NON-CONVENTIONAL POWER GENERATION SYSTEM SIMULATION BY USING MULTILEVEL INVERTERS

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Abstract: This paper presents comparison between modified five level and nine level inverters for an efficient renewable power generation system. A multi-level inverter is developed and applied for injecting the real power of the renewable power into the grid to reduce the switching power loss, harmonic distortion, and electromagnetic interference caused by the switching operation of power electronic devices. Here a dual buck configuration with full bridge inverter is used for the MLI implementation. The input of the dual-buck converter is dc capacitor voltage sources. The output voltage of the dual-buck converter supplies to the full-bridge inverter. The power electronic switches of the full-bridge inverter are switched in low frequency synchronous with the utility voltage to convert the output voltage of the dual-buck converter to a multi-level ac voltage. The output current of the multi-level inverter is controlled to generate a sinusoidal current in phase with the utility voltage to inject into the grid. Five level and nine level topologies are developed to verify the performance of the developed renewable power generation system. The results of MATLAB modeling of the system detail the comparative operation of inverter topologies which are conventional five level inverter and nine level inverter topology to reduce total harmonic distortions in grid voltage and electromagnetic interference. The proposed control scheme to mitigate the power quality issues for power quality improvement in grid integrated DER simulated using MATLAB/ SIMULINK in power system block set.

Keywords: Boost Converter, Multi Level Inverter (MLIS), Total Harmonic Distortions (THD), Voltage Sources Inverter (VSI).

I. INTRODUCTION

In recent years, there has been an increasing interest in electrical power generation from renewable-energy sources, such as photovoltaic (PV) or wind-power systems [1], [2]. The benefits of power generation from these sources are widely accepted. They are essentially inexhaustible and environmentally friendly. Among the different renewable-energy sources possible to obtain electricity, solar energy has been one of the most active research areas in the past decades, both for grid-connected and stand-alone applications [3]–[7]. The exponential rate of growth in the worldwide cumulative PV capacity is mainly due to enhancement in grid-connected inverter topologies. The PV array and the battery are connected to the AC grid via a common DC/AC inverter. AC output voltage is created by switching the full bridge in an appropriate sequence .The inverter topologies can be divided with two types, that are single and multi stage inverter. The single stage inverter has advantage such as low cost, high efficiency, robust performance, high reliability and simple structure. On the other hand, the multi stage inverter accept a wide range of input voltage variations, high cost, low efficiency, complicated structured and isolated topologies with high frequency transformers can extract power from the source even when DC voltage is very low present the comparison of expense of power semiconductors and passive components of a (2.3 kV, 2.4 MVA) 2-level, 3-level NPC, three-level flying capacitor, four-level flying-capacitor, and five-level series connected H-bridge voltage source converter on the basis of the state-of-the-art insulated gate bipolar transistors for industrial medium-voltage drives. And illustrate that in three level inverter topology net total harmonics distortion is reduced in the output wave form without decreasing in inverter output power .

The conventional single-phase inverter topologies for grid connection include half-bridge and full bridge [1]–[4]. The half-bridge inverter is configured by one capacitor arm and one power electronic arm. The dc bus voltage of the half-bridge inverter must be higher than double of the peak voltage of the output ac voltage. The output ac voltage of the half-bridge inverter is two levels. The voltage jump of each switching is the dc bus voltage of the inverter. The full-bridge inverter is configured by two power electronic arms. The popular modulation strategies for the full-bridge inverter are bipolar modulation and uni-polar modulation [3], [5]. The dc bus voltage of the full-bridge inverter must be higher than the peak voltage of the output ac voltage. The output ac voltage of the full-bridge inverter is two levels if the bipolar modulation is used and three levels if the unipolar modulation is used. The voltage jump of each switching is double the dc bus voltage of the inverter if the bi-polar modulation is used, and it is the dc bus voltage of the inverter if the uni polar modulation is used. All power electronic switches operate in high switching frequency in both half-bridge and full bridge inverters.

The switching operation will result in switching loss. The loss of power electronic switch includes the switching loss and the conduction loss. The conduction loss depends on the handling power of power electronic switch. The switching loss is proportional to the switching frequency, voltage jump of each switching, and the current of the power electronic switches. The power efficiency can be advanced if the switching loss of the dc–ac inverter is reduced. Multilevel inverter can effectively reduce the voltage jump of each switching operation to reduce the switching loss and increase power efficiency. The number of power electronics witches used in the multilevel inverter is larger than that used in the conventional half-bridge and full-bridge inverters. Moreover, its control circuit is more complicated. Thus, both the performance and complexity should be considered in designing the multilevel inverter. However, interest in the multilevel inverter has been aroused due to its advantages of better power efficiency, lower switching harmonics, and a smaller filter inductor compared with the conventional half-bridge and full-bridge inverters.

II. CIRCUIT IMPLEMENTATION

Five-level inverter applied to a photovoltaic power generation system is shown Fig.1 As can be seen, it is configured by a solar cell array, a dc–dc converter, a five-level inverter, two switches, and a controller. Switches SW_1 and SW_2 are placed between the five-level inverter and the utility, and they are used to disconnect the photovoltaic power generation system from the utility when islanding operation occurs. The load is placed between switches SW_1 and SW_2. The output of the solar cell array is connected to the input port of the dc–dc converter. The output port of the dc–dc converter is connected to the five-level inverter. The dc–dc converter is a boost converter, and it performs the functions of maximum power point tracking (MPPT) and boosting the output voltage of the solar cell array. This five-level inverter is configured by two dc capacitors, a dual buck converter, a full-bridge inverter, and a filter. The dual-buck converter is configured by two buck converters. The two dc capacitors perform as energy buffers between the dc–dc converter and the five-level inverter. The output of the dual-buck converter is connected to the full-bridge inverter to convert the dc voltage to ac voltage. An inductor is placed at the output of the full bridge inverter to form as a filter inductor for filtering out the high-frequency switching harmonic generated by the dual-buck converter

III. FIVE LEVEL INVERTER

The dc capacitor voltages V_{C2} and V_{C3} are balanced by controlling the five-level inverter, the dc capacitor voltages V_{C2} and V_{C3} can be

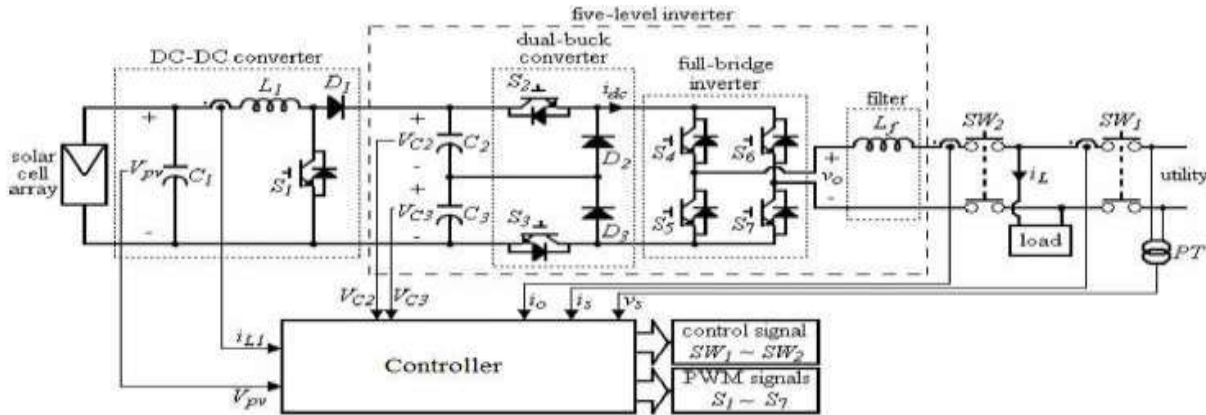$$V_{C2} = V_{C3} = \frac{1}{2} V_{dc}$$

represented as follows:

Fig.1. Circuit configuration of the developed photovoltaic power generation system with MLI.

The operation of power electronic switches S_2 and S_3 should guarantee the output voltage of the dual-buck converter is higher than the absolute of the utility voltage. The waveforms of output voltage of five-level inverter and utility voltage are shown in Fig. 2.
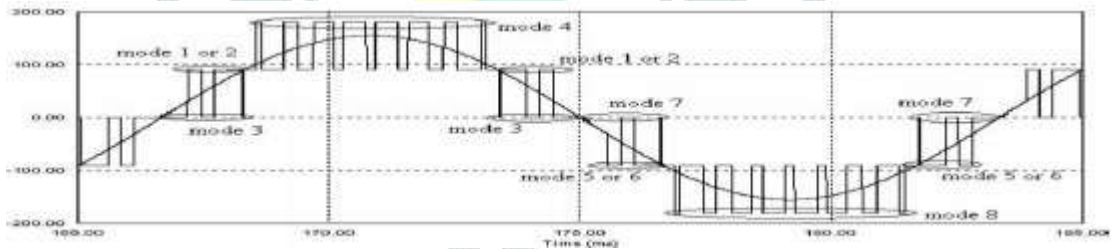

Fig. 2. Waveforms of output voltage and utility voltage

IV. FIVE-LEVEL INVERTER VOLTAGE BALANCING TECHNIQUE

Balancing the voltages of dc capacitors is very important in controlling the multilevel inverter. The voltage balance of DC capacitor voltages V_{C2} and V_{C3} can be controlled by the power electronic switches S_2 and S_3 easily. When the absolute of the utility voltage is smaller than $V_{dc/2}$, one power electronic switch either S_2 or S_3 is switched in high frequency and the other is still in the OFF state. Which power electronic switch is switched in high frequency depends on the dc capacitor voltages V_{C2} and V_{C3}. If dc capacitor voltage V_{C2} is higher than dc capacitor voltage V_{C3}, power electronic switch S_2 is switched in high frequency. In this situation, the voltage source V_{Cx} in Fig. 3(a) is V_{C2}, and C_2 will be discharged. Thus, the dc capacitor voltages V_{C2} decreases and V_{C3} does not change. On the contrary, power electronic switch S_3 is switched in high frequency when voltage V_{C3} is higher than voltage V_{C2}. In this situation, the voltage source V_{Cx} in Fig. 3(a) is V_{C3}. Thus, the dc capacitor voltages $VC3$ decreases and V_{C2} does not change. In this way, the voltage balance of C_2 and C_3 can be achieved.
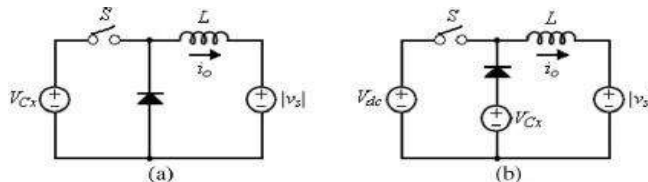

Fig. 3. Equivalent circuit. (a) |vs |< Vdc /2. (b) |vs |> Vdc /2.

When the absolute of the utility voltage is higher than $V_{dc/2}$, one power electronic switch either S_2 or S_3 is switched inhigh frequency and the other is still in the ON state. Which power electronic switch is switched in high frequency depends on thedc capacitor voltages V_{C2} and V_{C3}. If dc capacitor voltage V_{C2} is higher than dc capacitor voltage V_{C3}, the power electronic switch S_3 is switched in high frequency. The voltage source V_{Cx} in Fig. 3(b) is dc capacitor voltage V_{C2}. When the power electronic switch$S3$ is turned ON, both C_2 and C_3 are discharged. However, only C_2 supplies the power when the power electronic switchS_3 is turned OFF. Thus, C_2 will discharge more power than that of C_3. On the contrary, the power electronic switch S_2 is switched in high frequency when dc capacitor voltage V_{C3} is higher than dc capacitor voltage V_{C2}. The voltage source V_{Cx} in Fig. 3(b) is dc capacitor voltage V_{C3}. When the power electronic switch S_2 is turned ON, both C_2 and C_3 are discharged. However, only C_3 supplies the power when the power electronic switch S_2 is turned OFF. Thus, C_3 will discharge more power than that of C_2. In this way, the voltage balance of C_2 and C_3 can be achieved.

TABLE I: On/Off State Of S_2 and S_3

		$|v_x| < V_{dc}/2$	$|v_x| > V_{dc}/2$
$V_{c2} > V_{c3}$	S_2	PWM	On
	S_3	Off	PWM
$V_{c2} < V_{c3}$	S_2	Off	PWM
	S_3	PWM	on

As mentioned earlier, the operation of power electronics witches S_2 and S_3 can be summarized as Table I. The voltages of capacitors C_2 and C_3 can be easily balanced compared with the conventional multilevel inverter.

V. CONTROLLING SCHEME

The developed photovoltaic power generation system consists of a dc–dc power converter and the five-level inverter. The five-level inverter performs the functions of converting the dc power into high-quality ac power and injecting it into the utility, balancing two dc capacitor voltages V_{C2} and V_{C3} , and detecting the islanding operation. The dc–dc converter boosts the output voltage of the solar cell array and performs the MPPT to extract the maximum output power of the solar cell array. The controllers of both the dc–dc converter and the five-level inverter are explained as follows.

A.   Five-Level Inverter

Fig. 4 shows the control block diagram of five-level inverter. In the operation of the five-level inverter, the dc bus voltage must be regulated to be larger than the peak voltage of the utility and the dc capacitor voltages of C_2 and C_3 must be controlled to be equal. Besides, the five-level inverter must generate a sinusoidal current in phase with the utility voltage to be injected into the utility. As seen in Fig. 4, the voltages of dc capacitors C_2 and $C_3$are detected and then added to obtain a dc bus voltage V_{dc}. The added result is subtracted from a dc bus setting voltage V_{dc} set. The dc bus setting voltage V_{dc} set is larger than the peak voltage of the utility. The subtracted result is sent to a P-I controller. An islanding detection is also incorporated into the control of the five-level inverter. The concept of this islanding detection was proposed by authors [23]. However, it will not be addressed in this paper. As seen in Fig. 6, the utility current is detected and sent to an RMS detection circuit. The output of the RMS detection circuit is sent to a hysteresis comparator that contains a low threshold value and a high threshold value.
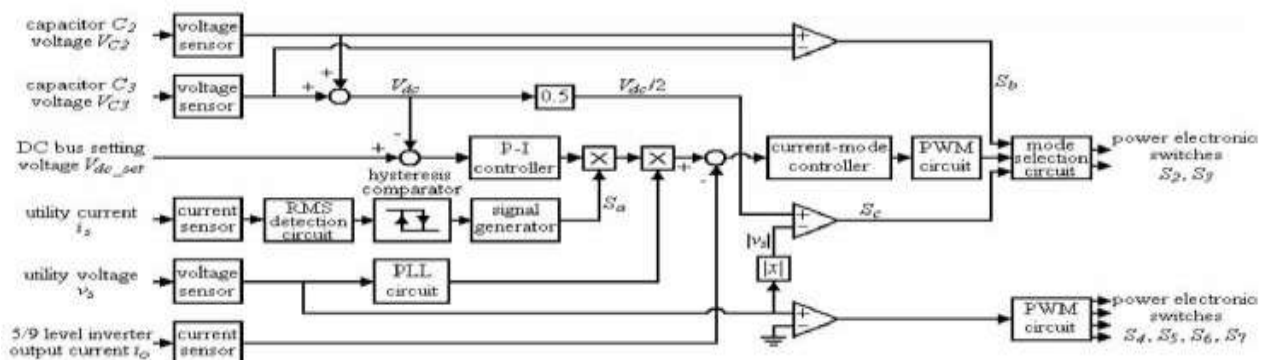

Fig. 4. Control block diagram of five/nine-level inverter.

The islanding control signal is a dc signal with unity amplitude if the output of the hysteresis comparator is low. On the contrary, the islanding control signal is a square wave with a frequency of 20 Hz (disturbance signal for islanding detection) when the output of the hysteresis comparator is high. The outputs of the PI controller and signal generator are sent to a multiplier, and the product of the multiplier is the amplitude of the reference signal. The utility voltage is detected and then sent to a phase-lock loop (PLL) circuit to generate an unity-amplitude sinusoidal signal whose phase is in phase with the utility voltage. The outputs of the multiplier and the PLL circuit are sent to the other multiplier. The product of this multiplier is the reference signal of the output current for the five-level inverter. The output current of the five-level inverter is detected by a current sensor. The reference signal and detected signal for the output current of the five-level inverter are sent to a sub-tractor. The subtracted result is sent to a current-mode controller. The output of the current-mode controller is sent to a PWM circuit to generate a PWM signal. The detected dc capacitor voltages V_{C2} andV_{C3} are also sent to a comparator to obtain signal S_b. When dc capacitor voltage V_{C2} is higher than dc capacitor voltageV_{C3}, S_b is a high value.

On the contrary, S_b is a low value when dc capacitor voltage VC2 is smaller than dc capacitor voltage V_{C3}. DC voltage V_{dc} is also sent to an amplifier with a gain of 0.5 to obtain voltage signal $V_{dc/2}$. The detected utility voltage is sent to an absolute circuit to obtain voltage signal |vs |. Voltage signals $V_{dc/2}$ and |vs | are compared to obtain signal S_c. When $V_{dc/2}$ >|vs S_c is a high value. On the contrary, S_c is a low value when $V_{dc/2}$ <|vs |. The output signal of the PWM circuit and signals Sb and Sc are sent to the mode selection circuit.

The output of the mode selection circuit will generate the control signals of power electronic switches S_2 and S_3 according to Table I. The detected utility voltage is also sent to a comparator to obtain complementary square signals that are synchronous with the detected utility voltage. The complementary square signals are the control signals of the power electronic switches of the full-bridge inverter. As mentioned earlier, only two power electronic switches S_2 or S3 in the five-level inverter should be switched in high frequency, and only one of them is switched in high frequency at any time, and the voltage level of every switching is $V_{dc/2}$. Therefore, the five-level inverter can reduce the switching loss effectively.

B. DC–DC Converter

Fig. 5 shows the control block of the dc–dc converter. The input of the dc–dc converter is the output of the solar cell array.
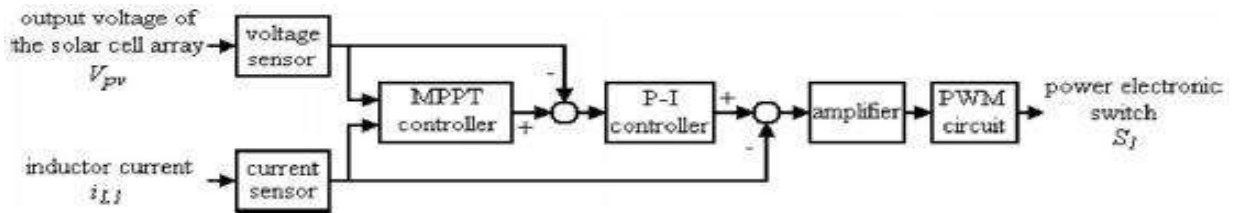

Fig.5. Control block of the dc–dc converter.

A ripple voltage with a frequency double that of the utility will appear in the dc bus voltage V_{dc}, while the five-level inverter injects real power into the utility. The function of MPPT will be degraded, while the output voltage of solar cell array contains a ripple voltage. Therefore, the ripple voltage superimposed on the dc bus voltage V_{dc} must be blocked by the dc–dc converter for improving the function of MPPT. Accordingly, the dual control loops, an outer voltage control loop, and an inner current control loop are applied to control the dc–dc converter. Since the output voltage of the dc–dc converter is the dc bus voltage that is controlled to be a constant voltage by the five-level inverter, the outer voltage control loop is used to regulate the output voltage of the solar cell array. The inner current control loop is applied to control the inductor current to approach a constant current to block the ripple voltage of dc voltage V_{dc}. The perturbation and observation method is adopted to obtain the function of MPPT [24], and it is incorporated into the controller of the dc–dc converter. The output of the MPPT controller is the desired output voltage of the solar cell array, and it is the reference voltage of the outer voltage control loop.

The output voltage of the solar cell array is perturbed first, and then the output power variation of the solar cell array is observed to determine the next perturbation for the output voltage of the solar cell array. The output power of the solar cell array is calculated from the product of the output voltage of the solar cell array and the inductor current. Therefore, the output voltage of the solar cell array and the inductor current are detected and sent to a MPPT controller to determine the desired output voltage of the solar cell array. The detected output voltage and desired output voltage of the solar cell array are sent to a sub tractor, and the subtracted result is sent to a P-I controller. The output of the P-I controller is the reference signal of the inner current control loop. The reference signal and the detected inductor current are sent to a subtractor, and the subtracted result is sent to an amplifier to complete the inner current control loop. The output of the amplifier is sent to the PWM circuit. The output signal of the PWM circuit is the driving signal for the power electronics witch of the dc– dc converter. For protecting the renewable power generation system from the voltage rise, the MPPT function will be disabled and the power electronic switch S_1 will be turned OFF when the inverter stage is interrupted after detecting the islanding operation. Therefore, the output voltage of solar cell array is limited to the open-circuit voltage of solar cell array, and the dc bus voltage V_{dc} is also limited. The control technique and operation is same for nine level inverter also.

VI. SIMULATION RESULTS

To verify the performance of the photovoltaic power generation system using the five-level and nine level inverter ,simulations are performed in MATLAB/SIMULINK. The main parameters of the simulations are listed in Table II. The solar cell array consists of two strings, and each string contains eight solar modules connected in series. The capacity of solar cell array is 1.2 kW. The output power of the solar cell array in the developed photovoltaic power generation system is about 830 W. Therefore, the developed photovoltaic power generation system can track the maximum power point of the solar cell array effectively.

Fig.6 shows the simulation voltage of the five-level inverter. As seen in Fig. 6(c), the dual-buck converter outputs a DC voltage with three levels V_{dc}, $V_{dc/2}$, and 0. Fig. 6(b) shows the output voltage of the dual-buck converter is further converted to an ac voltage with five voltage levels V_{dc}, $V_{dc/2}$, 0, $-V_{dc/2}$, and $-V_{dc}$ by the full-bridge inverter. The voltage variation of each level is $V_{dc/2}$. This verified that the five-level inverter can generate a five-level output ac voltage according to the utility voltage and only the power electronic switches of the dual-buck Converter is switched in high frequency. Fig .7 shows the simulation voltages of nine level inverter. Fig. 7(c), the dual-buck converter outputs a DC voltage with five levels. Fig. 7(b) shows the output voltage of the dual-buck converter is further converted to an ac voltage with nine level voltages by the full-bridge inverter. This verified that the five-level inverter can generate a nine-level output ac voltage according to the utility voltage and only the power electronic switches of the dual-buck converter is switched in high frequency.
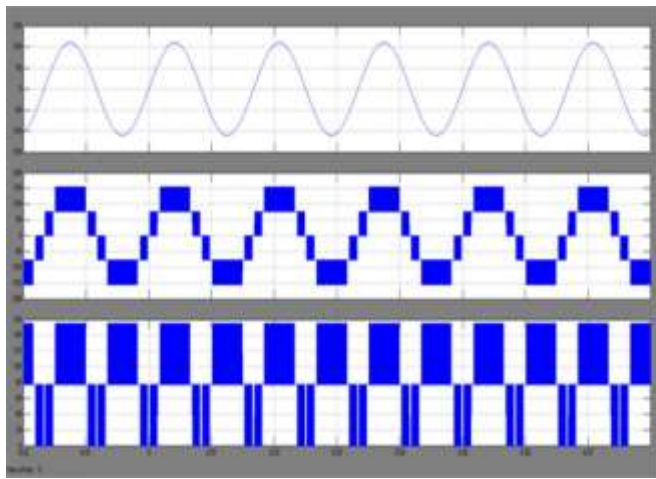
Fig.6.Simulation results of the five-level inverter. (a) Utility voltage. (b) Output voltage of the full-bridge inverter. (c) Output voltage of the dual buck converter.
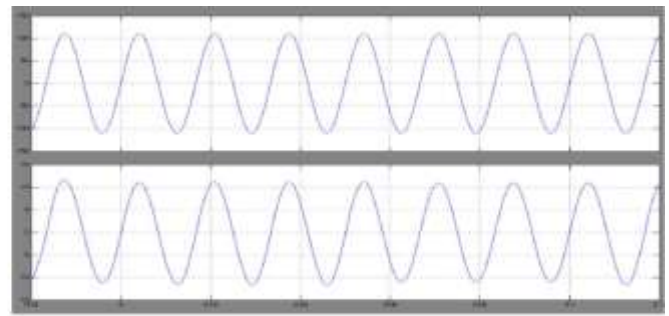
Fig.8.Simulation results for the developed photovoltaic power generation system under the distorted utility voltage. (a) Utility Voltage. (b) Output current of the five-level inverter
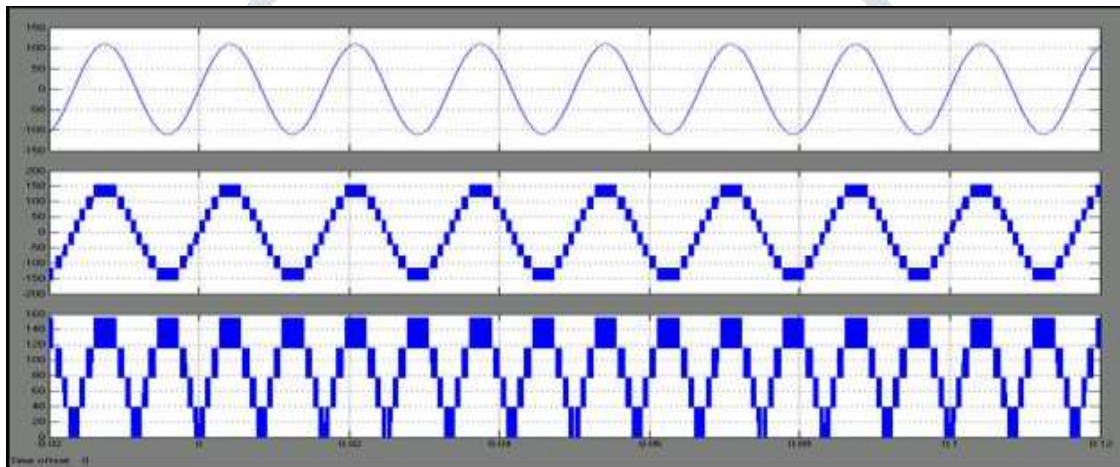

Fig.7.Simulation results of the Nine-level inverter. (a) Utility voltage. (b) Output voltage of the full-bridge inverter. (c) Output voltage of the dualbuck converter

Fig. 8 shows the simulation results for the developed photovoltaic power generation system under the distorted utility voltage. As seen in Fig. 8(a), the utility voltage is distorted, and its THD% is 8.6%. As seen in Fig. 8(b), the output current of the five-level inverter is still close to sinusoidal, and its THD% is only 4.7% and the power factor is 0.99. This experiment verifies the controller of the five-level inverter can control the output current with low THD% even when the utility voltage is distorted. From the results we can clearly observe that nine level inverter shows superior performance over conventional five level inverter.

VII. CONCLUSION

The MLIs are very beneficial as the number of switches in inverter increases this increases the level of inverter the harmonics distortion in AC output voltage and current decreases, it also provide reactive power compensation to the AC grid and reduction in electromagnetic emissions because they operate on lower switching frequency. A photovoltaic power generation system with a 5-level and 9 level inverter are developed in this paper. The nine-level inverter can perform the functions of regulating the dc bus voltage, converting solar power to ac power with sinusoidal current and in phase with the utility voltage, balancing the two dc capacitor voltages, and detecting islanding operation. The simulation results are verifying the developed photovoltaic power generation system, and the nine-level inverter achieves the better performance over 5 level inverter.

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