International Journal For Technological Research In Engineering
Volume 2, Issue 7, March-2015 *ISSN (Online): 2347 - 4718*

AN ENRICHED MULTILEVEL INVERTER TOPOLOGY FOR GRID CONNECTED PV SYSTEMS

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Abstract: this paper proposes a new solar power generation system, which is composed of a dc/dc power converter and a new seven-level inverter. The dc/dc power converter integrates a dc–dc boost converter and a transformer to convert the output voltage of the solar cell array into two independent voltage sources with multiple relationships. This new seven-level inverter is configured using a capacitor selection circuit and a full-bridge power converter, connected in cascade. The capacitor selection circuit converts the two output voltage sources of dc–dc power converter into a three-level dc voltage, and the full-bridge power converter further converts this three-level dc voltage into a seven-level ac voltage. In this way, the proposed solar power generation system generates a sinusoidal output current that is in phase with the utility voltage and is fed into the utility. The salient features of the proposed seven-level inverter are that only six power electronic switches are used, and only one power electronic switch is switched at high frequency at any time. A prototype is developed and tested to verify the performance of this proposed solar power generation system.

Index Terms: Grid-connected, multilevel inverter, pulse-width modulated (PWM) inverter.

I. INTRODUCTION

The power conversion interface is important to grid connected solar power generation systems because it converts the dc power generated by a solar cell array into ac power and feeds this ac power into the utility grid. An inverter is necessary in the power conversion interface to convert the dc power to ac power [2]–[4]. Since the output voltage of a solar cell array is low, a dc–dc power converter is used in a small-capacity solar power generation system to boost the output voltage, so it can match the dc bus voltage of the inverter. The power conversion efficiency of the power conversion interface is important to insure that there is no waste of the energy generated by the solar cell array. The active devices and passive devices in the inverter produce a power loss. The power losses due to active devices include both conduction losses and switching losses [5]. Conduction loss results from the use of active devices, while the switching loss is proportional to the voltage and the current changes for each switching and switching frequency. A filter inductor is used to process the switching harmonics of an inverter, so the power loss is proportional to the amount of switching harmonics. The voltage change in each switching operation for a multilevel inverter is reduced in order to improve its power conversion efficiency and the switching stress of the active devices. The amount of switching harmonics is also attenuated, so the power loss caused by the filter inductor is also reduced. Therefore, multilevel inverter technology has been the subject of much research over the past few years. In theory, multilevel inverters should be designed with higher voltage levels in order to improve the conversion efficiency and to reduce harmonic content and electromagnetic interference (EMI). Conventional multilevel inverter topologies include the diode clamped, the flying-capacitor, and the cascade H-bridge types. Diode-clamped and flying capacitor multilevel inverters use capacitors to develop several voltage levels. But it is difficult to regulate the voltage of these capacitors. Since it is difficult to create an asymmetric voltage technology in both the diode-clamped and the flying capacitor topologies, the power circuit is complicated by the increase in the voltage levels that is necessary for a multilevel inverter. For a single-phase seven-level inverter, 12 power electronic switches are required in both the diode-clamped and the flying-capacitor topologies. Asymmetric voltage technology is used in the cascade H-bridge multilevel inverter to allow more levels of output voltage, so the cascade H-bridge multilevel inverter is suitable for applications with increased voltage levels. Two H-bridge inverters with a dc bus voltage of multiple relationships can be connected in cascade to produce a single phase seven-level inverter and eight power electronic switches are used. More recently, various novel topologies for seven-level inverters have been proposed. For example, a single-phase seven-level grid-connected inverter has been developed for a photovoltaic system. This seven-level grid-connected inverter contains six power electronic switches. However, three dc capacitors are used to construct the three voltage levels, which results in that balancing the voltages of the capacitors is more complex. A seven-level inverter topology, configured by a level generation part and a polarity generation part, is proposed. There, only power electronic switches of the level generation part switch in high frequency, but ten power electronic switches and three dc capacitors are used. A modular multilevel inverter with a new modulation method is applied to the photovoltaic grid-connected generator. The modular multilevel inverter is similar to the cascade H-bridge type. For this, a new modulation method is proposed to achieve dynamic capacitor voltage balance. A multilevel dc-link inverter is presented to overcome the problem of partial shading of individual photovoltaic sources that are connected in series. The dc bus of a full-bridge inverter is configured by several individual dc blocks, where each dc block is composed of a solar cell, a power electronic switch, and a diode. Controlling the power electronics of the dc blocks will result in a multilevel dc-link voltage to supply a full-bridge inverter and to simultaneously overcome the problems of partial shading of individual photovoltaic sources.

II. PROPOSED SYSTEM

This paper proposes a new solar power generation system. The proposed solar power generation system is composed of a dc/dc power converter and a seven-level inverter. The seven-level inverter is configured using a capacitor selection circuit and a full-bridge power converter, connected in cascade. The seven-level inverter contains only six power electronic switches, which simplifies the circuit configuration. Since only one power electronic switch is switched at high frequency at any time to generate the seven-level output voltage, the switching power loss is reduced, and the power efficiency is improved. The inductance of the filter inductor is also reduced because there is a seven-level output voltage. In this study, a prototype is developed and tested to verify the performance of the proposed solar power generation system.

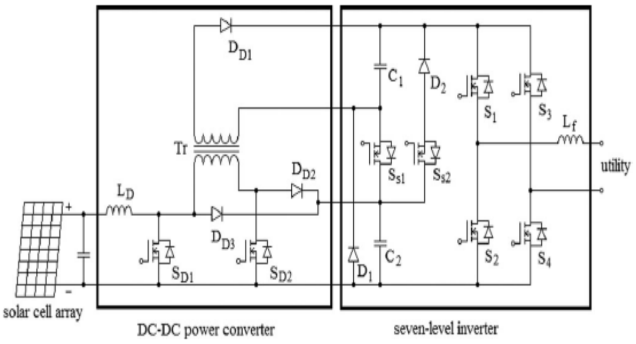

Fig. 1. Configuration of the proposed solar power generation system.

A. Circuit Description

Fig. 1 shows the configuration of the proposed solar power generation system. The proposed solar power generation system is composed of a solar cell array, a dc–dc power converter, and a new seven-level inverter. The solar cell array is connected to the dc–dc power converter, and the dc–dc power converter is a boost converter that incorporates a transformer with a turn ratio of 2:1. The dc–dc power converter converts the output power of the solar cell array into two independent voltage sources with multiple relationships, which are supplied to the seven-level inverter.

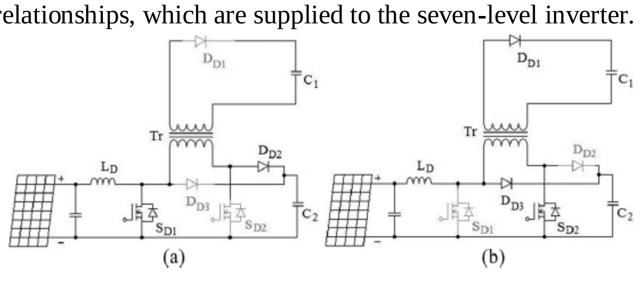

Fig. 2. Operation of dc–dc power converter: (a) SD1 is on and (b) SD1 is off.

This new seven-level inverter is composed of a capacitor selection circuit and a full-bridge power converter, connected in a cascade. The power electronic switches of capacitor selection circuit determine the discharge of the two capacitors while the two capacitors are being discharged individually or in series. Because of the multiple relationships between the voltages of the dc capacitors, the capacitor selection circuit outputs a three-level dc voltage. The full-bridge power converter further converts this three-level dc voltage to a seven-level ac voltage that is synchronized with the utility voltage. In this way, the proposed solar power generation system generates a sinusoidal output current that is in phase with the utility voltage and is fed into the utility, which produces a unity power factor. As can be seen, this new seven-level inverter contains only six power electronic switches, so the power circuit is simplified.

III. CONTROL BLOCKS

The proposed solar power generation system consists of a dc– dc power converter and a seven-level inverter. The seven-level inverter converts the dc power into high quality ac power and feeds it into the utility and regulates the voltages of capacitors$C1$ and $C2$. The dc–dc power converter supplies two independent voltage sources with multiple relationships and performs maximum power point tracking (MPPT) in order to extract the maximum output power from the solar cell array.

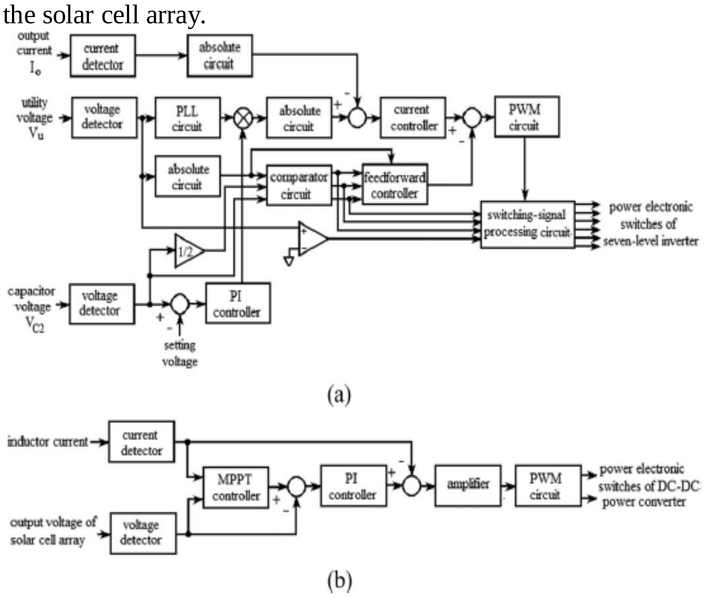

Fig. 3. Control block: (a) seven-level inverter and (b) dc–dc power converter.

A. Seven-Level Inverter

Fig. 3(a) shows the control block diagram for the seven-level inverter. The control object of the seven-level inverter is its output current, which should be sinusoidal and in phase with the utility voltage. The utility voltage is detected by a voltage detector, and then sent to a phase-lock loop (PLL) circuit in order to generate a sinusoidal signal with unity amplitude. The voltage of capacitor C2 is detected and then compared with a setting voltage. The compared result is sent to a PI controller. Then, the outputs of the PLL circuit and the PI controller are sent to a multiplier to produce the reference signal, while the output current of the seven-level inverter is detected by a current detector. The reference signal and the detected output current are sent to absolute circuits and then sent to a subtractor, and the output of the subtractor is sent to a current controller. The detected utility voltage is also sent to an absolute circuit an then sent to a comparator circuit, where the absolute utility voltage is compared with both half and whole of the detected voltage of capacitor C2 , in order to determine the range of the operating voltage. The comparator circuit has three output signals, which correspond to the operation voltage ranges, (0, Vdc/3), (Vdc/3, 2Vdc/3), and (2Vdc/3, Vdc). The feed-forward control eliminates the disturbances of the utility voltage, Vdc/3 and 2Vdc/3, as shown in (3) and (5). The absolute value of the utility voltage and the outputs of the compared circuit are sent to a feed-forward controller to generate the feed-forward signal then, the output of the current controller and the feed-forward signal are summed and sent to a PWM circuit to produce the PWM signal. The detected utility voltage is also compared with zero, in order to obtain a square signal that is synchronized with the utility voltage. Finally, the PWM signal, the square signal, and the outputs of the compared circuit are sent to the switching signal processing circuit to generate the control signals for the power electronic switches of the seven-level inverter. The current controller controls the output current of the seven-level inverter, which is a sinusoidal signal of 60 Hz. Since the feed-forward control is used in the control circuit, the current controller can be a simple amplifier, which gives good tracking performance. The gain of the current controller determines the bandwidth and the steady state error. The gain of the current controller must be as large as possible in order to ensure a fast response and a low steady-state error. But the gain of the current controller is limited because the bandwidth of the power converter is limited by the switching frequency.

B. DC–DC Power Converter

Fig. 3(b) shows the control block diagram for the dc–dc power converter. The input for the DC-DC power converter is the output of the solar cell array. A ripple voltage with a frequency that is double that of the utility appears in the voltages of C1 and C2, when the seven-level inverter feeds real power into the utility. The MPPT function is degraded if the output voltage of solar cell array contains a ripple voltage. Therefore, the ripple voltages in C1 and C2 must be blocked by the dc–dc power converter to provide improved MPPT. Accordingly, dual control loops, an outer voltage control loop and an inner current control loop, are used to control the dc–dc power converter. Since the output voltages of the DC-DC power converter comprises the voltages of C1 and C2, which are controlled by the seven-level inverter, the outer voltage control loop is used to regulate the output voltage of the solar cell array. The inner current control loop controls the inductor current so that it approaches a constant current and blocks the ripple voltages in C1 and C2. The perturbation and observation method is used to provide MPPT. 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 for the solar cell array. Then the detected output voltage and the desired output voltage of the solar cell array are sent to a subtractor and the difference is sent to a PI controller. The output of the PI 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 difference is sent to an amplifier to complete the inner current control loop. The output of the amplifier is sent to the PWM circuit. The PWM circuit generates a set of complementary signals that control the power electronic switches of the dc–dc power converter.

IV. EXPERIMENTAL RESULTS

To verify the performance of the proposed solar power generation system, a prototype was developed with a controller based on the DSP chip TMS320F28035. The power rating of the prototype is 500 W, and the prototype was used for a single-phase utility with 110Vand 60 Hz. Table II shows the main parameters of the prototype.

TABLE II: PARAMETERS OF THE PROTOTYPE

DC-DC power converter	
input voltage	70V
inductor	1mH
PWM frequency	15360Hz
seven-level inverter	
capacitor C_1, C_2	1000μF
filter inductor	1.9 mH
PWM frequency	15360Hz

Figs. 4 and 5 show the experimental results for the seven-level inverter when the output power of solar power generation system is 500 W. Fig. 4 shows the experimental results for the AC side of the seven-level inverter. Fig. 4(b) shows that the output voltage of the seven-level inverter has seven voltage levels. The output current of the seven-level inverter, shown in Fig. 4(c), is sinusoidal and in phase with the utility voltage, which means that the grid-connected power conversion interface feeds a pure real power to the utility. The total harmonic distortion (THD) of the output current of the seven-level inverter is 3.6%.

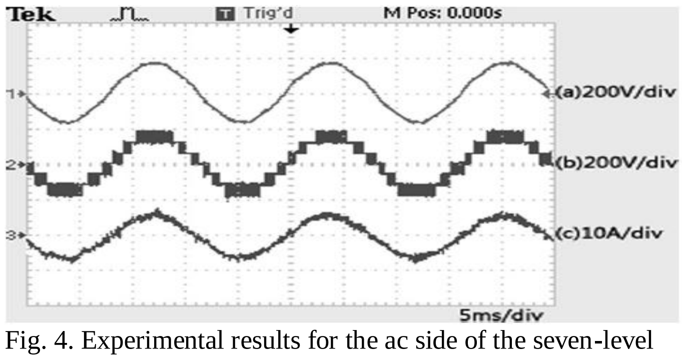

Fig. 4. Experimental results for the ac side of the seven-level inverter: (a) Utility voltage, (b) output voltage of seven-level inverter, and (c) output current of the seven-level inverter.

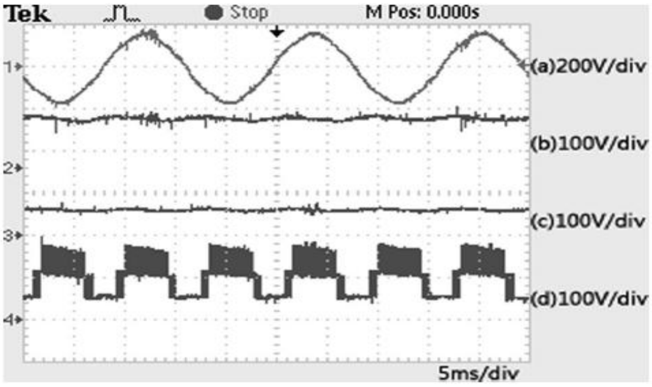

Fig. 5. Experimental results for the dc side of the seven-level inverter: (a) utility voltage, (b) voltage of capacitor C2, (c) voltage of capacitor C1, and (d) output voltage of the capacitor selection circuit.

Fig. 5 shows the experimental results for the dc side of the seven-level inverter. Fig. 5(b) and (c) show that the voltages of capacitors C2 and C1 of the capacitor selection circuit have multiple relationships and are maintained at 60 and 120 V, respectively. Fig. 5(d) shows that the output voltage of the capacitor selection circuit has three voltage levels (60, 120, and 180 V). Fig. 6. Experimental results of the dc–dc power converter: (a) ripple current of inductor, (b) ripple voltage of capacitor C2, and (c) ripple voltage of capacitor C1. Fig. 7. Output power scans of the solar cell array. Shows the experimental results for the dc–dc power converter. Fig. 6(b) and (c) shows that the ripple voltages in capacitors C1 and C2 of the capacitor selection circuit are evident. However, the ripple current in the inductor of the dc–dc power converter is less than 0.5 A when the average current of inductor is 8 A, as shown in Fig. 6(a).

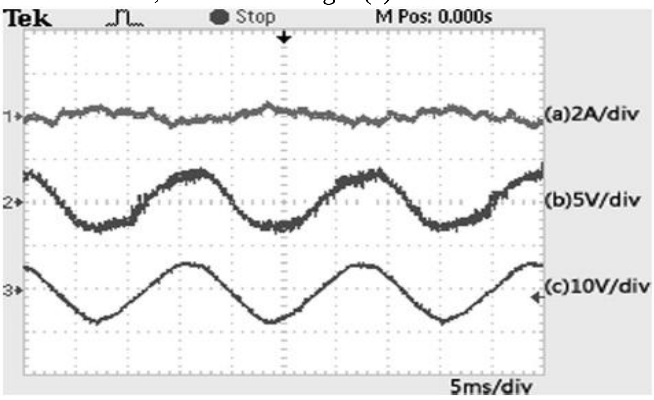

Fig. 6. Experimental results of the dc–dc power converter: (a) ripple current of inductor, (b) ripple voltage of capacitor C2, and (c) ripple voltage of capacitor C1.

Therefore, the ripple voltages in C1 and C2 are blocked by the dc–dc power converter. Fig. 7 shows the output power scan for the solar cell array when the output voltage changes from 40 to 70 V. Fig. 8 shows the experimental results for the beginning of MPPT for the dc–dc converter. Fig. 13 shows that the output power of the solar cell array is almost constant when maximum power tracking is achieved and its value is very close to the maximum power shown in Fig. 7.

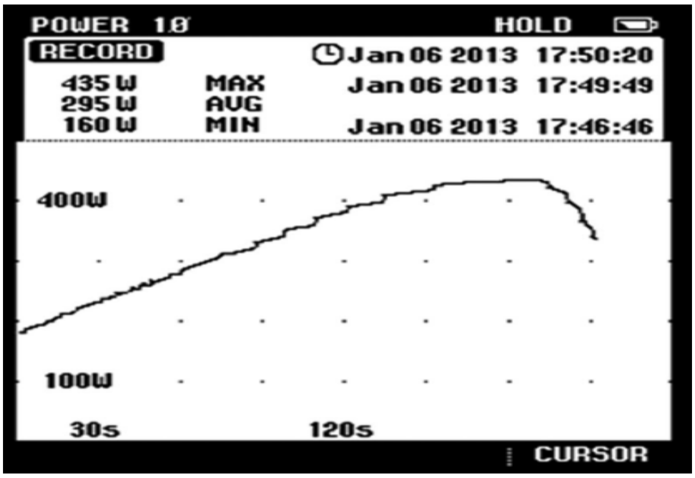

Fig. 7. Output power scan of the solar cell array.

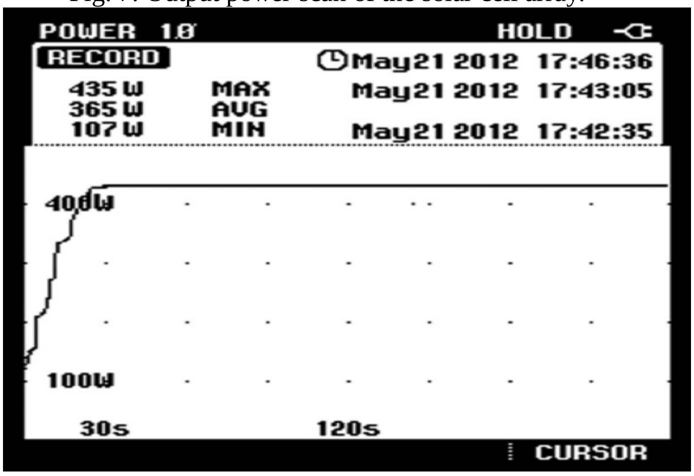

Fig. 8. Experimental results for the MPPT performance of the proposed solar power generation system.

Fig. 9 shows the experimental results for the power efficiency of the proposed solar power generation system. The solar cell array was replaced by a dc power supply to simplify the adjustment of output power in the experimental process. With higher step-up gain of the dc–dc power converter, there is lower power efficiency. Hence, the higher input voltage of solar power generation system will result in better power efficiency of the dc–dc power converter. Since a transformer is used in the dc–dc power converter of the proposed solar power generation system, this degrades the power efficiency of the proposed solar power generation system.

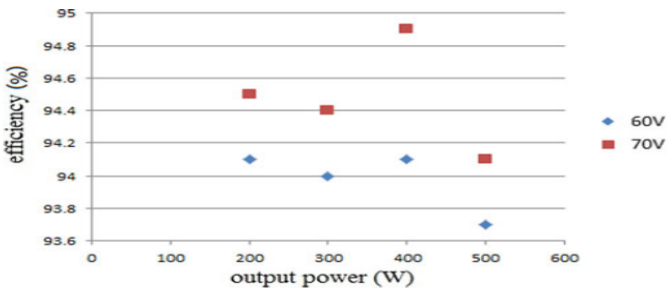

Fig. 10. Experimental results for the power efficiency of the proposed solar power generation system.

However, the power transferred by the transformer is less than one third of the solar output power in the proposed dc–dc power converter, and the energy stored in the magnetizing inductance of the transformer is transferred forward to the output capacitor. Hence, the degradation of power efficiency caused by use of the transformer in the proposed solar power generation system is not serious.

V. CONCLUSION

This paper proposes a solar power generation system to convert the dc energy generated by a solar cell array into ac energy that is fed into the utility. The proposed solar power generation system is composed of a dc–dc power converter and a seven-level inverter. The seven-level inverter contains only six power electronic switches, which simplifies the circuit configuration. Furthermore, only one power electronic switch is switched at high frequency at any time to generate the seven-level output voltage. This reduces the switching power loss and improves the power efficiency. The voltages of the two dc capacitors in the proposed seven-level inverter are balanced automatically, so the control circuit is simplified. Experimental results show that the proposed solar power generation system generates a seven-level output voltage and outputs a sinusoidal current that is in phase with the utility voltage, yielding a power factor of unity. In addition, the proposed solar power generation system can effectively trace the maximum power of solar cell array.

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