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Single-Phase Seven-Level Grid-Connected Inverter for Photovoltaic System

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***Abstract*—In 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 (Vdc, $2V$dc/3, Vdc/3, 0 ,$-V$dc,$-2V$dc/3,$-V$dc/3) from the dc supply voltage. The photovoltaic (PV) energy is presented as one of the most promising source of clean energy, and so a good way for greenhouse gas emissions mitigation and reduce the fossil fuel dependence. Within it, the photovoltaic energy has caused a huge interest in the electronic converters, and the need to improve their efficiency and reducing their cost. With this work I present a solution for a module scale grid-connected single-phase inverter. The solution consists in a two-stage inverter insolated with a grid line transformer. To the boost control it is implemented a Maximum Power Point Tracking algorithm that can optimize the power extraction from the PV source and for the inverter it is used a sliding mode hysteretic control.**

***Index Terms*— Inverters, Photovoltaic, Power Electronics, Renewable Energies, Grid connected, modulation index, multilevel inverter, pulse width-modulated (PWM).**

I. INTRODUCTION

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]. [22]–[21], and modified H-bridge multilevel [23]–[24]. 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. PV ENERGY SYSTEM

Photovoltaic technology uses sunlight to generate electricity. Sunlight is a renewable energy source that could theoretically be exploited to supply energy abundantly for an infinite time into the future. Completely free of cost, sunlight is widely available on Earth regardless of geographical location. On the other hand, the intermittency of sunlight causes the operation of PV to rely directly on the time of day and weather. On a cloudy day or at night, the power supply is diminished or cut off unless some other source of electricity is used. Additionally, the power density of sunlight is low (1 kW/m2 in clear conditions), so large-scale PV electricity production requires either a large area covered with PV modules or mirrors for concentrating sunlight on a smaller area.

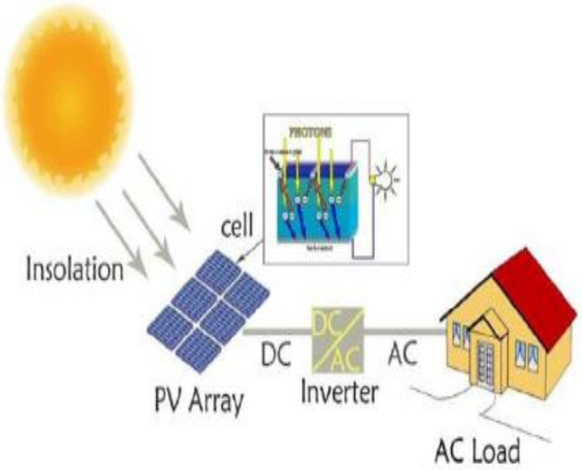

Figure 1 Photovoltaic Energy System

The power generated by a PV module depends on the module technology and on the intensity of sunlight. The power that a module produces at a given moment is proportional to the perpendicular sunlight intensity on the module surface. Power is therefore reduced if conditions are cloudy or if the angle of incidence of sunlight is large. In general, the average power production of a PV system can be reliably estimated on a monthly basis from previously measured meteorological data. Shorter time intervals introduce uncertainty, but weather forecasts can well be used to predict power production one day in advance. PV arrays can be built ranging from a few watts up to several megawatts due to their modular design. Existing arrays can always be expanded to meet growing electricity demand, although the electronics in the system may need updating. An inverter, or DC-AC converter, is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any

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required voltage and frequency with the use of appropriate transformers, switching, and control circuits. Photovoltaic cells are DC power suppliers, so it is necessary the use of an inverter to feed the AC devices or to connect the PV system to the grid.

III. PROPOSED 7 LEVEL INVERTER

It comprises a single-phase conventional H-bridge inverter, two bidirectional switches, and a capacitor voltage divider formed by dc link capacitors (*C*1, *C*2, and *C*3). The H-bridge topology with bidirectional switches is significantly advantageous over other topologies, i.e., less power switch, power diodes, and less capacitor for inverters of the same number of levels. Photovoltaic (PV) arrays were connected to the inverter via a dc–dc boost converter [9]. A filtering inductance L_f is used to filter the current. 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.

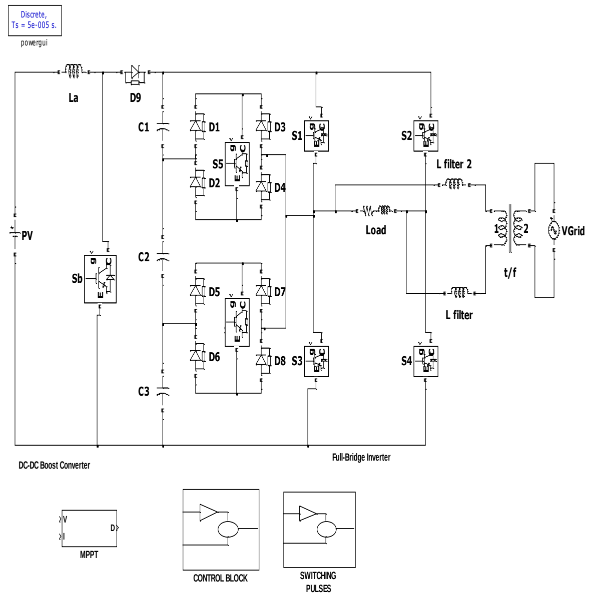

Figure 2 MATLAB/SIMULINK diagram of 7-level Inverter

As figure 3.1 shows, the control system comprises a MPPT algorithm, a dc-bus voltage controller 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 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 seven-level PWM inverter, the change of the duty cycle changes the voltage at the output of the PV panels. A PI 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 PI 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 [12], [18].

IV. MPPT CONTROL TECHNIQUE

A maximum power point tracking (MPPT) method or algorithm, which has quick-response characteristics and is able to make good use of the electric power generated in any weather, is needed to solve the aforementioned problem. Various MPPT control methods have been discussed in detail in. Constant *m* is derived from the MPPT algorithm. The perturb-and-observe algorithm is used to extract maximum power from PV arrays and deliver it to the inverter. The instantaneous current error is fed to a PI controller. The integral term in the PI controller improves the tracking by reducing the instantaneous error between the reference and the actual current. The resulting error signal *u* which forms *V*ref1, *V*ref2 & Vref3 for 7-level inverter) is compared with a triangular carrier signal, and intersections are sought to produce PWM signals for the inverter switches [18].

PERTURB AND OBSERVE TECHNIQUE

As the name of the perturb-and-observe (P&O) states, this process works by perturbing the system by increasing or decreasing the array operating voltage and observing its impact on the array output power. The operating voltage is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage V_{mp}. Figure 3 summarized the control method of the P&O.

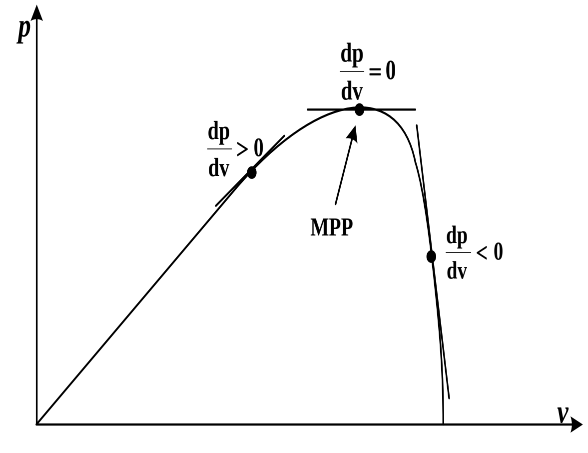

Figure 3 Summarization of Perturb & Observe Method

The value of the reference voltage, Vref, will be changed according to the current operating point. When the controller senses that the power from solar array increases (dP> 0) and the voltage decreases (dV< 0), it will decrease (-) Vref by a step size C1, so Vref is closer to the MPP. The oscillation around a maximum power point causes a power loss that depends on the step width of a single perturbation. The value of the ideal step width is system dependent and needs to be determined experimentally to pursue the trade-off of increased losses under stable or slowly changing conditions. In fact, since the AC component of the output power signal is much smaller than the DC component and will contain a high noise level due to the switching DC-DC converter, an increase in the amplitude of the modulating signal had to be implemented to improve the signal to noise ratio (SNR). However, this will lead to higher oscillations at the MPP and therefore increase power losses even under stable environmental conditions [12], [18].

V. PWM SWITCHING TECHNIQUE

The two different methods of switching techniques are employed in the MATLAB/SIMULINK diagram. Different types of logic gates are used for these techniques. A novel PWM modulation technique is employed to produce the PWM switching signals. For the seven-level inverter three reference signals (V_{ref1}, V_{ref2}& V_{ref3}) are compared with a carrier signal ($V_{carrier}$). The reference signals have same amplitude & frequency. The reference signals are in phase with an offset value that is equivalent to the amplitude of the carrier signal. The each reference signal is compared with a carrier signal. If V_{ref1} has exceeded the peak amplitude of $V_{carrier,}$ V_{ref2} is compared with the $V_{carrier}$ until it has exceeded the peak amplitude of the $V_{carrier.}$ Then, further, V_{ref3} would be compared with $V_{carrier}$ until V_{ref3} crosses the zero crossing. Now, V_{ref2} would be compared until it reaches zero. Then, V_{ref1} would be compared with $V_{carrier}$ [15], [17].

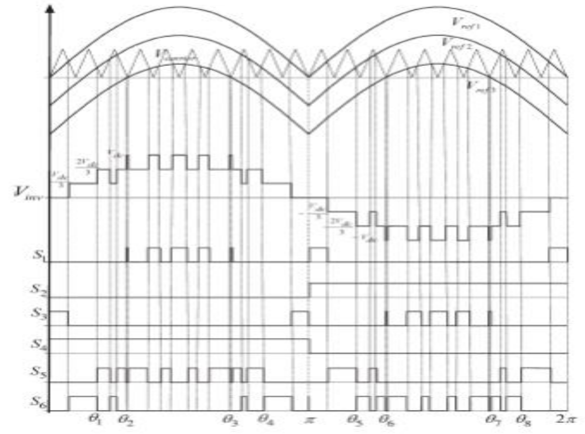

Figure 4 Switching Pattern for the single-phase seven-level inverter.

Table 4.2 Inverter output voltage of 7-level during S_1-S_6 switches on & off

V_o	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*

VI. BLOCK MODEL

Simulation block model of 7-level inverters are shown for various values of modulation indicates. 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 figure 5. 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. Photovoltaic (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.

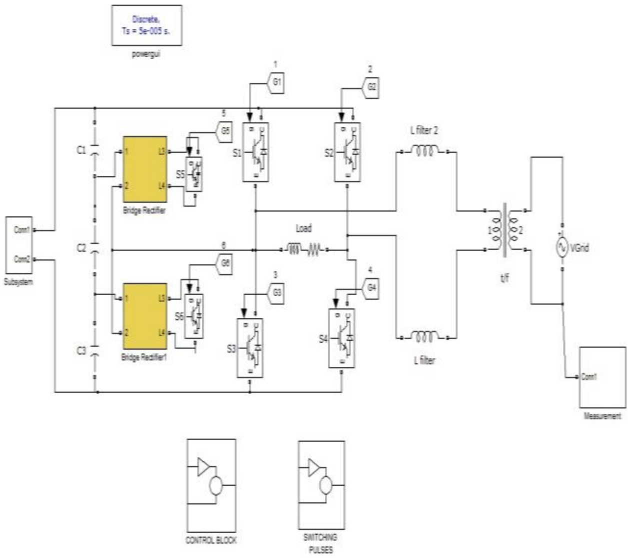

Figure 5 Main Block Model

Pv block model shown in figure 6

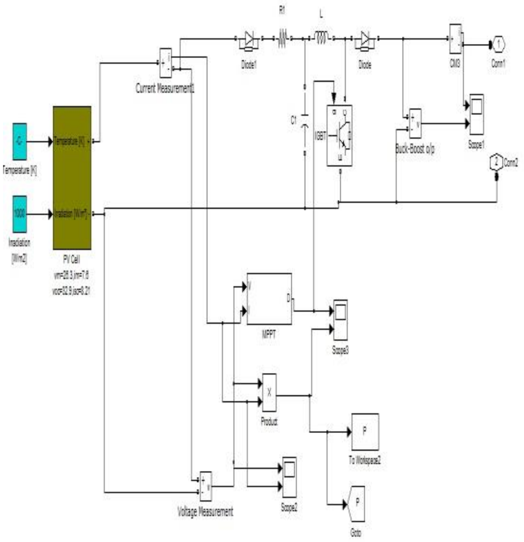

Figure 6 PV Model

The feedback controller used in this application utilizes the PI algorithm. As shown in Figure 5.3 the current injected into the grid, also known as grid current *Ig*, is sensed and fed back to a comparator which compares it with the reference current *I*ref. Reference current *I*ref is obtained by sensing the grid voltage and converting it to reference current and multiplying it with constant *m*. This is to ensure that *Ig*is in phase with grid voltage *Vg* and always at near-unity power factor [15], [18]. The constant m is known as modulation index which is utilized in the switching techniques for varying amplitude of the reference waves.

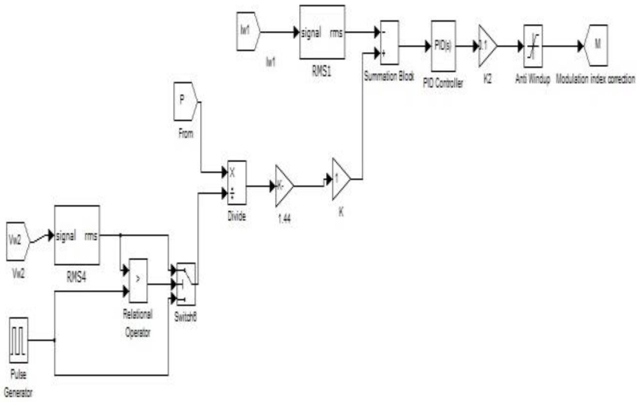

Figure 7 Control block model

Switching Pulse generation block model show in figure 8 and output measurement block show in figure 9

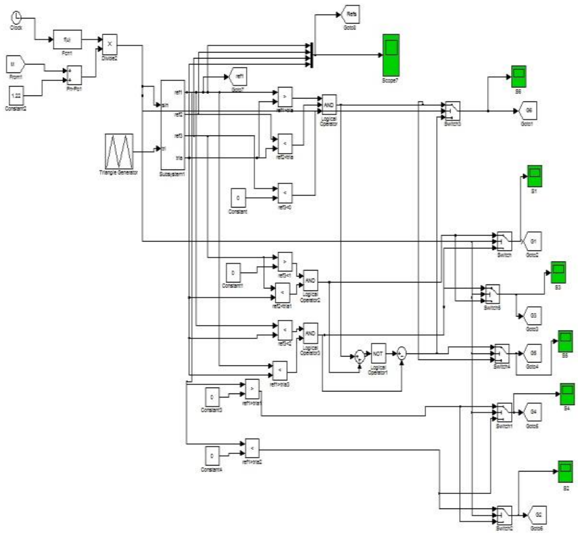

Figure 8 Switching Pulse block model

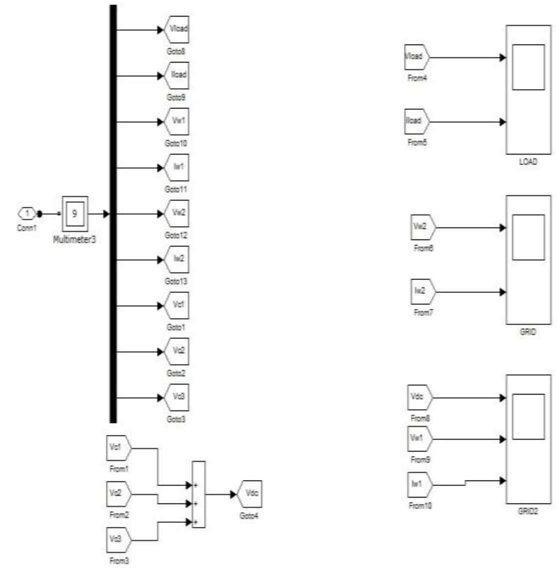

Figure 9 Output measurement block

VII. RESULTS

MATLAB SIMULINK simulated the proposed configuration before it was physically implemented in a prototype. The PWM switching patterns were generated by comparing three reference signals (*V*ref1, *V*ref2, and *V*ref3) against a triangular carrier signal show in figure 5.6. Subsequently, the comparing process produced PWM switching signals for switches *S*1–*S*6, as figure 5.7-5.12 show.

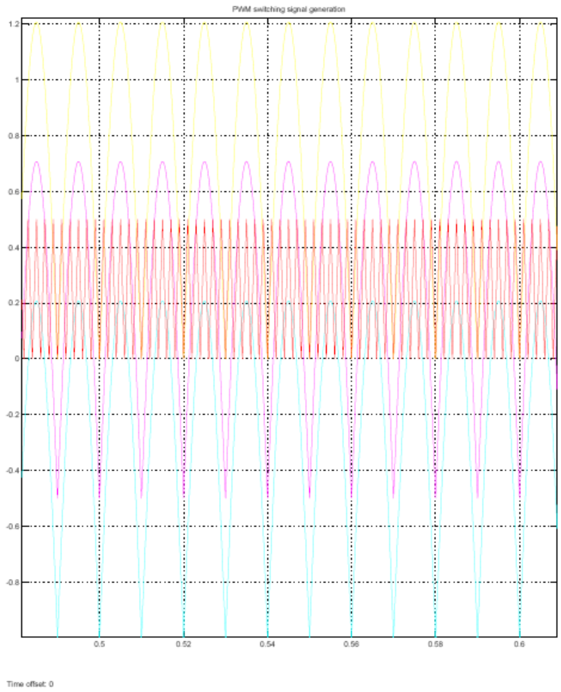

Figure 5.6 PWM Switching Signal Generation

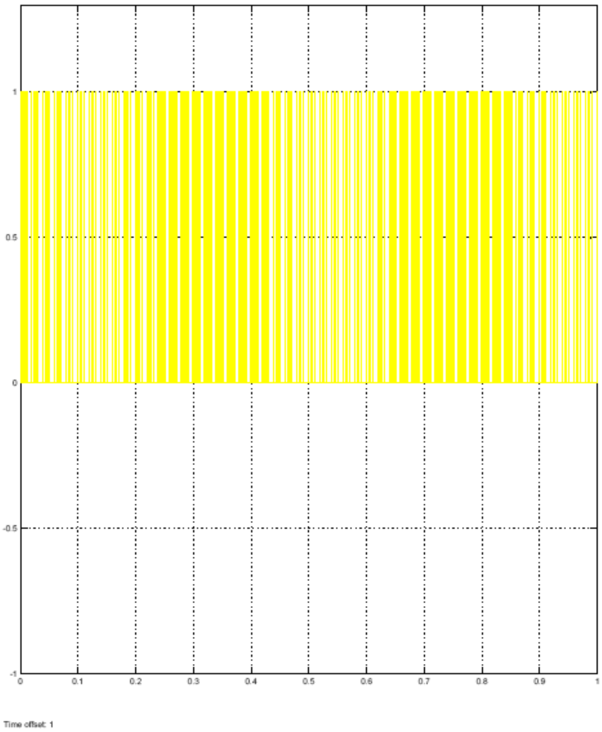

Figure 5.7 Switching Pulses S1

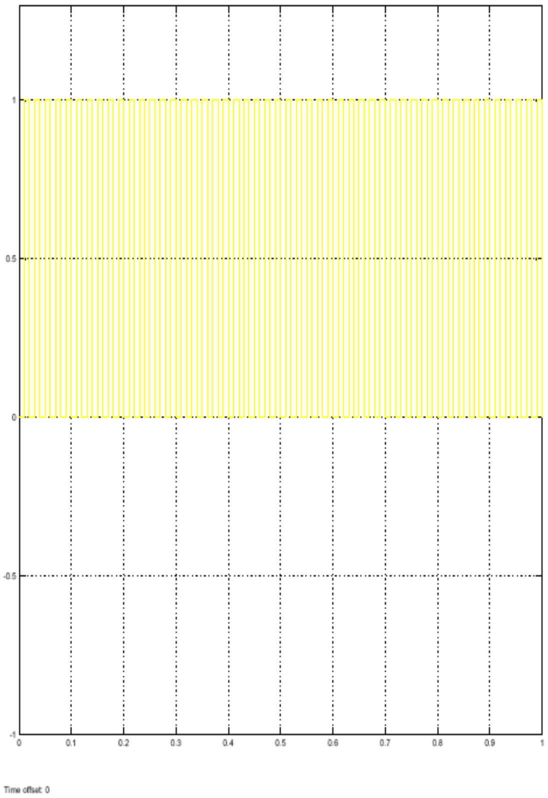

Figure 5.8 Switching Pulses S2

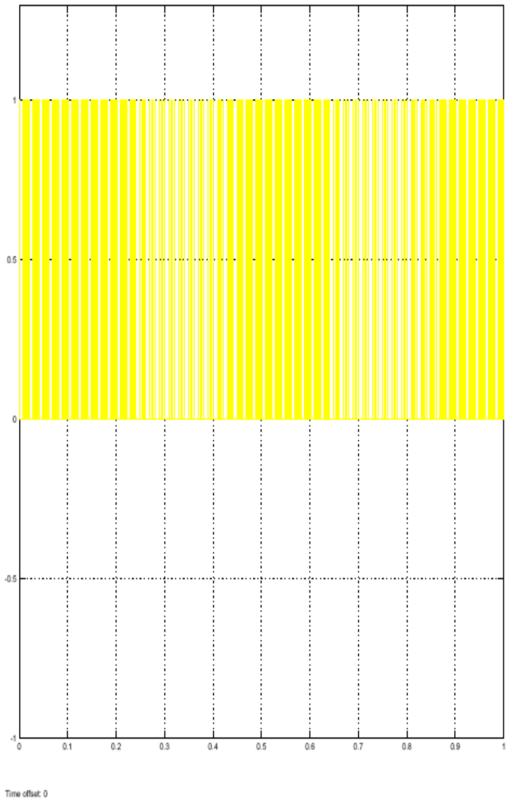

Figure 5.9 Switching Pulses S3

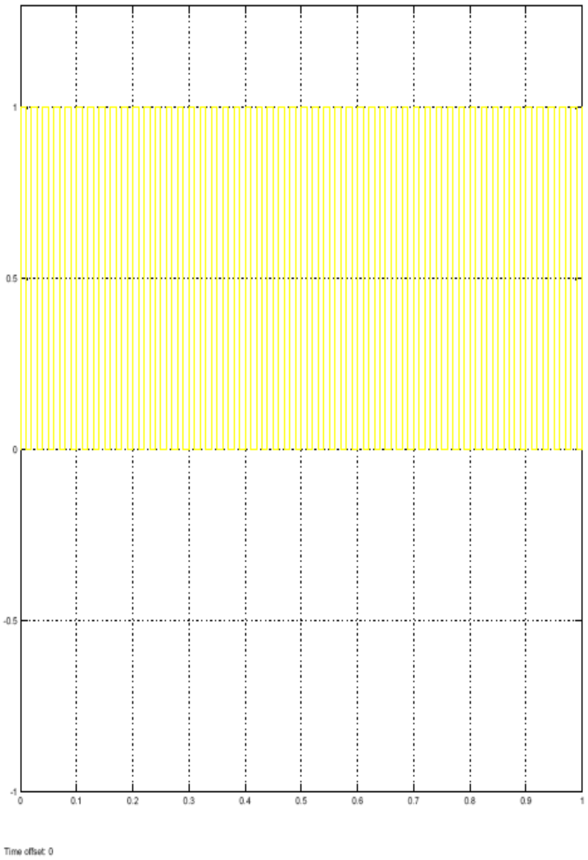

Figure 5.10 Switching Pulses S4

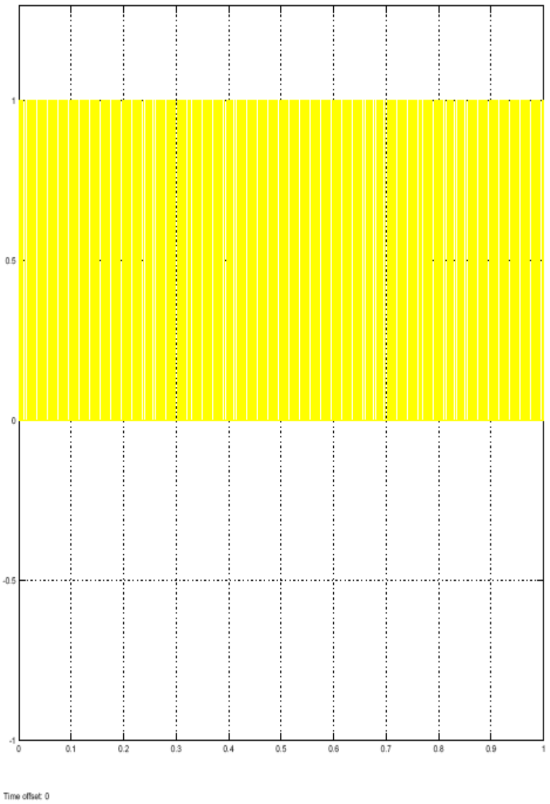

Figure 5.11 Switching Pulses S5

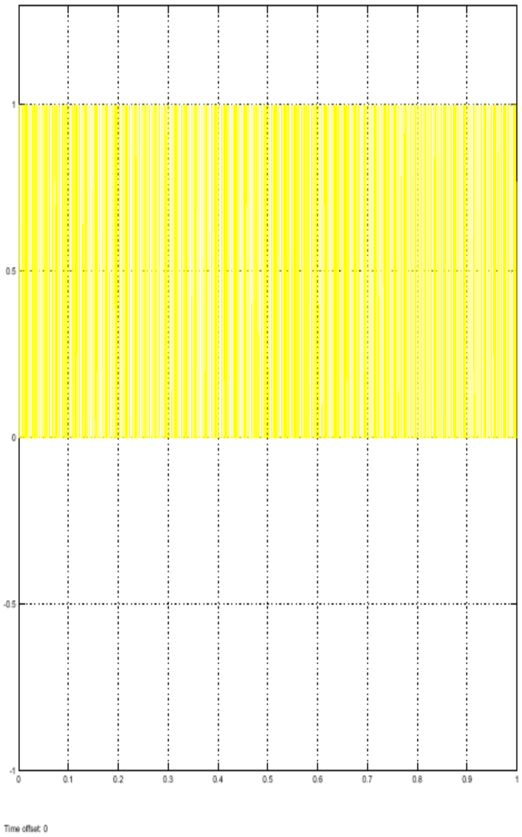

Figure 5.12 Switching Pulses S6

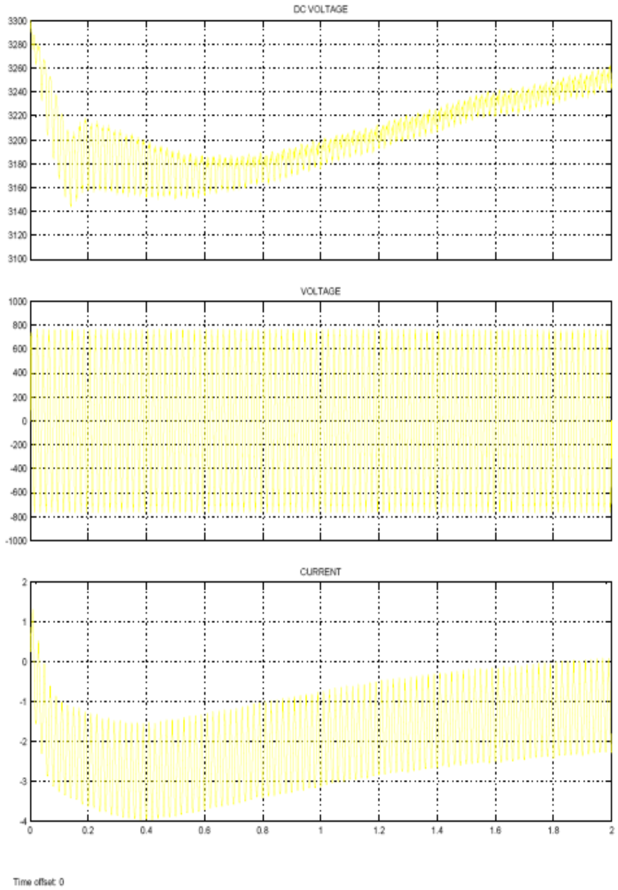

Figure 5.14 Grid-2 Voltages and Current

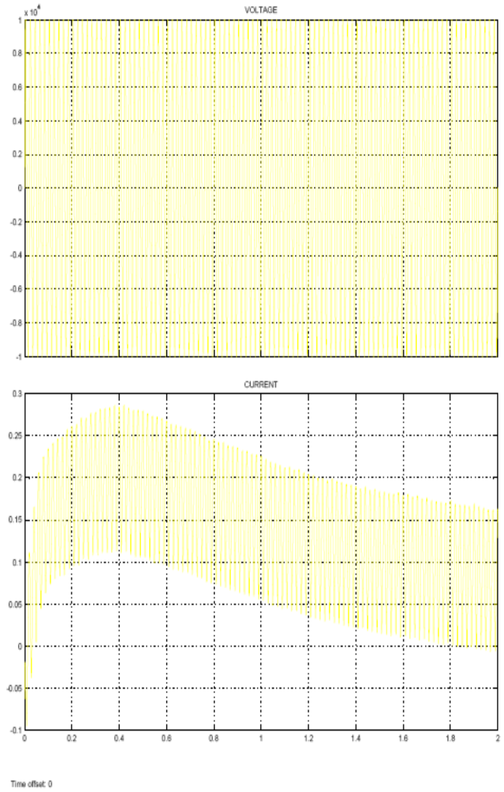

Figure 5.13 Grid-1 voltage and Current

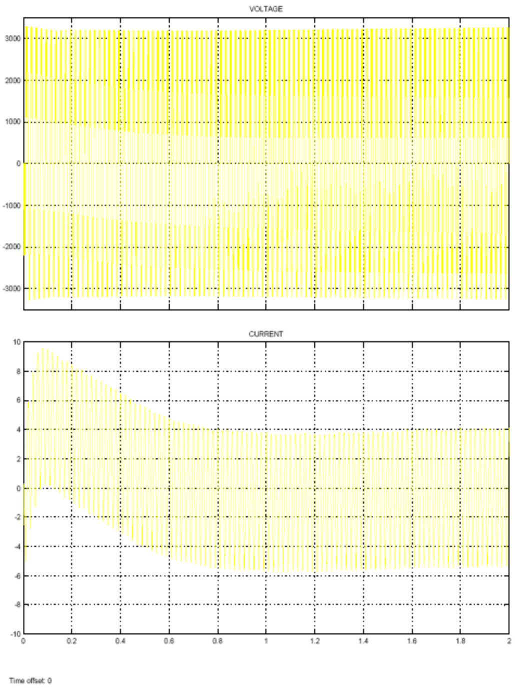

Figure 5.16 Load Voltages and Current

VIII. CONCLUSION

In this paper has provided a brief summary of 7-level inverter circuit topology and its analysis with respect to different types of loads. In the dissertation report, a control technique is used for maximization of the energy transferred from PV arrays to the grid, and generation of the sinusoidal current with minimum harmonic distortion. A PI controller is used to keep the output voltage of the dc-dc boost converter (V_{dc}) constant by comparing V_{dc} & V_{dcref} & feeding the error into the PI controller, which tries to reduce the error. In the dissertation work inverter utilizes the perturb-&-observe (P & O) algorithm for its wide usage in MPPT due to its simple structure & requirement of only a few measured parameters.

we have successfully presented the multilevel inverters offer improved output waveforms. 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.

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