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MATLAB-Simulink environment based power quality improvement in photovoltaic system using multilevel inverter

Introduction. In this world of technical advancement, conventional resources are at the stage of destruction. To avoid such problems, we are going to use an alternative energy source namely solar by photovoltaic effect. The demand for multilevel inverters increased as they are used for different dynamic (high) voltage and dynamic (high) power appliances as they are capable of producing the output wave shape with low total harmonic distortion. **Novelty.** A new multilevel inverter is used in adding a (bidirectional) two way switch in between the capacitor and a traditional H-bridge module. This produces a better sine wave. By series connection of these two H-bridge modules, nine levels output voltage including zero is possible. The **purpose** of the proposed topology is reduction in the number of switches and it gives the good result with comparatively less power loss when it is compared with the other normal basic traditional inverters of the same output quality. **Methods.** In this paper, sinusoidal pulse width modulation technique is used for the working of the switches in the multilevel inverter. The **results** are verified by using simulation and also experimental setup is done. From the results it is observed that the proposed topology with reduced number of switches gives lower electromagnetic interference, lower harmonic distortion. **Practical value.** The total harmonic distortion value in the simulation is 14.4 % and practically it is 13.8 %. References 25, table 4, figures 15.

Key words: multilevel inverter, pulse width modulation, cascaded multilevel inverter, standard test conditions, cascaded H-bridge multilevel, space vector modulation.

Вступ. У світі технічного прогресу звичайні ресурси перебувають у стадії руйнації. Щоб уникнути таких проблем, ми збираємося використати альтернативне джерело енергії, а саме сонячну енергію з фотоелектричним ефектом. Попит на багаторівневі інвертори збільшився, оскільки вони використовуються для різних динамічних (високих) напруг та динамічних (високих) потужностей, оскільки вони здатні формувати вихідну форму хвилі з низьким гармонічним загальним спотворенням. **Новизна.** Новий багаторівневий інвертор використовується для додавання двостороннього перемикача між конденсатором і традиційним модулем H-моста. Це дає найкращу синусоїду. При послідовному з'єднанні двох модулів H-моста можливо дев'ять рівнів вихідної напруги, включаючи нуль. **Метою** запропонованої топології є зменшення кількості перемикачів, що дає хороший результат при порівняно менших втратах потужності порівняно з іншими традиційними звичайними інверторами з такою ж вихідною якістю. **Методи.** У цій статті для роботи перемикачів у багаторівневому інверторі використовується метод широтно-імпульсної синусоїдальної модуляції. **Результати** перевіряються за допомогою моделювання, а також виконується експеримент. З результатів видно, що запропонована топологія зі зменшеною кількістю перемикачів дає менші електромагнітні перешкоди, менші гармонійні спотворення. **Практична цінність.** Сумарне значення гармонійних спотворень при моделюванні складає 14,4 %, а практично – 13,8 %. Бібл. 25, табл. 4, рис. 15.

Ключові слова: багаторівневий інвертор, широтно-імпульсна модуляція, каскадний багаторівневий інвертор, стандартні умови випробувань, каскадний багаторівневий H-міст, просторово-векторна модуляція.

Introduction. The demand for non-conventional resources has increased drastically due to scarcity of fossil fuels and greenhouse effect. Among these, wind and solar energy are admired because of the improvement in power electronics technology. Solar energy has many applications because of its advantages of having low maintenance and pollution free. Over the last 20 years, the necessity for non-renewable solar energy has expanded by the range of 20-25 % per year. This is mainly because of its decrease in the prices of solar panels. This resulted in the subsequent modifications: 1) the η of solar cells has raised; 2) industrialized machinery developments; 3) economies value of the scale. The relevant harmonics can be decreased by enhancing the output of the inverter. In current years, researchers and manufacturers are concentrating on multilevel inverters [1] because of their various benefits over the conventional pulse width modulation (PWM) inverters because as they have improved smaller filter size, lesser total harmonic distortion (THD), output waveforms, lower electromagnetic interference (EMI) and others [2].

One of the most desirable converters is the multilevel inverters (MLIs). MLIs are nothing but the converters which have the higher quantity of the output voltage levels when compared with the conventional inverters [3]. The main benefit of these MLIs is the higher output voltage levels [4] i.e. like a staircase wave shape, which is closer as that of the sinusoidal waveform. Hence

these MLIs will have a lower THD. The various types of MLIs are cascaded H-bridge (CHB), flying capacitor (capacitor clamped), and diode clamped (neutral clamped). The most common type of MLIs is the CHB because of its modular structure [5].

Among these three, cascaded MLI (CMLI) has a modular structure and it has advantages of having less number of components when compared with the other two topologies, and moreover, it has many applications in the electrical engineering field [6]. There are several modulation and control strategies being, including the following: [7] multilevel selective harmonic elimination, multilevel sinusoidal, and space vector modulation (SVM). The main disadvantage of the SVM is that the mathematical modeling and the selection of switching states are complicated [2, 8, 9]. To overcome these drawbacks, multicarrier PWM is used as the control strategy.

PV array. The Earth has an abundant supply of solar energy. The sun has the capability of providing enough energy to the world per annum. In fact, the proportion of solar radiation reaching the earth surface for three-day duration is equal to the energy stored in all the non-renewable energy sources.

The smallest building block of a solar module comprises a P-N junction which is useful for converting the light energy into electrical energy and it is called the solar cell. The equivalent circuit of the solar cell is shown

in Fig. 1. It is a form of a tool for which the electrical parameters, such as current, voltage, or resistance, varies when exposed to sunlight [10]. The solar panels can be used as a light sensitive cell (photo detector), which is helpful for detecting the solar light (infrared detectors), near the visible range [11]. The basic principle of operation of a photovoltaic (PV) cell has 3 basic requirements:

- either electron-hole pair generating or exacting by the absorption of light;
- the detachment of charge carriers of opposing types;
- the distinct extraction of these carriers to another exterior circuit.

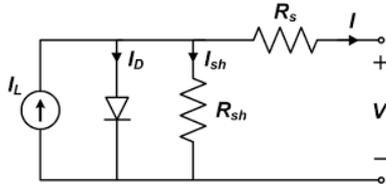


Fig. 1. Equivalent circuit of solar cell

On Fig. 1: I_L is the light developed current; I_D is the diode current; R_{sh} is the shunt resistance that gives us the information about the leakage current; R_s is the series resistance which tells us about the migration of charge carriers. A group of PV cells forms the solar arrays and solar modules. It consists of the following formula:

$$I = n_p \cdot I_g - n_p \cdot I_{rs} \left[\exp\left(\frac{q}{k \cdot T \cdot A \cdot n_s}\right) - 1 \right], \quad (1)$$

where n_p is the count of cells that are coupled in parallel; I_g is the insulation current; I_{rs} is the reverse saturation current; n_s is the series connected solar cells; T is the temperature, K; A is the ideality factor; q is the charge; k is the Boltzmann constant [12].

I-V and P-V characteristics. Figure 2 shows the $I-V$ and $P-V$ characteristics of the solar cell. A curve drawn between current and voltage is nothing but $I-V$ curve. This shows an inverse relation. The area of this curve gives us the information about the maximum power that a panel could produce at the maximum current and the maximum voltage conditions. The region of this curve declines while increasing the solar cell voltage due to its incline in temperature. Because of the variations in habitat conditions, the maximum power point will also change which indicates the change in temperature and irradiance levels [13].

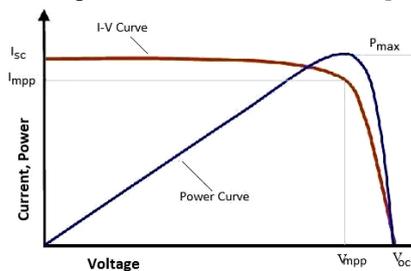


Fig. 2. $I-V$ and $P-V$ characteristics of solar cell

The final PV solar model is evaluated in standard test conditions (STC). These conditions are kept same in all over the world and performed in irradiance of 1000 W/m^2 under a temperature of $25 \text{ }^\circ\text{C}$. Simulation of the solar PV model executes the $I-V$ and $P-V$ characteristics curves. Generally a good agreement was observed between various performance

parameters results of reference model and simulated PV model at STC.

Proposed topology. The main disadvantage of conventional CMLI is more number of DC sources and as the level increases, the number of devices also inclines [14-16]. So as to achieve this, an improved topology has been introduced. The merits of this novel topology are the number of switches and the numbers of sources that are required are reduced [17]. The proposed topology is shown in Fig. 3.

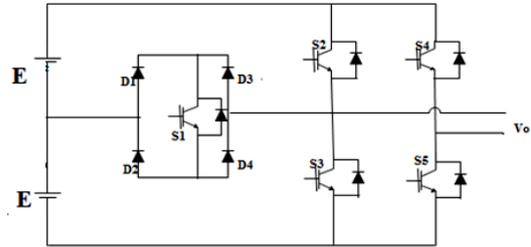


Fig. 3. Five levels CMLI

Based on the operating principle, Fig. 3 generates five levels of output voltage i.e. $2E$, E , 0 , $-E$, $-2E$. The switch combination has been shown in Table 1.

Table 1

Five level CMLI output voltage

Switching sequence*					Output voltage (V_o)
S1	S2	S3	S4	S5	
0	1	0	0	1	$2E$
1	0	0	0	1	E
0	0 or 1	1 or 0	0 or 1	1 or 0	0
1	0	0	1	0	$-E$
0	0	1	1	0	$-2E$

*(switch ON = 1, switch OFF = 0)

To obtain the output voltage $2E$, S2 and S5 switches have to be turned ON, and for obtaining the level E , S1 and S5 has to be in ON position. Similarly for 0 either S3 and S5 or S2 and S4 has to be in turn ON position, for $-E$ switches S1 and S4 need to be turned on; for $-2E$ devices S3 and S4 are to be turned ON.

Nine-level inverter. The circuit topology of a nine-level inverter is shown in Fig. 4 and in Table 2.

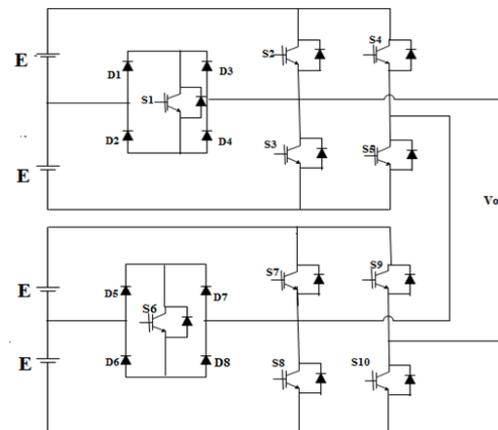


Fig. 4. Nine level CMLI

In five-level each module in the inverter produces $2E$, E , 0 , $-E$, $-2E$. Hence the proposed nine-level multilevel inverter can be formed by cascading operation of two five-level inverters. This produces the nine output voltages as $4E$, $3E$, $2E$, E , 0 , $-E$, $-2E$, $-3E$, $-4E$. Since each of the terminal in the output of the inverter is

connected in series; the output voltage will be obtained by adding the terminal voltages of every inverter [18-20].

Table 2

Switching sequence*										Output voltage (V_o)
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	
0	1	0	0	1	0	1	0	0	1	$4E$
1	0	0	0	1	0	1	0	0	1	$3E$
0	0	0	0	0	0	1	0	0	1	$2E$
0	0	0	0	0	1	0	0	0	1	E
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	1	0	$-E$
0	0	0	0	0	0	0	1	1	0	$-2E$
1	0	0	1	0	0	0	1	1	0	$-3E$
0	0	1	1	0	0	0	1	1	0	$-4E$

*(switch ON = 1, switch OFF = 0)

Modulation technique. The classification of the modulation techniques are shown in Fig. 5. MLI control strategy uses two types of PWM methods. One of them is the high switching frequency and the other is fundamental switching frequency [21].

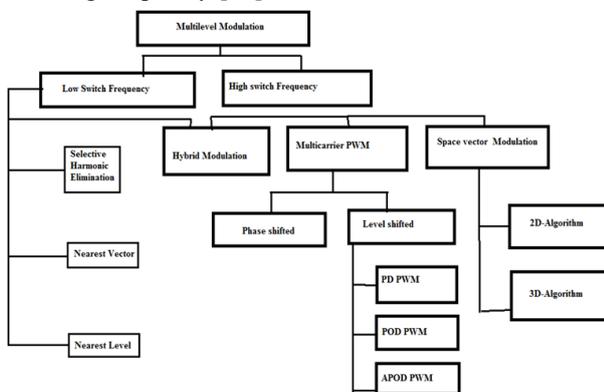


Fig. 5. Classification of multilevel modulation

The categorization of high switching frequency is as follows: space vector PWM, selective harmonics elimination PWM and SPWM [22]. Among these techniques, the popular method is SPWM that is used for most of the multilevel inverters, because of its simplicity and ease of implementation [23].

In this paper multicarrier PWM technique is used. This can be used for three or more than three levels. These are classified into two types namely level shift, and phase shift.

Level shifting PWM. Level shift is again subdivided into phase opposition disposition PWM (POD PWM), alternate phase opposition disposition PWM (APODPWM) and phase disposition PWM (PD PWM) [24, 25].

In this process, all carriers will be in phase with each other and also have the identical magnitude along with the identical frequency. This is done by comparing the reference sinusoidal wave with the vertically shifted carrier wave as shown in Fig. 6. This uses $N-1$ carrier signs to produce the output voltage of the inverter with N -level.

Some of the advantages of PWM based switching power converter over the other techniques and the conventional PWM is the most widely used technique all over the world because of its advantages or because of that its disadvantages do not have that big concern in most of the applications compared with its advantages. Some can be in

its easy to implement and control and in its compatibility with almost all the modern digital applications. However it has also some disadvantages that might reduce its volatility in some applications, such as its attenuation of the fundamental frequency amplitude, its THD is reduced by increasing the switching frequency but that will lead to the increase of switching losses; which means greater stresses on the associated switching devices and creation of high frequency components with high amplitudes.

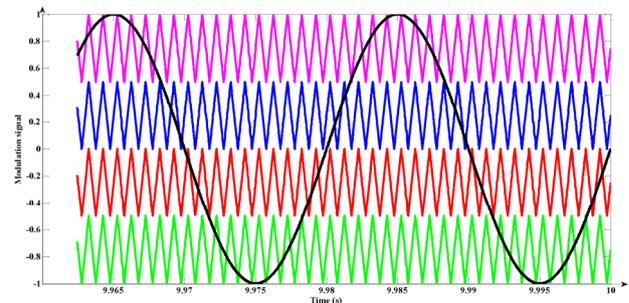


Fig. 6. Multicarrier PWM technique

Simulation results. All this proposed work is verified in MATLAB. The technique of multicarrier modulation is used for pulse generation. The solar panel is connected to the cascaded H-bridge MLI and the results are observed in Simulink. Figures 7, 8 show the PV and V - I characteristics of the solar collector. The output of this solar collector is taken at the temperature of 25°C and at the radiance of 1000 W/m^2 .

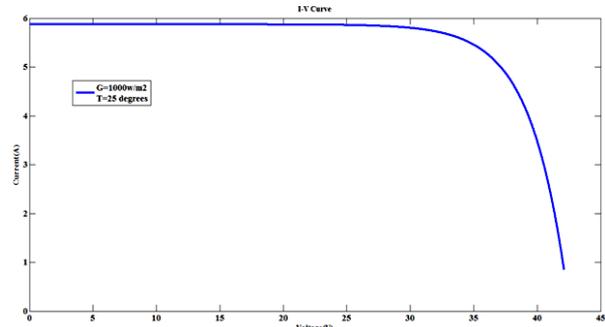


Fig. 7. I - V characteristics of solar panel

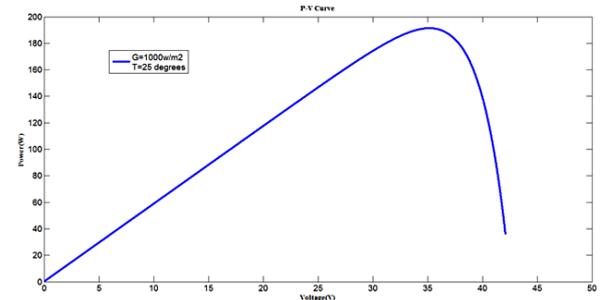


Fig. 8. P - V characteristics of solar panel

Figures 9-12 show the different levels of the output terminal voltage waveform. This concludes that as the modulation index declines the count of levels also declines and the magnitude of the voltage also gets declined as shown in the Table 3. It is also observed that the THD goes on increasing as the count of output voltage levels declines. Hence it is recommended to use a modulation index nearer to unity by which the count of the output levels gets increased.

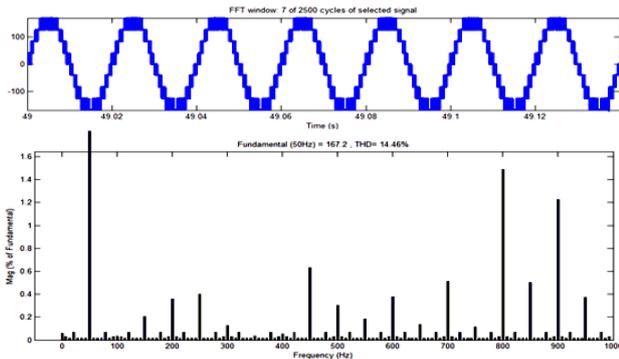


Fig. 9. Nine-level output voltage and FFT analysis of cascaded H-bridge MLI

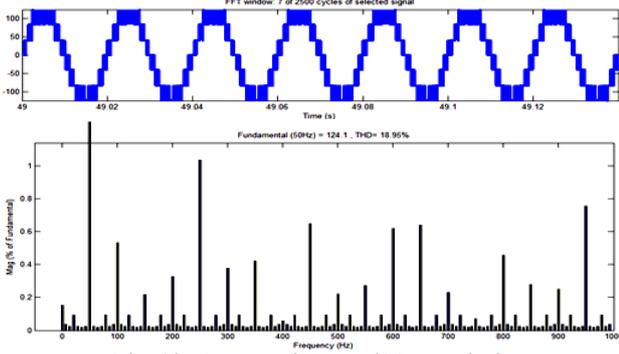


Fig. 10. Output voltage and FFT analysis of cascaded H-bridge MLI at $M=0.75$

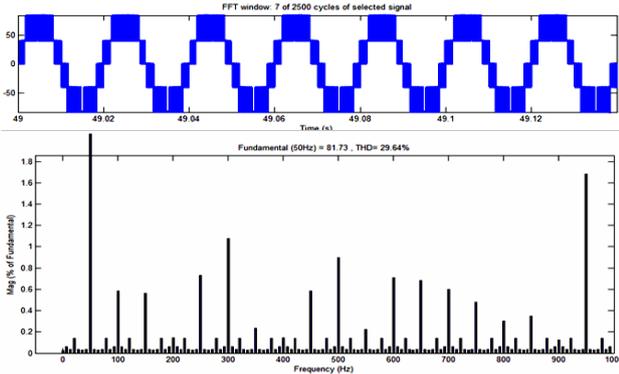


Fig. 11. Output voltage and FFT analysis of cascaded H-bridge MLI at $M=0.5$

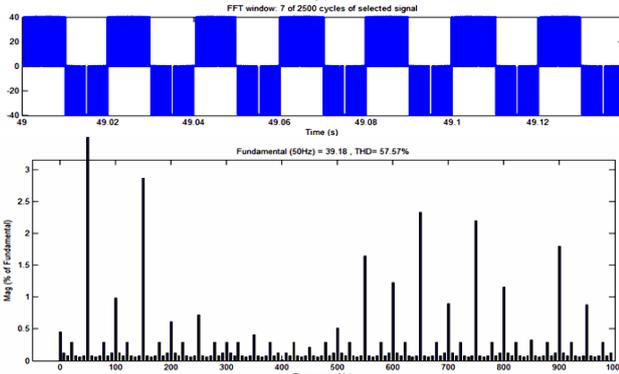


Fig. 12. Output voltage and FFT analysis of cascaded H-bridge MLI at $M=0.25$

Table 3

Variations of THD with various modulation index

Modulation index	Output voltage (V_o)	No. of levels	THD
1	167.2	9	14.46 %
0.75	124.91	7	18.95 %
0.5	81.73	5	29.64 %
0.25	39.18	3	57.57 %

Experimental results. A prototype single phase 9-level CHBM has been built using 12.3 V for each bridge, 1A MOSFET as switching device, firing pulses to the switching devices are given through a delay circuit. The experimental results are represented in Fig. 13-15.

Components which were used:

- Switching device IRF840 MOSFET – 10 pcs;
- Diodes FR107 – 8 pcs;
- DC link capacitors 2200 μ F/35 V – 4 pcs;
- Driver circuit IC for H-bridge IR2110 – 4 pcs;
- Driver circuit IC for bidirectional switch TLP250 – 2 pcs;
- OPTO isolator used for all PWM inputs 6N137 – 10 pcs;
- Buffer circuit used for impedance matching purpose cd4050ic – 3 pcs;
- Isolated +15 V power supply for driver circuits – 4 pcs;
- Power circuit input supply 12/1A DC – 2 pcs.

FPGA SPARTAN6 will be used to generate the gate signals for all switching devices miscellaneous items etc.

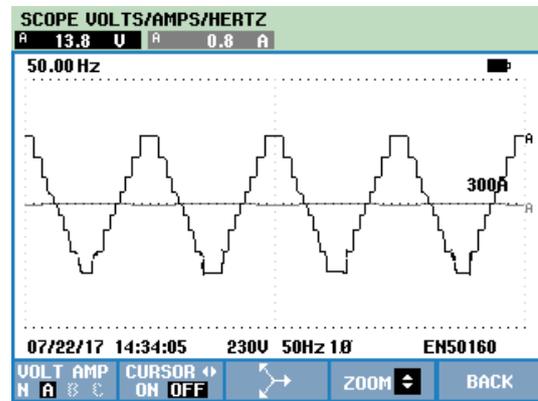


Fig. 13. 9-level output voltages

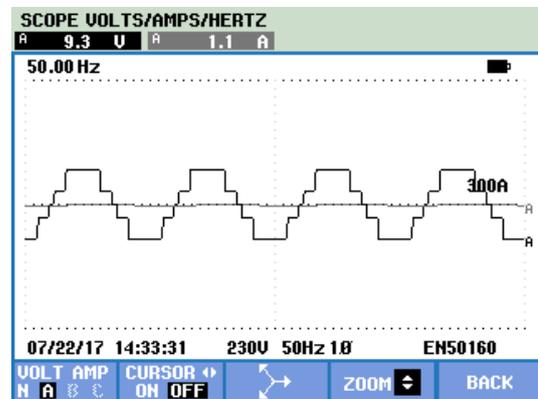


Fig. 14. Output of first H-bridge

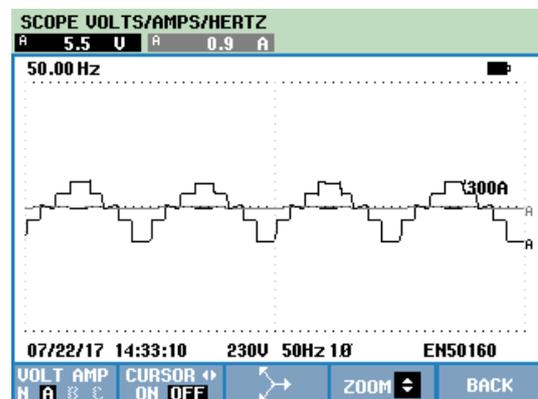


Fig. 15. Output of second H-bridge

In the Table 4 the practical values along with the simulated values are compared and the THD values are shown.

Table 4

Comparison of THD, %		
H-bridge	THD (practical)	THD (simulated)
Nine-level	13.8 %	14.4 %

Other MLIs are not capable of producing higher level of output voltage due to increase in switch, number of DC sources and cost; however CMLI is capable of producing higher level voltage with qualitative waveform by using less number of switches. THD content in experimental and in simulation is 13.8 % and 14.4 %, which indicate that the output waveform is nearly sinusoidal. Thus the proposed topology for MLI shows some encouraging attributes when compared to traditional topologies. The keen observation between the experimental and simulation is that the THD is less in the experiment point of view when compared to the simulation.

Conclusions. This undertaking deal with the outline and execution implementation of single-phase nine-level cascaded H-bridge multilevel inverter for R load with multicarrier level-shifted pulse width modulation method fed with solar panel. The proposed work has benefits like less count of the switches, less electromagnetic interference, lower harmonic distortion and the total harmonic distortion obtained in this work is 14.4 %. The forthcoming work of this topography can be enlarged by connecting it to the grid. The equivalent multilevel inverter topography can be used for the hybrid grid which uses the integration of DC and AC sources like solar, wind, batteries, AC loads. It can also be used for hybrid microgrid i.e., in the case of interlinking converters which is bidirectional.

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

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