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A Novel Nine Level Grid-Connected Inverter for Photovoltaic System

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***Abstract*-This paper proposes a single-phase seven-level inverter for grid-connected photovoltaic systems, with a novel pulse width-modulated (PWM) control scheme. Three reference signals that are identical to each other with an offset that is equivalent to the amplitude of the triangular carrier signal were used to generate the PWM signals. The inverter is capable of producing seven levels of output-voltage levels (V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, 0, $-V_{dc}$, $-2V_{dc}/3$, $-V_{dc}/3$) from the dc supply voltage. In this paper a new nine level inverter with reduced number of switches is proposed and Matlab/Simulink results are presented.**

***Index Terms*—**Grid connected, modulation index, multilevel inverter, photovoltaic (PV) system, pulse width-modulated (PWM), total harmonic distortion (THD).

I. INTRODUCTION

The ever-increasing energy consumption, fossil fuels soaring costs and exhaustible nature, and worsening global environment have created a booming interest in renewable energy generation systems, one of which is photovoltaic. Such a system generates electricity by converting the Sun's energy directly into electricity. Photovoltaic-generated energy can be delivered to power system networks through grid-connected inverters. A single-phase grid-connected inverter is usually used for residential or low-power applications of power ranges that are less than 10 kW [1]. Types of single-phase grid-connected inverters have been investigated [2]. A common topology of this inverter is full-bridge three-level.

The three-level inverter can satisfy specifications through its very high switching, but it could also unfortunately increase switching losses, acoustic noise, and level of interference to other equipment. Improving its output waveform reduces its harmonic content and, hence,also the size of the filter used and the level of electromagnetic interference (EMI) generated by the inverter's switching operation [3]. Multilevel inverters are promising; they have nearly sinusoidal output-voltage waveforms, output current with better harmonic profile, less stressing of electronic components owing to decreased voltages, switching losses that are lower than those of conventional two-level inverters, a smaller filter size, and lower EMI, all of which make them cheaper, lighter, and more compact [3], [4]. Various topologies for multilevel inverters have been proposed over the years. Common ones are diode-clamped [5]– [10], flying capacitor or multi cell [11]–[17] , cascaded H-bridge [18]–[24], and modified H-bridge multilevel [25]–[29].

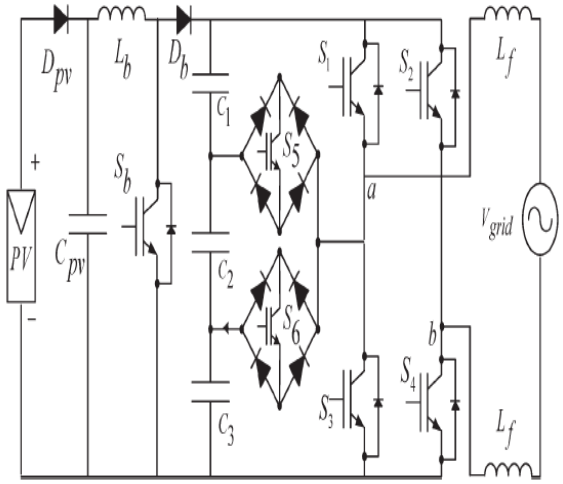


Fig.1. Proposed single-phase seven-level grid-connected inverter for photovoltaic systems.

This paper recounts the development of a novel modified H-bridge single-phase multilevel inverter that has two diode embedded bidirectional switches and a novel pulse width modulated (PWM) technique. The topology was applied to a grid-connected photovoltaic system with considerations for a maximum-power-point tracker (MPPT) and a current-control algorithm.

II. PROPOSED MULTILEVEL INVERTER TOPOLOGY

A Full H-Bridge

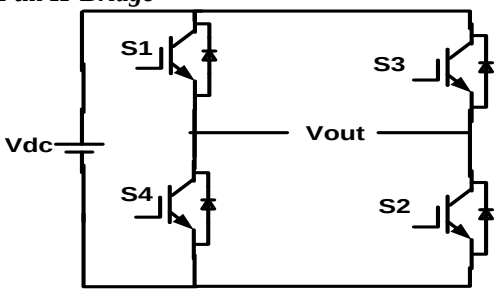


Figure. 2 Full H-Bridge

Fig.2 shows the Full H-Bridge Configuration. By using single H-Bridge we can get 3 voltage levels. The number output voltage levels of cascaded Full H-Bridge are given by 2n+1 and voltage step of each level is given by V_{dc}/n. Where n is number of H-bridges connected in cascaded. The switching table is given in Table 1.

Table 1. Switching table for Full H-Bridge

Switches Turn ON	Voltage Level
S1,S2	V_{dc}
S3,S4	$-V_{dc}$
S4,S2	0

B Hybrid H-Bridge

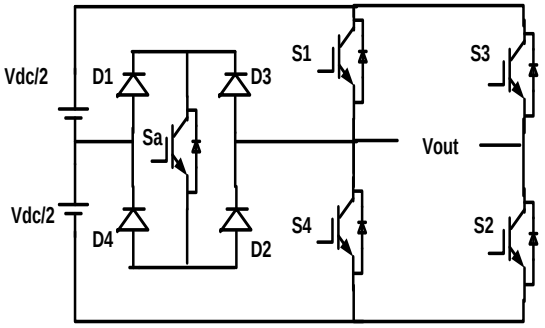


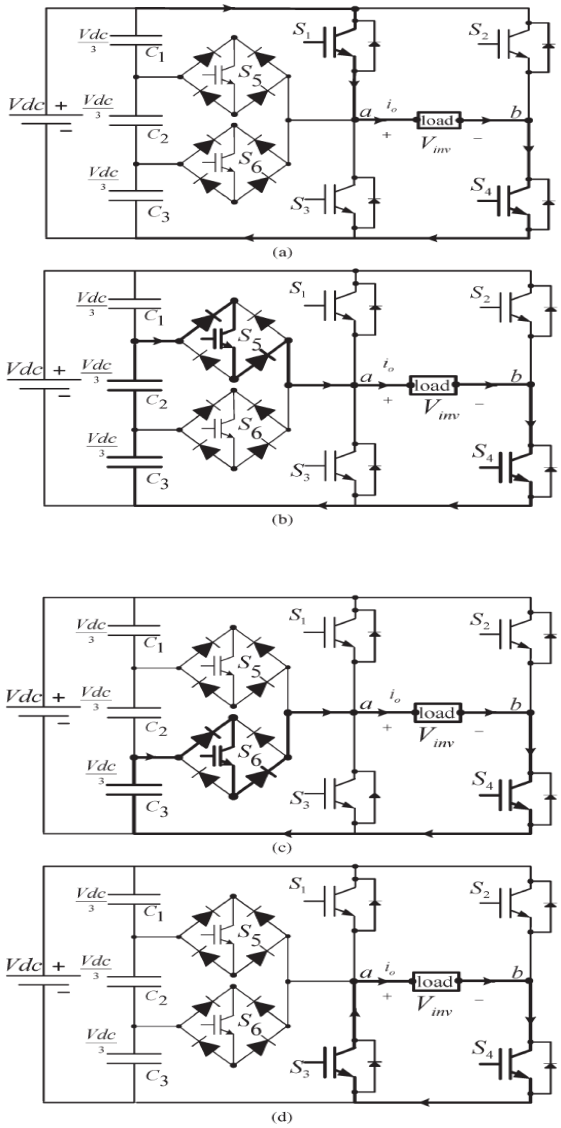
Figure. 3 Hybrid H-Bridge

Fig. 3 shows the Hybrid H-Bridge configuration. By using single Hybrid H-Bridge we can get 5 voltage levels. The number output voltage levels of cascaded Hybrid H-Bridge are given by 4n+1 and voltage step of each level is given by $V_{dc}/2n$. Where n is number of H-bridges connected in cascaded. The switching table of Hybrid H-Bridge is given in Table 2.

Table 2. Switching table for Hybrid H-Bridge

Switches Turn On	Voltage Level
Sa, S1	$V_{dc}/2$
S1,S2	V_{dc}
S4,S2	0
Sa,S3	$-V_{dc}/2$
S3,S4	$-V_{dc}$

The proposed single-phase seven-level inverter was developed from the five-level inverter in [25]–[29]. It comprises a single-phase conventional H-bridge inverter, two bidirectional switches, and a capacitor voltage divider formed by *C*1, *C*2, and *C*3, as shown in Fig. 1. The modified H-bridge topology is significantly advantageous over other topologies, i.e., less power switch, power diodes, and less capacitor for inverters of the same number of levels. Photo voltaic (PV) arrays were connected to the inverter via a dc–dc boost converter. The power generated by the inverter is to be delivered to the power network, so the utility grid, rather than a load, was used. The dc–dc boost converter was required because the PV arrays had a voltage that was lower than the grid voltage. High dc bus voltages are necessary to ensure that power flows from the PV arrays to the grid. A filtering inductance *Lf* was used to filter the current injected into the grid. Proper switching of the inverter can produce seven output-voltage levels (V_{dc}, $2V_{dc}/3$, $V_{dc}/3$, $0, -V_{dc}, -2V_{dc}/3, -V_{dc}/3$) from the dc supply voltage. The proposed inverter's operation can be divided into seven switching states, as shown in Fig. 4(a)–(g).



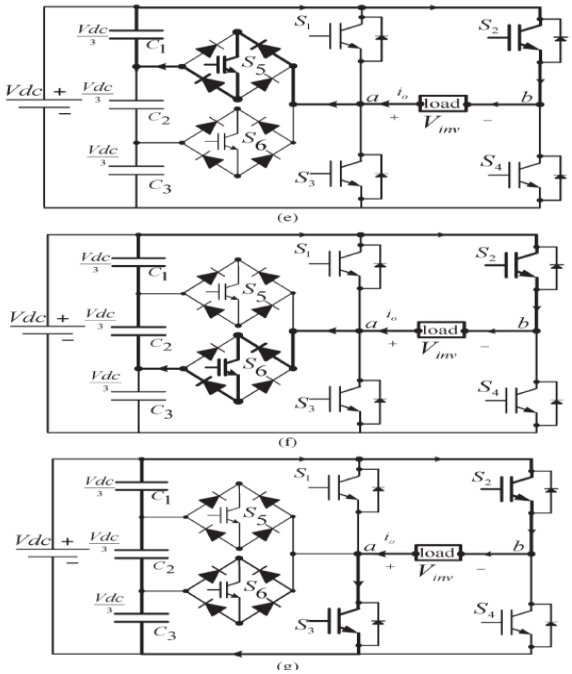


Fig. 4. Switching combination required to generate the output voltage (V_{ab}). (a) $V_{ab} = V_{dc}$. (b) $V_{ab} = 2V_{dc}/3$. (c) $V_{ab} = V_{dc}/3$. (d) $V_{ab}= 0$ (e) $V_{ab} = -V_{dc}/3$. (f) $V_{ab} = -2V_{dc}/3$. (g) $V_{ab} = -V_{dc}$.

OUTPUT VOLTAGE ACCORDING TO THE SWITCHES' ON–OFF CONDITION

v_0	S_1	S_2	S_3	S_4	S_5	S_6
V_{dc}	on	off	off	on	off	off
$2V_{dc}/3$	off	off	off	on	on	off
$V_{dc}/3$	off	off	off	on	off	on
0	off	off	on	on	off	off
0*	on	on	off	off	off	off
$-V_{dc}/3$	off	on	off	off	on	off
$-2V_{dc}/3$	off	on	off	off	off	on
$-V_{dc}$	off	on	on	off	off	off

Table 3. shows the switching combinations that generated the seven output-voltage levels ($0, -V_{dc}, -2V_{dc}/3, -V_{dc}/3, V_{dc}, 2V_{dc}/3, V_{dc}/3$).

III. PWM MODULATION

A novel PWM modulation technique was introduced to generate the PWM switching signals. Three reference signals (V_{ref1}, V_{ref2}, and V_{ref3}) were compared with a carrier signal ($V_{carrier}$). The reference signals had the same frequency and amplitude and were in phase with an offset value that was equivalent to the amplitude of the carrier signal. The reference signals were each compared with the carrier signal. If V_{ref1} had exceeded the peak amplitude of $V_{carrier}$, V_{ref2} was compared with $V_{carrier}$ until it had exceeded the peak amplitude of $V_{carrier}$. Then, onward, V_{ref3} would take charge and would be compared with $V_{carrier}$ until it reached zero. Once V_{ref3} had reached zero, V_{ref2} would be compared until it reached zero. Then, onward, V_{ref1} would be compared with $V_{carrier}$.

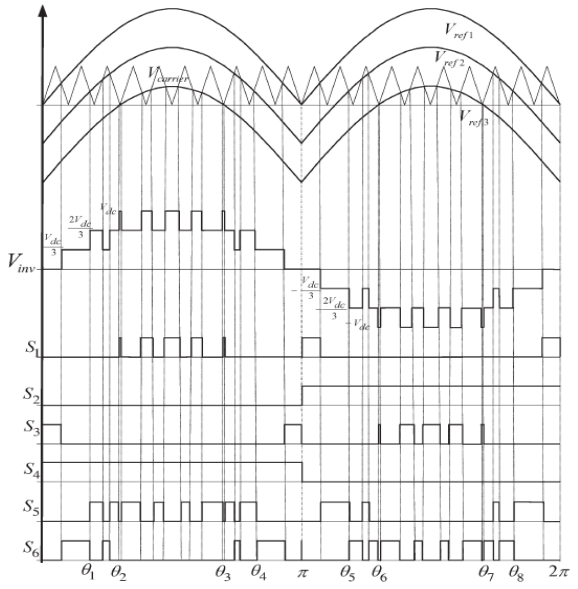


Fig. 5. Switching pattern for the single-phase seven-level inverter.

Fig.5 shows the resulting switching pattern. Switches *S*1, *S*3, *S*5, and *S*6 would be switching at the rate of the carrier signal frequency, whereas *S*2 and *S*4 would operate at a frequency that was equivalent to the fundamental frequency. For one cycle of the fundamental frequency, the proposed inverter operated through six modes. Fig. 6 shows the per unit output-voltage signal for one cycle. The six modes are described as follows:

Mode 1 : $0 < \omega t < \theta_1$ and $\theta_4 < \omega t < \pi$

Mode 2 : $\theta_1 < \omega t < \theta_2$ and $\theta_3 < \omega t < \theta_4$

Mode 3 : $\theta_2 < \omega t < \theta_3$

Mode 4 : $\pi < \omega t < \theta_5$ and $\theta_8 < \omega t < 2\pi$

Mode 5 : $\theta_5 < \omega t < \theta_6$ and $\theta_7 < \omega t < \theta_8$

Mode 6 : $\theta_6 < \omega t < \theta_7$.

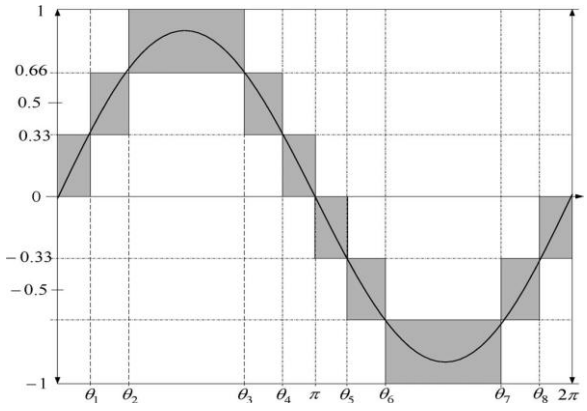


Fig. 6. Seven-level output voltage (V_{ab}) and switching angles.

IV CONTROL SYSTEM

Fig. 7 shows, the control system comprises a MPPT algorithm, a dc-bus voltage controller, reference-current generation, and a current controller. The two main tasks of the control system are maximization of the energy transferred from the PV arrays to the grid, and generation of a sinusoidal current with minimum harmonic distortion, also under the presence of grid voltage harmonics. The proposed inverter utilizes the perturb-and-observe (P&O) algorithm for its wide usage in MPPT owing to its simple structure and requirement of only a few measured parameters. It periodically perturbs (i.e., increment or decrement) the array terminal voltage and compares the PV output power with that of the previous perturbation cycle. If the power was increasing, the perturbation would continue in the same direction in the next cycle; otherwise, the direction would be reversed. This means that the array terminal voltage is perturbed every MPPT cycle; therefore, when the MPP is reached, the P&O algorithm will oscillate around it.

The P&O algorithm was implemented in the dc–dc boost converter. The output of the MPPT is the duty-cycle function. As the dc-link voltage V_{dc} was controlled in the dc–ac sevenlevel PWM inverter, the change of the duty cycle changes the voltage at the output of the PV panels. A PID controller was implemented to keep the output voltage of the dc–dc boost converter (V_{dc}) constant by comparing V_{dc} and $V_{dc\ ref}$ and feeding the error into the PID controller, which subsequently tries to reduce the error. In this way, the V_{dc} can be maintained at a constant value and at more than $\sqrt{2}$ of V_{grid} to inject power into the grid. To deliver energy to the grid, the frequency and phase of the PV inverter must equal those of the grid; therefore, a grid synchronization method is needed. The sine lookup table that generates reference current must be brought into phase with the grid voltage (V_{grid}).

A PI algorithm was used as the feedback current controller for the application. The current injected into the grid, also known as grid current I_{grid}, was sensed and fed back to a comparator that compared it with the reference current $I_{gridref}$. $I_{gridref}$ is the result of the MPPT algorithm. The error from the comparison process of I_{grid} and $I_{gridref}$ was fed into the PI controller. The output of the PI controller, also known as V_{ref} , goes through an anti windup process before being compared with the triangular wave to produce the switching signals for S_1–S_6. Eventually, V_{ref} becomes V_{ref1}, V_{ref2} and V_{ref3} can be derived from V_{ref1} by shifting the offset value, which was equivalent to the amplitude of the triangular wave. The mathematical formulation of the PI algorithm and its implementation in the DSP are discussed in detail in [28].

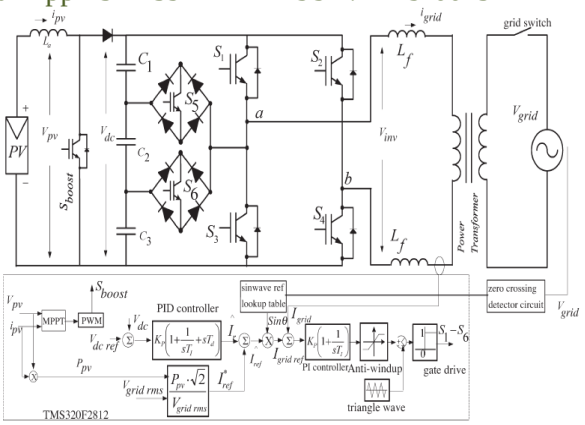


Fig. 7. Seven-level inverter with closed-loop control algorithm.

V. MATLAB/SIMULINK MODEL and SIMULATION RESULTS

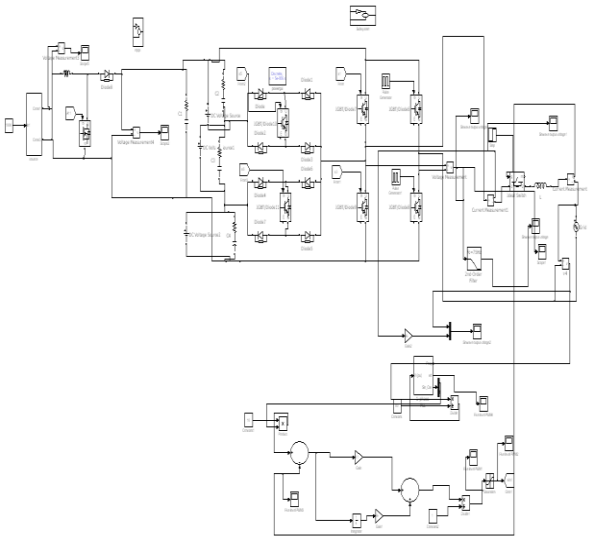


Fig. 8 Matlab/Simulink model of Grid connected PV system

Fig. 8 shows the Matlab/ Simulink model of grid connected photovoltaic system. It consist of a DC to DC conversion stage and Dc to AC multilevel inversion stage.

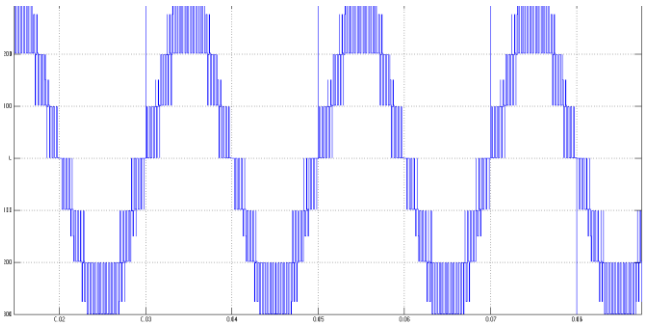


Fig. 9 Seven Level Voltage output

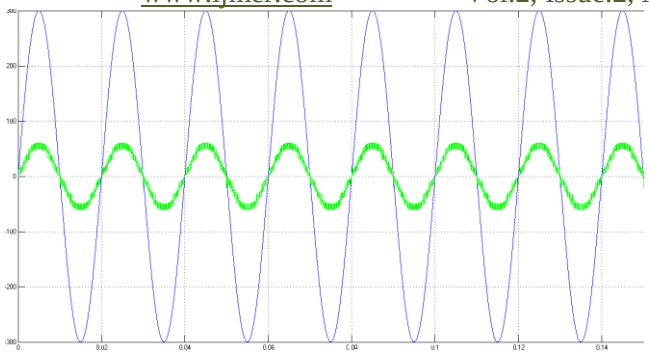


Fig.10 Grid Voltage and Grid Current

Fig. 9 shows the seven level PWM output. Fig. 10 show sthe grid voltage and grid current. From the figure it is clear that grid voltage and current are inpahse.

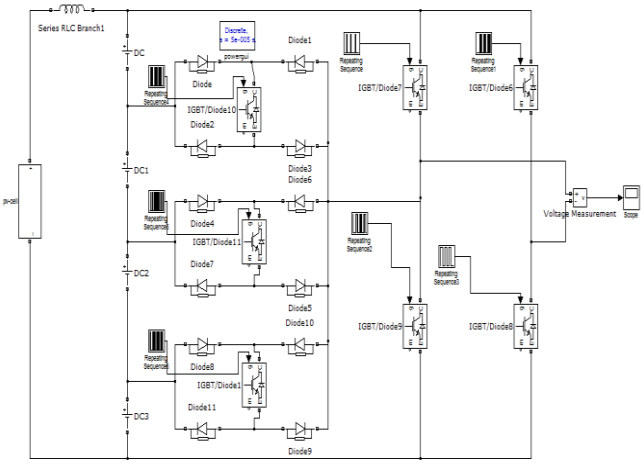


Fig.11 Matlab/SImulink modle of proposed Nine level Inverter

Fig. 11 shows the Matlab/Simulink model of proposed nine level Hybrid H-Bridge inverter.

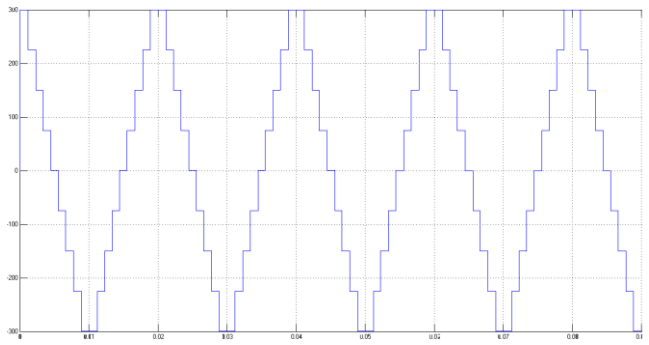


Fig.12 Nine level output of proposed converter

Fig. 12 shows the output of proposed nine level inverter. In proposed converter for nine level seven switches are required. In order to produce the same levels cascaded H-Bridge requires sixteen switches.

V CONCLUSION

Multilevel inverters offer improved output waveforms and lower THD. This paper has presented a novel PWM switching scheme for the proposed multilevel inverter. It utilizes three reference signals and a triangular carrier signal to generate PWM switching signals. The behavior of the proposed multilevel inverter was analyzed in detail. By controlling the modulation index, the desired number of levels of the inverter's output voltage can be achieved. Finally a nine level hybrid H-bridge inverter is proposed and simulation results are presented.

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