proposed modular MLI - I

| Parameters | Range |
|---|---|
| Input voltage (DC) | 115 V |
| Output voltage(Peak)/Ph. | 230 V |
| Output frequency | 50 Hz |
| Inverter switching frequency | 10 kHz |
| Modulation Index | 1 |
| Load resistance | 100 Ω |
| Power Rating | 1.587 kW |

In this proposed (Fig. 6) architecture, the number of switches is reduced to 6 ($m$–2) where $m$ is the number of levels. For MLI to work effectively, diodes are also required. The design and operation of this topology is more complicated than standard approaches. According to the generalization of configuration in symmetrical arrangement for $N$-level output, the principal switches used here are 6($m$–2) for three phases, where 'm' is the number of levels. If m value is 5, the total number of switches in this topology is 18, and two DC sources are necessary. The switching patterns of the proposed modular MLI are shown in Table 3. The switching patterns of the proposed MLI are shown in Table 4 lists the parameters which are used in the simulation analysis.

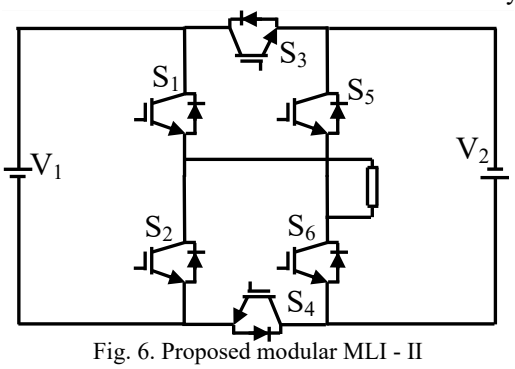

Fig. 6. Proposed modular MLI - II

Table 3

Switching patterns of proposed modular MLI - II

| Vo | S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|
| $+2V_{dc}$ | 1 | 0 | 0 | 1 | 1 | 0 |
| $+V_{dc}$ | 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $-V_{dc}$ | 0 | 1 | 1 | 0 | 1 | 0 |
| $-2V_{dc}$ | 0 | 1 | 1 | 0 | 0 | 1 |

Table 4

Design parameters of proposed modular MLI – II

| Parameters | Range |
|---|---|
| Input voltage (DC) | 115 V |
| Output voltage(Peak)/Ph. | 230 V |
| Output frequency | 50 Hz |
| Inverter switching frequency | 10 kHz |
| Modulation Index | 1 |
| Load resistance | 100 Ω |
| Power Rating | 1.2 kW |

**5. Results and discussion.**

**5.1 Proposed topology - I.** Figure 7 illustrates the MATLAB / Simulink Model of proposed - I MLI. Figure 8 depicts the modular five level three phase voltage output configuration over the load. The waveform yields the input and output voltages of 115 V and 230 V, respectively. Fast Fourier transform (FFT) analysis of alternate phase opposition disposition (APOD), phase opposition disposition (POD), and phase disposition (PD) based pulse width modulation is shown in Fig. 9–11. The switching pulse turn device sequence, as well as the cascaded MLI level output voltage.

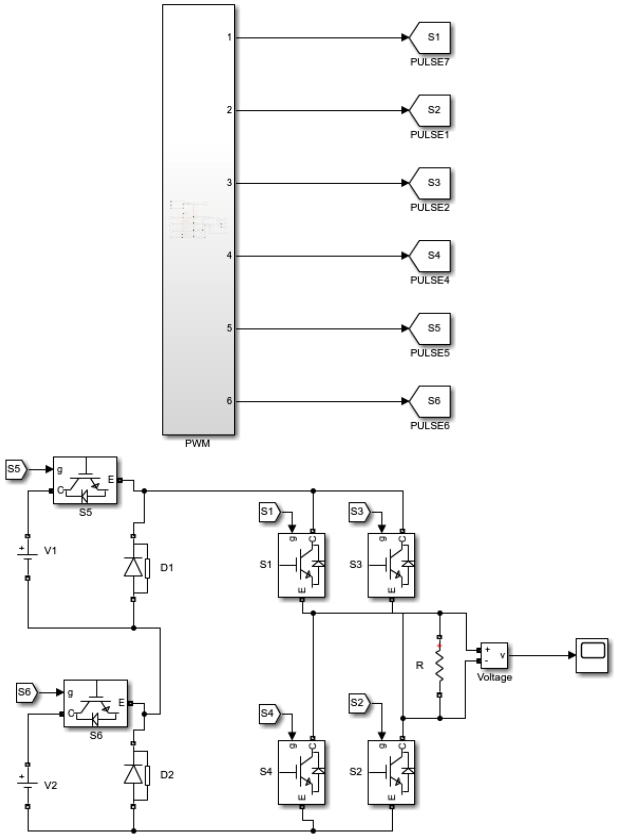


Fig. 7. MATLAB / Simulink model of proposed - I modular MLI

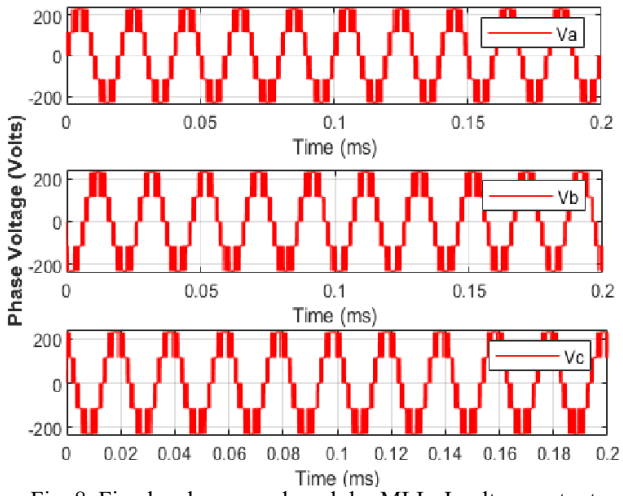


Fig. 8. Five level proposed modular MLI - I voltage output pattern for three phase system

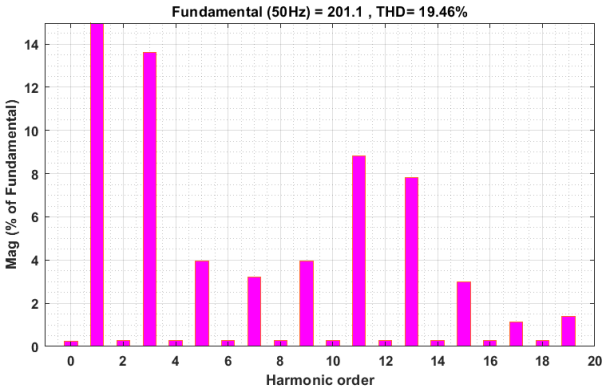


Fig. 9. FFT investigation of the proposed modular MLI - I with APOD

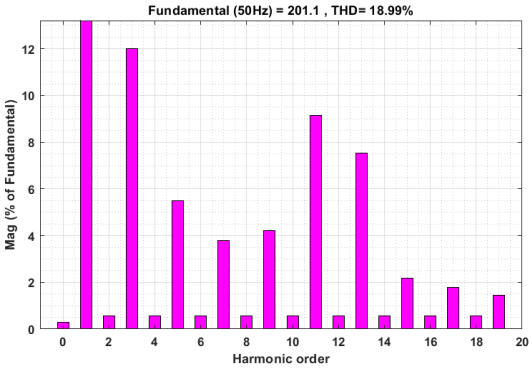


Fig. 10. FFT investigation of the proposed modular MLI - I with POD

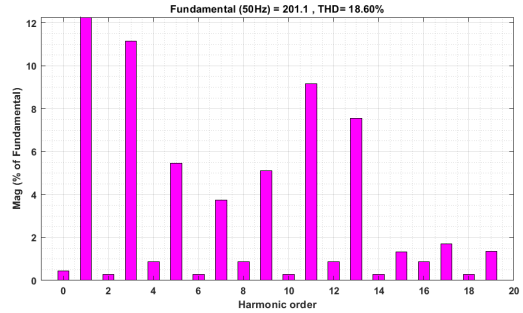


Fig. 11. FFT investigation of the proposed modular MLI - I with PD

**5.2 Proposed topology - II.** Figure 12 illustrates the MATLAB / Simulink model proposed - II MLI.

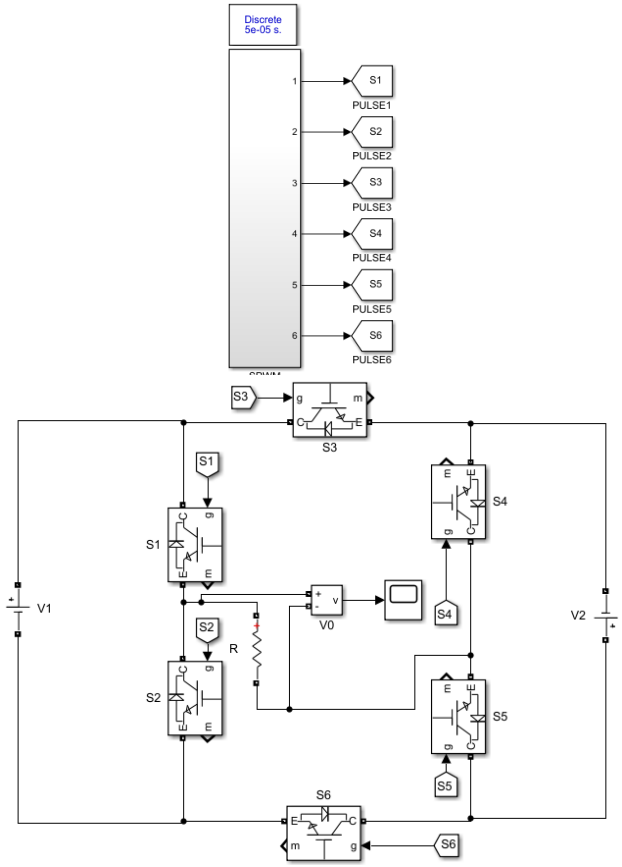


Fig. 12. MATLAB / Simulink model of proposed - II modular MLI

Figure 13 shows the switching pulses of modular MLI - I. Figure 14 illustrates the modular five and 230 V, respectively. FFT analysis of APOD, POD, and PD based pulse width modulation is shown in Fig. 15–17.

The switching pulse turn device sequence, as well as the cascaded MLI level output voltage. Figure 18 shows the switching pulses of modular MLI - II.

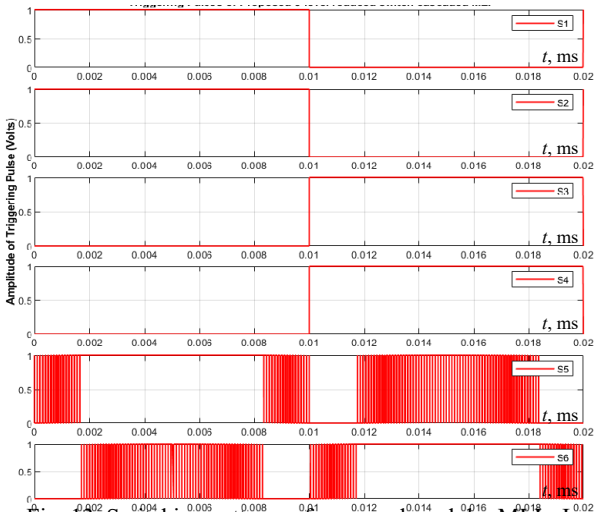


Fig. 13. Switching patterns of proposed modular MLI - I

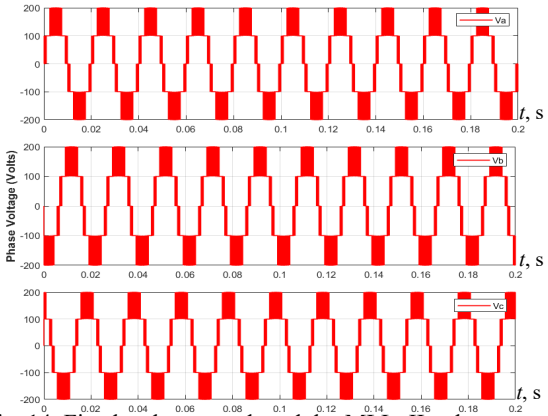


Fig. 14. Five level proposed modular MLI - II voltage output pattern for three phase system

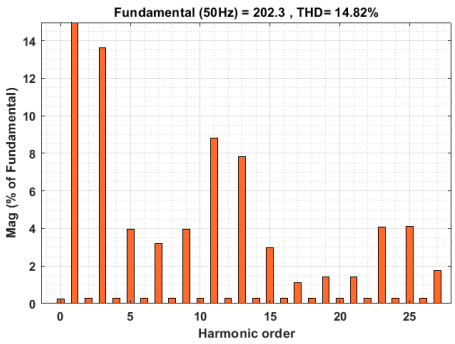


Fig. 15. FFT investigation of the proposed modular MLI - II with APOD

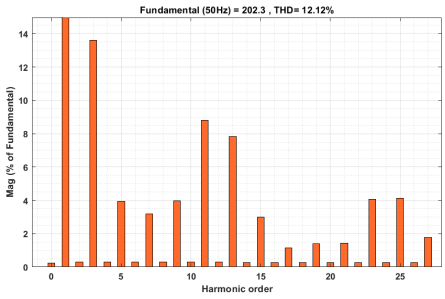


Fig. 16. FFT investigation of the proposed modular MLI - II with POD

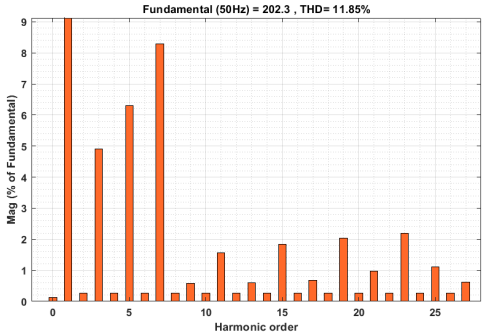


Fig. 17. FFT investigation of the proposed modular MLI - II with PD

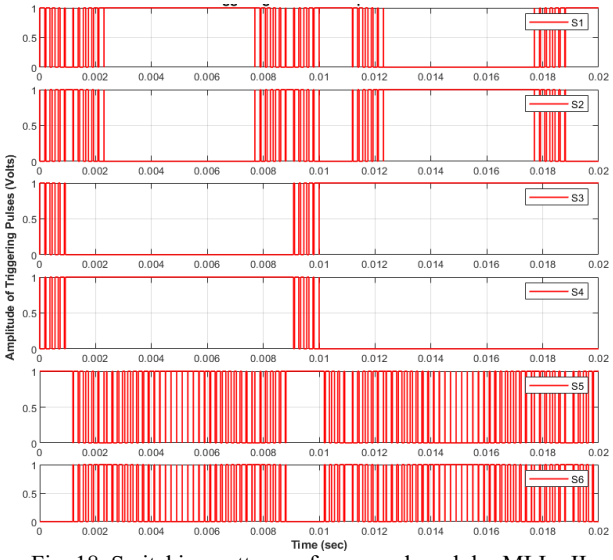


Fig. 18. Switching patterns of proposed modular MLI – II

Figures 19, 20 illustrate the detail of THD analysis of conventional and proposed modular MLI and switch count analysis of conventional and proposed modular MLI respectively which is calculated based on the mathematical expressions represented in Table 5.

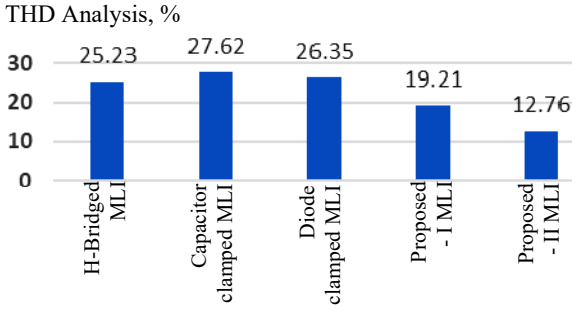


Fig. 19. THD analysis of conventional and proposed modular MLI

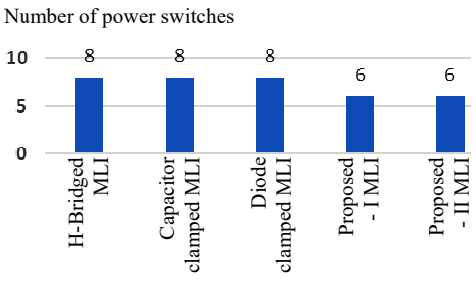


Fig. 20. Switch count analysis of conventional and proposed modular MLI

Table 5

Comparative properties of conventional and proposed MLIs

| MLI structure | Cascaded H-bridge | Diode clamped | Flying capacitor | Proposed topology – I | Proposed topology – II |
|---|---|---|---|---|---|
| Power semiconductor switches | 6($m$–1) | 6($m$–1) | 6($m$–1) | 6($m$–2) | 6($m$–2) |
| Bridged diodes | 6($m$–1) | 6($m$–1) | 6($m$–1) | 6($m$–2) | 6($m$–2) |
| Diodes for clamping | – | 3($m$–2) | – | – | – |
| Splitting capacitors for DC | – | $m$–1 | $m$–1 | – | – |
| Clamping capacitors for DC | – | – | 3$m$ | – | – |
| Other diodes | – | – | – | $m$+1 | $m$+1 |

**6. Experimental results and discussion.** In order to evaluate the performance of the proposed 5-level structure, IGBTs are employed as switching devices in the proposed 5-level MLI prototype. The experimental setup arrangement for the proposed 5-level single large multilevel power converter (SL-MLPC) is depicted in Fig. 21. The field-programmable gate array is used in this research to generate pulses for the power switches. In Xilinx software, the Verilog-language is utilised to program all of the switching states of the proposed topology. The switching pulses are eventually transported through optic-wires to the gate driver circuits, where they are employed to power the IGBTs in the proposed topology. Several experimental results predicated on a 620 W laboratory model are provided in this part to validate the results of the designed inverter. A PV simulator was employed as a power supply in this case, and the recommended point of common coupling was used to communicate the accuracy of the control system, which was controlled by a Texas instrument.

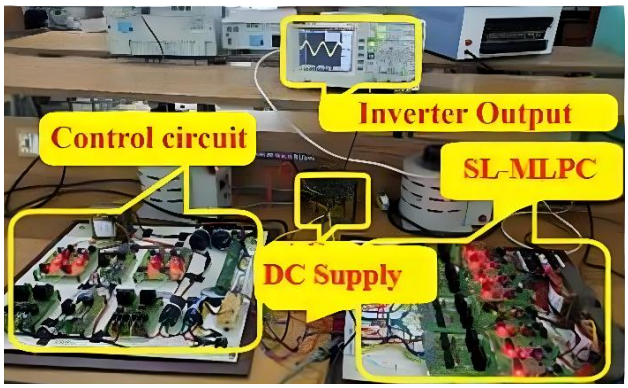


Fig. 21. Experimental prototype of the proposed inverter

Figures 22, 23 illustrate the inverter's five-level voltage waveform with a maximum value of 203 V, which would be required to inserting power into the transmission system, as well as the sinusoidal injected current with unity power factor, which provides the proposed topology output results. The supply current to the power network has a maximum amplitude of roughly 5 A, as seen in the graph. The 50 Hz network reference voltage and single phase five level of the proposed inverter are shown in Figures 22, 23.

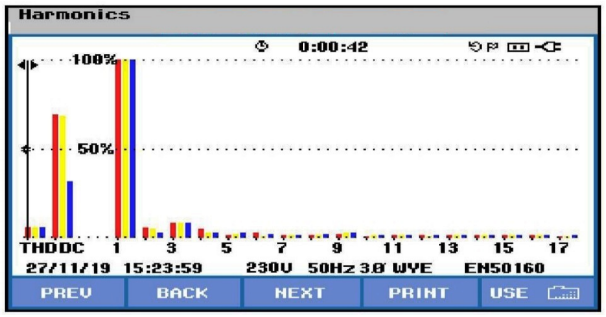


Fig. 22. Five level proposed – I MLI topology

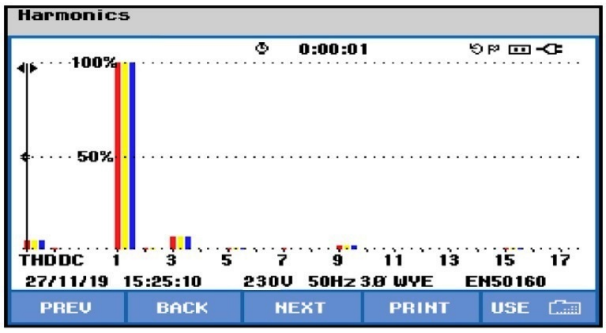


Fig. 23. Five level proposed – II MLI topology

**7. Conclusions.** The suggested multilevel inverter architecture may be a viable option for powering photovoltaic applications. A five-level inverter was explored and controlled using a multi-carrier approach, which required fewer switching states each cycle. The recommended new modular multilevel inverter with a system to obtain and the switching patterns of five-level multilevel inverter are generated based on the working pattern of power electronic switching devices, according to the MATLAB / Simulink and hardware results. When compared to earlier multilevel inverter topologies, the suggested topology achieves good results in terms of reducing power switching components, total harmonic distortion, driver circuits, device stress, and switching losses. In that approach the proposed – I and II multilevel inverter give the total harmonic distortion values are 19.21 % and 12.76 % respectively which is compared less than the value of conventional topologies. Due to the presence of completely power switches based proposed – II multilevel inverter topology give lesser harmonics than proposed – I multilevel inverter. The total harmonic distortion value is also minimized in this proposed model using different multicarrier pulse width modulation approaches.

**Conflict of interest.** The authors declare that they have no conflicts of interest.

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