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Five-Level Switched Capacitor Inverter for Photovoltaic Applications

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ABSTRACT

This paper proposes a switched-capacitor based single-phase five-level inverter configuration that operates under boost operation and generates a voltage that is more than the DC source voltage. The proposed five-level inverter uses a capacitor and boots the output voltage. In this proposed inverter, capacitor gets charged in parallel while it discharges in series connections so that output voltage may attain higher magnitude than the DC source voltage. Sinusoidal Pulse Width Modulation-based techniques are considered to produce the required gate pulses for operating the switching devices of the inverter. The five-level switched-capacitor inverter is combined with the PV system via DC–DC boost converters to extract the maximum power using MPPT algorithm. To verify its capability, the PV-based system is further integrated to the utility grid. The operation and performance of the suggested switched-capacitor inverter coupled with the grid-connected PV system are also analyzed by developing its model in MATLAB/Simulink environment.

KEYWORDS

DC–DC converter; MPPT; Multi-level inverter; Photovoltaic application; SPWM; Switched capacitor

1. INTRODUCTION

Power electronic converters are getting evolved due to technological advancement in the design of power electronic devices as well as increase in its demand for more applications. The growth in demand for inverters has been observed because due to its application in the renewable energy source. The lesser costs of modern power electronics components make them useful for manufacturing and helping them to compete in the market. However, multi-level inverters use more switches; it is still economical to replace two-level inverters with MLIs because of several benefits such as lesser harmonic content, switching stress, and power losses [1–3]. Many scholars have paid attention to improve inverter topologies and their control methods. The lesser number of power electronics components used in multilevel inverters can further reduce the manufacturing cost [4–6]. The Cascaded H-bridge (CHB) inverter [7] and Neutral Point Clamped (NPC) inverter [8,9] are two standard multilevel inverters and having several industrial applications such as EV/HEV, HVDC, renewable energy sources, high-power motor drives, FACTs, STATCOM [10,11]. Several three-phase and single-phase MLI topologies of high voltage and medium power have been implemented for different applications [12,13]. A five-level inverter using two diodes, six switches, and two capacitors is proposed in [14]. Though it has fewer switches, it requires diodes and a complex control algorithm to balance and capacitor voltage. The inverter topology discussed in [15] and [16] has similarities, as they are based on a switched capacitor cell and generates nine violate levels in the output. The five-level inverter using four diodes, seven switches, and two capacitors is suggested in [17], which has a complex design, as well as control, to get the balanced output. Two similar variants of inverter configuration are proposed in [18,19]. This inverter requires two and six isolated dc sources for single and three-phase configuration, respectively [18]. This inverter configuration can produce five-level output voltage and employs one capacitor and one dc source. The three-phase configuration of this inverter is also proposed.

Many countries have begun to use solar power to fulfill their energy requirements. Renewable energy sources require the power electronic inverters to transmit AC power to loads and grids. In several papers, the reduction of environmental emissions by improving the performance and reducing power losses of grid-connected inverters are listed [20–24]. Single-phase multi-level inverter can play a crucial role in transforming the Photo-Voltaic (PV) system's dc voltage into a smooth ac waveform that can be used by loads and transmitted to grids using much smaller harmonic filters [25–27]. A seven-level PUC inverter using a limited number of components has been proposed in [28,29]. In PUC inverter, the maximum generated output voltage will be equal to the overall voltage of the dc sources.

In this paper, a switched-capacitor based single-phase five-level inverter is suggested. It is having the ability to attain the output voltage equal to two times the input DC voltage. The proposed topology of the switched-capacitor based inverter generates five-level output voltages using only one condenser, only one dc source, and eight switching devices. The inverter is mentioned as a five level switched-capacitor inverter and that is systemically inspected and analyzed in this article. In Section 2, the working of the proposed five levels switched-capacitor inverter and evaluation of capacitance is explained. In Section 3, implementation of modulation technique for five-level inverter is briefly explained. Section 4 explains the application of the proposed inverter for grid connection PV system. In Section 5, the simulation results of the proposed topology of the five-level inverter coupled with utility grid and PV panel are addressed. Section 6 presents the conclusion.

2. FIVE-LEVEL SWITCHED CAPACITOR INVERTER

The switched-capacitor based five-level inverter topology, which can generate maximum output voltage equal to twice the magnitude of the input DC source voltage, is shown in Figure 1.

The proposed five level inverter topology consists of eight power electronics switches, a DC source, and a capacitor.

Table 1 represents the six efficient switching states of the proposed inverter to achieve the five levels in the voltage output.

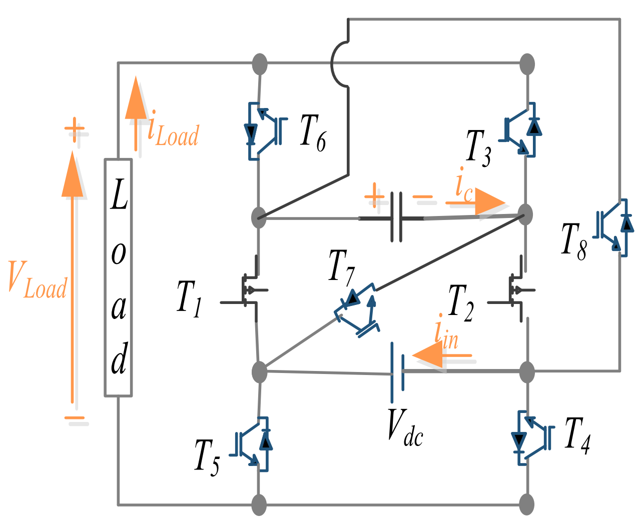

Figure 1: Proposed configuration of the five-level switched-capacitor inverter.

Table 1: Switching status for the proposed inverter

Mode	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	Output
1	1	1	1	1	0	0	0	0	0
2	1	1	0	1	0	1	0	0	V_{dc}
3	0	0	0	1	0	1	1	0	$2V_{dc}$
4	1	1	0	0	1	1	0	0	0
5	1	1	1	0	1	0	0	0	$-V_{dc}$
6	0	0	1	0	1	1	0	1	$-2V_{dc}$

2.1 Modes of Operation for the Inverter

The proposed inverter is operating in six valid operating modes to generate five levels in the output voltage as presented in Figure 2.

(A) *Mode 1:* Under this mode, the inverter will have zero output voltage and the switching status is presented in Figure 2(a). Charging of capacitor happens in this mode, and a strong inrush current may be drawn if the capacitor voltage is zero. The power electronics switching devices T_5, T_6, T_7, and T_8 are OFF, whereas remaining switching devices T_1, T_2, T_3, and T_4 are ON. The capacitor is getting charged from the input dc source and its steady-state voltage may reach up to the voltage magnitude of the DC source.

(B) *Mode 2:* It is noticed from Figure 2(b) that the DC source voltage (V_{dc}) is being applied across the load under this mode of inverter operation. The T_1, T_2, T_4, and T_6 switches are ON and other power electronics switches are in OFF state. The capacitor inside inverter is also charging from the input DC source voltage.

(C) *Mode 3:* As in Figure 2(c), the voltage produced by the inverter may become identical to double the magnitude of the input DC source ($2V_{dc}$). The switches T_4, T_6, and T_7 are ON, while the other switches are OFF in this mode.

(D) *Mode 4:* As in Figure 2(d), the inverter generates zero voltage at the output while the capacitor connected to the input DC source through T_1 and T_2 switches is getting charged. Only T_1, T_2, T_5 and T_6 switches are ON while other switches are OFF.

(E) *Mode 5:* As in Figure 2(e), the output voltage generated by the inverter under this mode is having negative polarity and the magnitude is same as the DC source voltage (V_{dc}). The T_1, T_2, T_3, and T_5 switches are ON, while T_4, T_6, T_7, and T_8 switches remain OFF. The capacitor under this mode is getting charged from the DC voltage source. The steady-state voltage of the capacitor may reach up to the voltage magnitude of DC source.

(F) *Mode 6:* As in Figure 2(f), the inverter produces output voltage of negative polarity and its magnitude can become twice the input DC source voltage

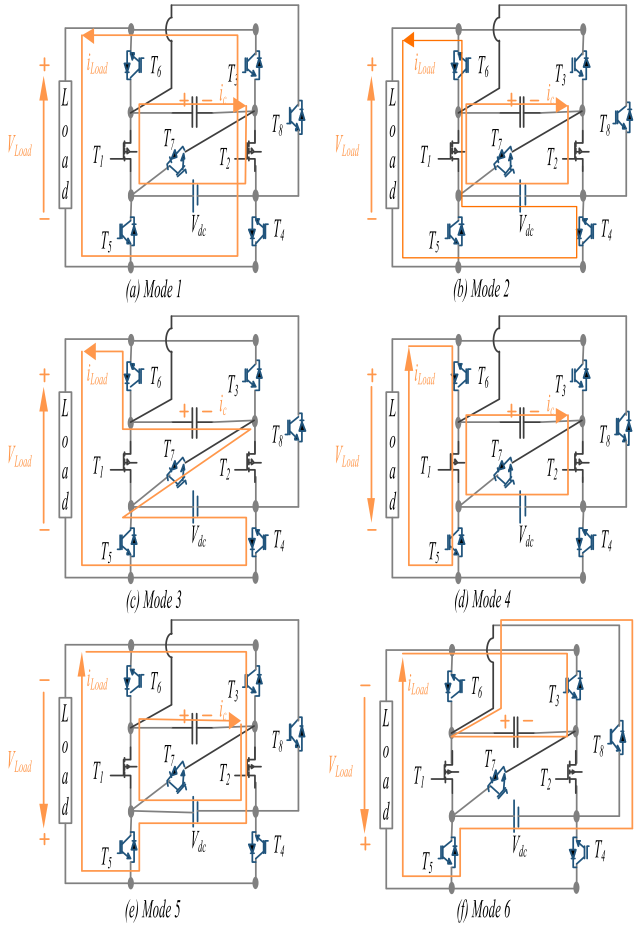

Figure 2: Different modes of operation for the switched-capacitor five-level inverter.

($2V_{dc}$). The T_3, T_5 and T_8 switches are ON, while the others are OFF.

2.2 Design of Capacitor

The selection of capacitor of proper rating is very important to ensure the least ripple in the output voltage; in the absence of this, an asymmetry in the waveform of the output voltage may appear. In mode 2 and mode 4, the dc source is only connected to the capacitor and it is getting charged up to the magnitude of DC source voltage as shown in Figure 2(a), and (d). The voltage (V_c) and current associated with the capacitor (i_c) can be expressed as follows:

$$V_c = V_{dc} \tag{1}$$

$$i_c = i_{in} \tag{2}$$

In mode 2 and mode 5, the capacitor and load are in parallel as shown in Figure 2(b) and (e). The capacitor is still in charging mode. Now the equation of capacitor voltage

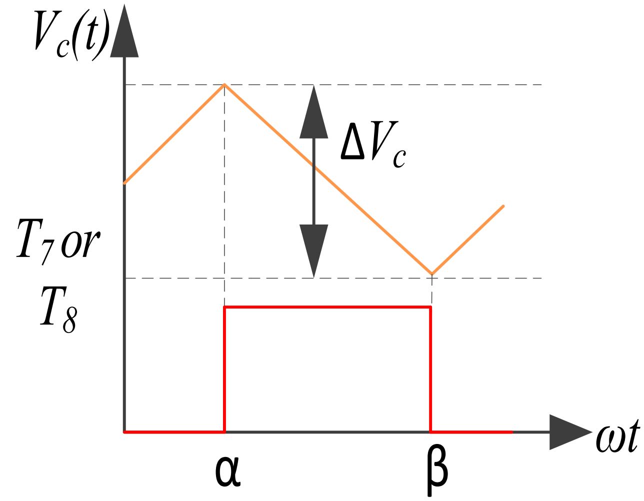

Figure 3: Ripple voltage of the capacitor.

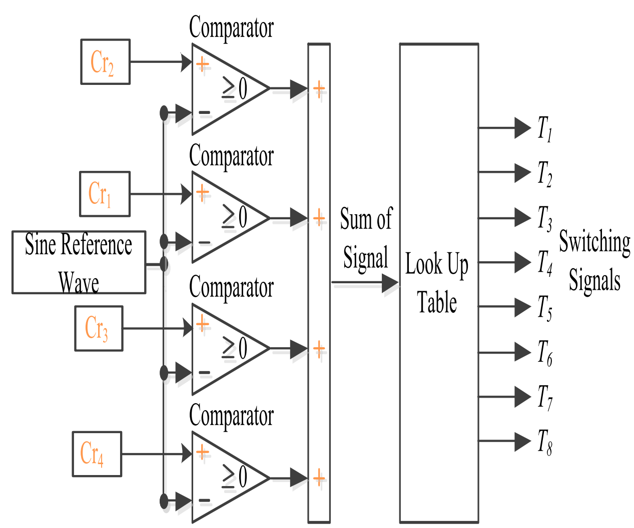

Figure 4: Switching signal generation for the recommended five-level inverter.

and current in these modes are as follows:

$$V_c = V_{dc} \tag{3}$$

$$i_c = i_{in} - i_{load} \tag{4}$$

According to Figure 2(c) and (d), the capacitor is in series with the load. The capacitor is discharging in both modes 3 and 6, and the expression for the current through the capacitor and voltage across it is as follows:

$$V_c = V_o - V_{dc} \tag{5}$$

$$i_c = -i_{in} \tag{6}$$

The ripple in the capacitor voltage is presented in Figure 3.

Table 2: Voltage and current rating of switches

Switch	Voltage rating	Current rating
T_1	V_{dc}	I_{in}
T_2	V_{dc}	I_{in}
T_3	V_{dc}	I_{in}
T_4	V_{dc}	I_{in}
T_5	V_{dc}	I_{in}
T_6	V_{dc}	I_{in}
T_7	V_C+V_{dc}	I_{in}
T_8	V_C+V_{dc}	I_{in}

The capacitor is discharging only when the inverter output voltage is $\pm V_c + V_{dc}$ and switches T_7 or T_8 remains ON. The change in the amount of stored charge during continuous discharging angle of α to β is:

$$\Delta Q = \int_{\alpha}^{\beta} \left(\frac{i(t)}{\omega}\right) d(\omega t) \tag{7}$$

Here, i (t) is the load current.

From Equation (7), the ripple in capacitor voltage can be evaluated as

$$\Delta V_{ripple} = \int_{\alpha}^{\beta} \left(\frac{i(t)}{\omega C}\right) d(\omega t) \tag{8}$$

From (7) and (8), the minimum value of the capacitance (C_{min}) can be derived as

$$C_{\min} = \int_{\alpha}^{\beta} \left(\frac{i(t)}{\omega \Delta V_{ripple}}\right) d(\omega t) \tag{9}$$

The current and voltage rating of switches are mentioned in Table 2. The voltage rating of switches T_7 and T_8 are higher than other switches and same as inverter voltage rating. While the rating of other switches will depend on DC source voltage.

3. MODULATION TECHNIQUE

The pulse width modulation is broadly used at a specified switching frequency to operate the switching devices of power converters. The pulse pattern produced under the SPWM technique gives lesser Total Harmonics Distortion (THD) content in the output of the inverter at a higher modulation index. In addition, the capacitor ripple voltage, output current ripple, and switching losses can be reduced with the implementation of suitable modulation schemes. On the basis of carrier management, multi-carrier SPWM method is classified as (i) Phase Shifted-Pulse Width Modulation (PS-PWM) and (ii) Level Shifted-Pulse Width Modulation (LS-PWM). In this paper, LS-PWM is considered implemented for the suggested five-level switched-capacitor inverter. To obtain the gate pulses for the switching devices of the n-level single-phase inverter, a reference signal is systematically compared with $n-1$ number of triangular carrier waves [30]. The basic representation of LS-PWM for producing switching signals for the switches of five-level inverter is shown in Figure 4.

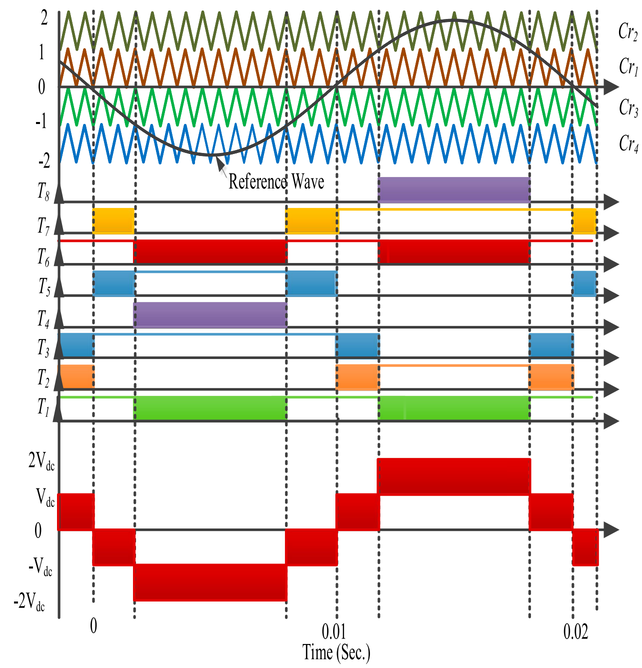

Figure 5: Typical waveforms of the SC-MLI with LS-PWM.

Four carrier waves and a sinusoidal reference signal are employed for the suggested five-level inverter configuration. The LS-PWM method for the proposed five levels inverter is shown in Figure 5.

For the five-level inverter, four carrier waves (Cr_1, Cr_2, Cr_3 and Cr_4) and the reference signal are used. All carrier signals have same magnitude and frequency but have different dc offset. The evaluated switching pulses for switches (T_1 to T_8) based on Table 1 and the output voltage waveform of the proposed switched capacitor five-level inverter is represented in Figure 5.

4. PHOTOVOLTAIC APPLICATIONS OF THE SUGGESTED INVERTER

The suggested five-level switched-capacitor MLI is recommended for the application in renewable energy. The output of PV arrays is fed to boost converters so that the maximum power could be efficiently extracted and delivered to the load. In this regard, a perturb and observe (P&O) based MPPT algorithm is considered to manipulate the duty cycle of the boost converter for the purpose of drawing maximum power from the PV source [31–33].

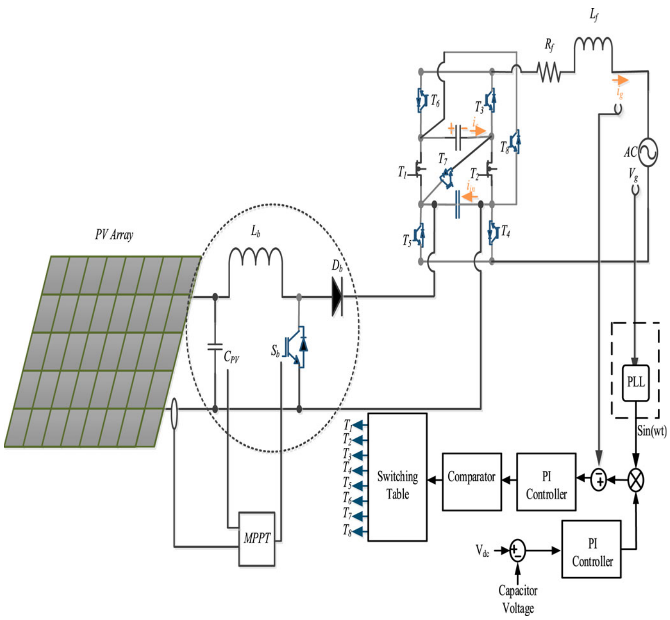

Figure 6: Schematic diagram of the recommended switched-capacitor inverter-based grid-connected PV system with recommended controller.

Table 3: Specifications of the PV array and device parameters

Array type	1Soltech 1STH-215-*P*
Maximum output power (P_{max})	100 kW
Output voltage at P_{max}	290 V
Output current at P_{max}	300 A
Grid Frequency	50 Hz
Boost converter inductor	1.45 mH
Boost converter capacitor	3227 μF
Current ripple	4%
Voltage ripple	1%
Converter switching frequency	5 kHz
Inverter switching frequency	3 kHz

The proposed inverter is connected to the output terminal of boost converter to transform the upscaled DC input voltage to required AC output power for operating AC loads or transferring to the grid. The complete PV system can be operated in islanding mode feeding local loads or in grid-connected to provide extra power. Figure 6 represents the schematic diagram of a five-level switched capacitor inverter-based grid-connected PV system.

5. SIMULATION RESULTS

The Simulink model of the grid-tied PV system is designed in MATLAB/Simulink software to investigate the performance of the recommended five levels switched-capacitor inverter.

The 1Soltech 1STH-215-P PV module is considered for designing the required PV array. The short circuit current

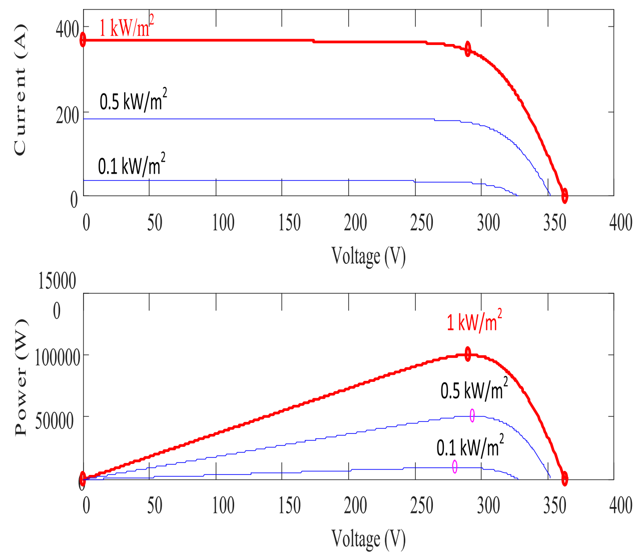

Figure 7: Electrical characteristics of 100 kW PV arrays (1Soltech 1STH-215-P).

(I_{sc}) and open-circuit voltage (V_{oc}) of the considered PV module are 7.84 A and 36.30 V, respectively. PV modules are joined together in series to form one string and one string contains ten number of these modules. Forty-seven such strings are further combined in parallel to design the PV array of 290 V and 100 kW. The electrical specification of the PV array and required parameters of the designed boost converter are represented in Table 3. The electrical characteristics of the PV array at 1000 W/m^2, 500 and 100 kW/m^2 are obtained from the simulated model and shown in Figure 7.

The output voltage of PV array is upscaled from 290 to 450 V using boost converter. The boost converter for the output voltage of 450 V with 4% current ripple and 1% voltage ripple with switching frequency of 5 kHz is designed. The optimum parameters for designing the boost converter are found using fundamental equations and enlisted in Table 3. The P&O-based MPPT algorithm is implemented and the steady-state duty cycle ratio is approximately 33.33%. The carrier frequency for the proposed inverter is considered as 3 kHz to minimize the capacitor voltage ripple and harmonics existing in the output voltage of the inverter. Hence size of the filter inductor gets reduced.

The output of the inverter changes with the variation of the irradiance while maintaining same number of voltage levels in the output. To analyze the efficacy of the recommended inverter, the modulation index is varied in stages, as represented in Figure 8. The output voltage levels of the inverter are found varying from five levels to three levels, with the variation in the modulation

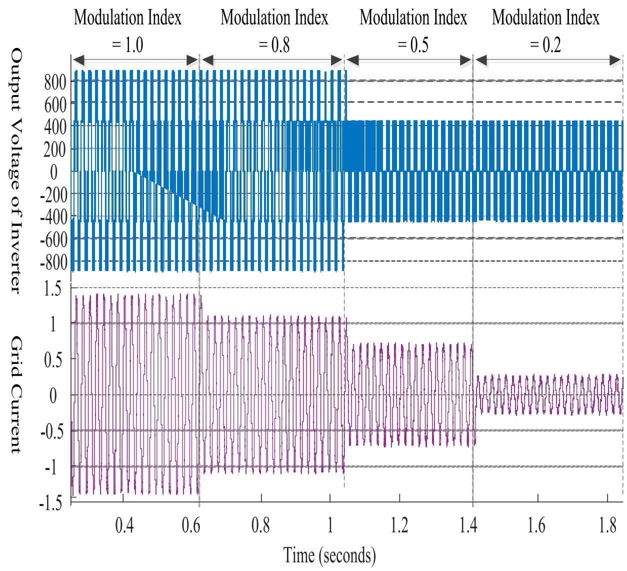

Figure 8: Output voltage and current waveform of the proposed inverter at different modulation indices.

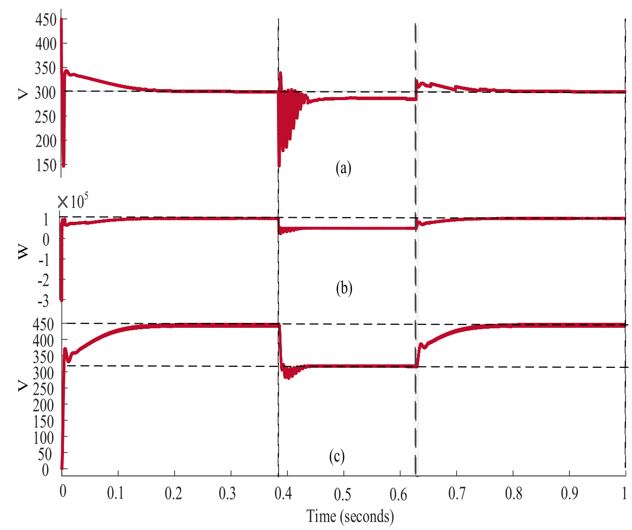

Figure 9: V_{pv}, power of PV array, and output voltage of boost converter operating at MPP.

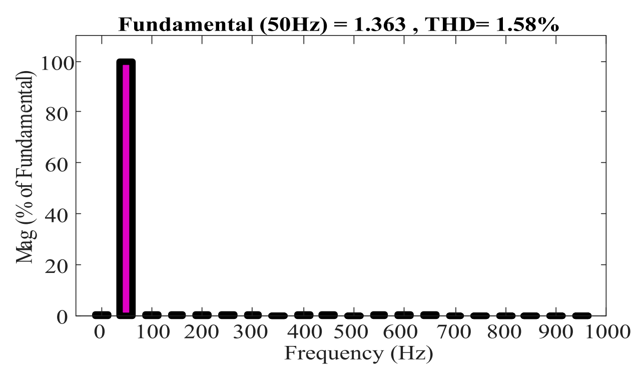

Figure 10: Harmonic spectrum for the inverter-injected grid current.

index from 1 to 0.2. The magnitude of output current is also declining with the modulation index as shown in Figure 8.

The performance of the recommended five-level swit ched-capacitor inverter for the application in grid-connected PV system is studied under varying irradiance conditions. The irradiation at 25°C is taken down from 1000to 500 W/m^2 at 385 ms and after settling down to the steady state it is again brought back from 500 to 10,000 kW/m^2 at 630 ms. The output voltage generated by the PV source is varying according to the irradiance as shown in Figure 9(a). The steady-state output voltage of the PV array is 290 V at irradiance of 1000 W/m^2. The variation in maximum power extracted by the boost converter from the PV array is also observed with respect to irradiance as represented in Figure 9(b). It is detected that, with the variation in irradiance from 1 to 500 kW/m^2, the output power of the PV array at 25°C changes from 100 to 50 kW. The voltage output of the boost converter also shifts from 450 to 320 V with a change in irradiance, as shown in Figure 9(c).

It is observed from the Simulink model of the proposed PV-based grid-tied system that the boost converter is delivering output power of nearly 99.6 kW for the input power of 100 kW at irradiation of 1000 W/m^2. Hence, the boost converter efficiency is about 99.6%.

The harmonic spectrum for the grid current at 1000 W/m^2 is captured and represented in Figure 10. The THD observed in the grid current is 1.58% which is lesser than the IEEE STD limit of 5% harmonic.

6. CONCLUSION

The proposed five-level switched-capacitor inverter topo logy for the PV application has been investigated in this paper. The developed single-phase switched-capacitor based inverter configuration consists of eight switching devices, only one DC source and one switched-capacitor. The inverter can produce five levels output voltage and the maximum amplitude can be twice the magnitude of DC voltage source. Moreover, it is also noticed that the charging as well as discharging of the switched-capacitor in the proposed multilevel inverter topology is symmetrical for both polarities of the output. Hence, the issue of capacitor voltage balancing is solved by using the switched capacitor of the suggested rating. The model of the recommended inverter-based grid-tied PV system is established in MATLAB/ Simulink environment and the performance of inverter under different modulation indexes is found satisfactory. The effectiveness of a grid-tied system was also investigated under different irradiance. Hence it can be resolved from the analysis that the proposed inverter is proficient for the application of a grid-tide PV system.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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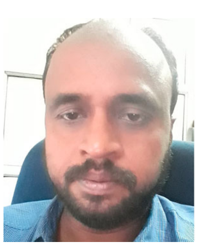

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