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Single-Phase nine-level inverter for photovoltaic application

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Abstract - *Electrical power play a very important rule in 21th century, but non-conventional sources scale down day by day. Not only that concern for the environmental pollution around the world, so now a day's photovoltaic (PV) power systems are getting more and more widespread with the increase in the energy demand. This paper proposed a Single-Phase nine level inverter with voltage control method using semi conductor power devices for photovoltaic systems. The proposed inverter system gives better voltage regulation, smooth results and efficiency compared to multi-level inverters. The inverter is capable of producing nine levels of output voltage levels (V_{pv}, $3V_{pv/4}$,$V_{pv/2}$, $V_{pv/4}$, 0, -$V_{pv/4}$, -$V_{pv/2}$, -$3V_{pv/4}$, -V_{pv}). The proposed inverter was verified by using simulation of Matlab / Simulink software.*

Résumé - *L'énergie électrique joue un rôle très important au 21ème siècle, mais on observe une réduction progressive des ressources non conventionnelles. De nos jours, les systèmes photovoltaïques (PV) sont de plus en plus répandus en raison de l'augmentation croissante de la demande en énergie. Cet article propose un onduleur monophasé à neuf niveaux avec une méthode de contrôle du voltage qui met en jeu des dispositifs de puissance à semi-conducteurs destinés aux systèmes photovoltaïques. L'onduleur proposé permet une meilleure régulation de la tension et donne des résultats plus réguliers avec un rendement plus élevé que celui observé avec des onduleurs multi-niveaux. L'onduleur est capable de produire neuf niveaux de tension de sortie (V_{pv}, $3V_{pv/4}$, $V_{pv/2}$,$V_{pv/4}$, 0, -$V_{pv/4}$, , -$V_{pv/2}$, -$3V_{pv/4}$, -V_{pv}). L'onduleur proposé a été vérifié en effectuant des simulations sur Matlab/Simulink.*

Keywords: Photovoltaic (PV) system, Multi-level inverter, Semi conductor power devices, THD.

1. INTRODUCTION

As the world is troubled with the fossil fuel exhaustion and environmental problem caused by usual power generation, particularly solar have become very popular and demanding. PV sources are used in many applications because they have advantage of being maintenance and pollution free. It is used to convert the dc power from solar module to ac power to feed into load.

The production voltage of the inverters may be a square wave, quasi square wave or six stepped wave. Due to non sinusoidal nature, the inverter output voltage will have fundamental and the associated harmonics. Filters are used to reduce the harmonics. The recent development in power electronics has initiated to increase the level of inverter instead increasing the size of filter.

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The total harmonic distortion of the conventional two level inverter is very high. While multilevel inverter provides improved performance compare to the conventional two-level inverters. Multilevel inverters have less total harmonic distortion. The author [1] analyzed the total harmonic distortion between conventional two-level inverters and multilevel inverters. A well-known topology of this inverter is full-bridge three-level. Multilevel inverters are promising; they have nearly sinusoidal output-voltage waveforms, output current with better harmonic profile, less stressing of electronic components due to reduced 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 condensed [2, 3].

A variety of topologies for multilevel inverters have been proposed over the years. Familiar ones are diode-clamped [4, 5], flying capacitor or multicell [6, 7], cascaded Hbridge [8, 9], and simplified H-bridge multilevel [10, 11]. This paper describes the development of a simplified H-bridge single-phase multilevel inverter.

This paper is organized as follows. First, the photovoltaic system introduction, the power circuit advantages in section II and its configuration presented in section 3. Then, the power circuit operation includes the modes of operation in detail is discussed in section 4. Section 5 describes the simulation results and functionality verification with photovoltaic system.

2. PHOTOVOLTAIC SYSTEMS

A Photovoltaic system directly converts sunlight into electricity. The basic device of a photovoltaic system is the PV cell. Cells may be grouped to form arrays or panels. The voltage and current accessible at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. [12] A photovoltaic cell is basically a semiconductor diode whose p–n junction is exposed to light. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short-circuited.

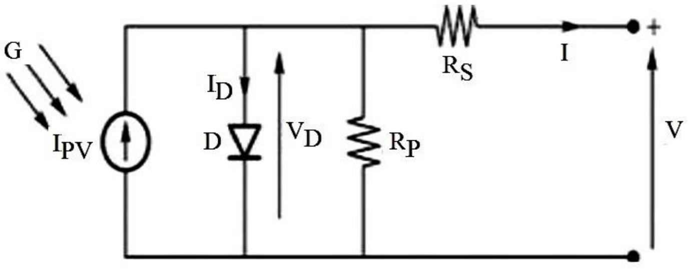

Fig. 1: Equivalent Circuit of a PV system

The correspondent circuit of PV cell is shown in Figure 1. In the above diagram the PV cell is represented by a current source in parallel with diode. R_S and R_P represent series and parallel resistance respectively. The output current and voltage from PV cell are represented by I and V.

The I-V characteristics of PV Cell are shown in figure 2. The net cell current I is composed of the light- generated current I_{pv} and diode current I_d.

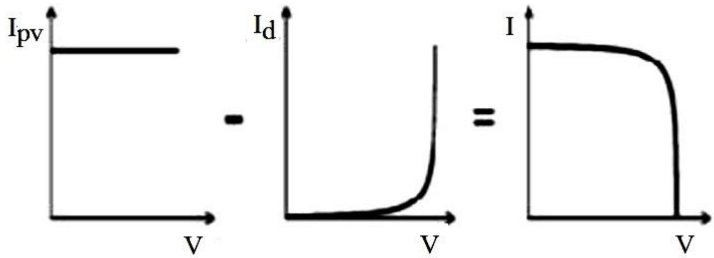

Fig. 2: Characteristic I–V curve of the PV cell

$$I = I_{pv} - I_d \qquad (1)$$

Where, I_0, leakage current of the diode, $I_d = I_0 \exp(q\,V / a.k.T)$, q, electron charge, k, Boltzmann constant, T, temperature of pn junction, a, diode ideality constant.

The fundamental equation (1) of PV cell does not represent the I-V characteristic of a practical PV array. Practical array are composed of several connected PV cells and the examination of the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation.

$$I = I_{pv} - \left[\exp(V + \frac{R_{Sl}}{V_{ta}}) - 1 \right] - \frac{(V + R_{Sl})}{R_p} \qquad (2)$$

Where, $V_t = NskT / qs$, is the thermal voltage of the array with Ns cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. The I-V characteristics of a practical PV cell with maximum power point (MPP), short circuit current (I_{SC}) and open circuit voltage (V_{OC}) is shown in figure 3. The MPP represents the point at which maximum power is obtained.

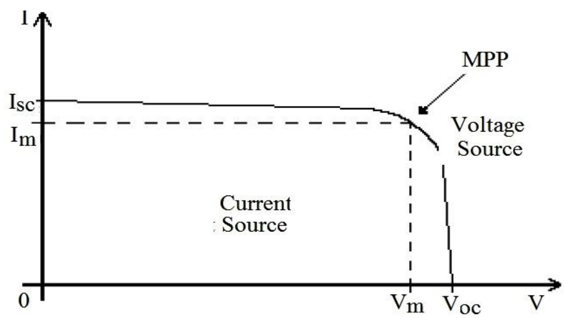

Fig. 3: I-V Characteristic of the practical PV cell

V_m and I_m are voltage and current at MPP respectively. The output from PV cell is not the same throughout the day, it varies with varying temperature and radiation. Therefore with varying temperature and insulation maximum power should be tracked so as to achieve the efficient operation of PV system.

3. POWER CIRCUIT

3.1 Power Circuit Advantages

A single-phase simplified multilevel inverter has the following merits over other existing multilevel inverter topologies.

1) It consists of single-phase conventional H-bridge inverter, bidirectional auxiliary switches (number varies depending upon level) and a capacitor voltage divider formed by capacitors.

2) Improved output waveforms.

3) Smaller filter size.

4) Lower electromagnetic interference (EMI) and total harmonic distortion (THD).

5) Reduced number of switches employed.

6) Less complexity of the circuit as the levels increase.

7) Attains minimum 40% drop in the number of main power switches required. Moreover, since the capacitors are connected in parallel with the main dc power supply, no significant capacitor voltage swing is produced during normal operation, avoiding a problem that can limit operating range in some other multilevel configurations.

The single-phase simplified nine-level inverter proposed was developed from the five-level inverter in [10, 13]. It contains a single-phase conventional H-bridge inverter, three supplementary switches S5, S6, S7 and a capacitor voltage divider formed by four capacitors namely Cl, C2, C3 and C4, as illustrated in figure 5. The supplementary switches, formed by the controlled switch S5, S6 and S7.The single-phase simplified nine-level inverter proposed power circuit with supplementary switches is shown in figure 4.

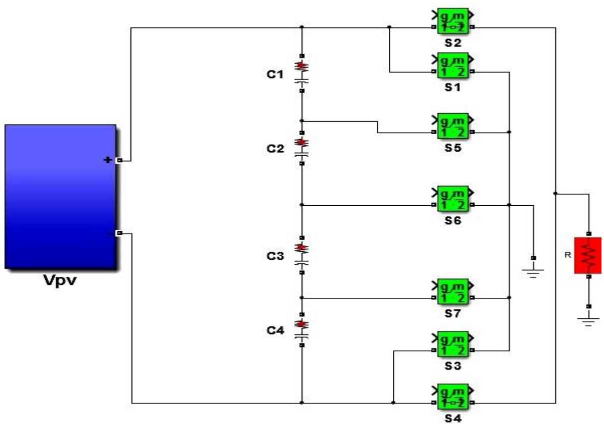

Fig. 4: Simplified nine-level inverter proposed power circuit

4. POWER CIRCUIT OPERATION

The single-phase proposed is capable of producing nine different levels of output-voltage levels (Vpv, $3Vpv/4$, $2Vpv/4$, $Vpv/4$, 0, $-Vpv/4$, $-2Vpv/4$, $-3Vpv/4$, $-Vpv$) from the dc supply voltage Vpv, shown in figure 5.

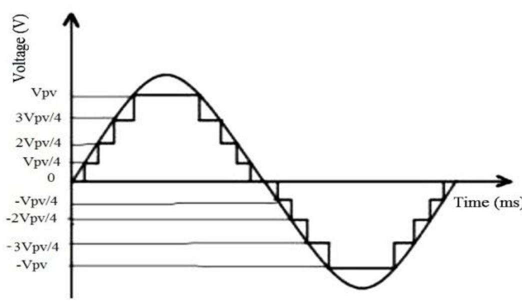

Fig. 5: Single-phase proposed output voltage waveform

The required nine levels of output voltage were generated as follows and can be easily understand by the **Table 1**.

A. Mode 1 operation

The switch S1 is ON, connecting the load positive terminal to Vpv, and S4 is ON, connecting the load negative terminal to ground. Remaining switches S2, S3, S5, S6 and S7 are OFF; the voltage across the load terminals R is Vpv.

B. Mode 2 operation

The bidirectional switch S5 is ON, connecting the load positive terminal, and S4 is ON, connecting the load negative terminal to ground. Remaining switches Sl, S2, S3, S6 and S7 are OFF; the voltage across the load terminals R is 3Vpv/4.

C. Mode 3 operation

The bidirectional switch S6 is ON, connecting the load positive terminal, and S4 is ON, connecting the load negative terminal to ground. Remaining switches Sl, S2, S3, S5 and S7 are OFF; the voltage across the load terminals R is 2Vpv/4.

D. Mode 4 operation

The bidirectional switch S7 is ON, connecting the load positive terminal, and S4 is ON, connecting the load negative terminal to ground. Remaining switches S1, S2, S3, S5 and S6 are OFF; the voltage across the load terminals R is Vpv/4.

E. Mode 5 operation

This mode of operation has two possible switching combinations. Either switches S3 and S4 are ON, remaining switches S1, S2, S5, S6 and S7 are OFF or S1 and S2 are ON, remaining switches S3, S4, S5, S6 and S7 are OFF. In both switching combinations terminal ab is short circuited, hence the voltage across the load terminals R is zero.

F. Mode 6 operation

The switch S2 is ON, connecting the load negative terminal, and bidirectional switch S5 is ON, connecting the load positive terminal to ground. Remaining switches S1, S3, S4, S6 and S7 are OFF; the voltage across the load terminals R is −Vpv/4.

G. Mode 7 operation

The switch S2 is ON, connecting the load negative terminal, and bidirectional switch S6 is ON, connecting the load positive terminal to ground. Remaining switches S1, S3, S4, S5 and S7 are OFF; the voltage across the load terminals R is −2Vpv/4.

H. Mode 8 operation

The switch S2 is ON, connecting the load negative terminal, and bidirectional switch S7 is ON, connecting the load positive terminal to ground. Remaining switches S1, S3, S4, S5 and S6 are OFF; the voltage across the load terminals R is −3Vpv/4.

I. Mode 9 operation

The switch S2 is ON, connecting the load negative terminal to Vpv, and S3 is ON, connecting the load positive terminal to ground. Remaining switches S1, S4, S5, S6 and S7 are OFF, the voltage across the load terminals R is −Vpv.

In the nine-level inverter circuit three capacitors in the capacitive voltage divider are connected directly across the dc supply voltage Vpv and since all switching combinations are activated in an output cycle, the dynamic voltage balance between the three capacitors is automatically restored.

Table 1: Switching combinations required to generate the nine-level output voltage waveform

Vo	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*
Vpv	1	0	0	1	0	0	0
3Vpv/4	0	0	0	1	1	0	0
2Vpv/4	0	0	0	1	0	1	0
Vpv/4	0	0	0	1	0	0	1
0	1	1	0	0	0	0	0
0+	0	0	1	1	0	0	0
(-)Vpv/4	0	1	0	0	1	0	0
(-)2Vpv/4	0	1	0	0	0	1	0
(-)3Vpv/4	0	1	0	0	0	0	1
(-)Vpv	0	1	1	0	0	0	0

5. SIMULATION RESULTS

The Matlab Simulink model of the single-phase simplified nine-level inverter and photovoltaic system circuit is shown in figure 6.

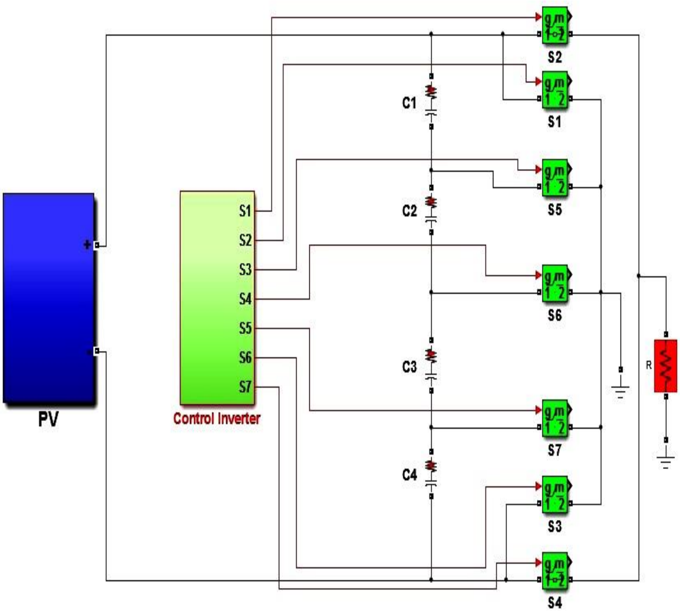

Fig. 6: Single-phase inverter and PV system simulation circuit

This form, developed using the Simulink power system block set, comprises of components such as power electronic devices (MOSFETs) and elements such as capacitors and resistors.

The PWM signals for each of the switching devices in the power circuit come from the PWM generator block. This block includes all the PWM signals required for switches are multiplexed on a single bus to the nine –level inverter power circuit. The switching sequence required for the simplified nine-level inverter proposed circuit is shown in figure 7.

Fig. 7: Switching sequence required for switches S1-S7

Figure 8 shows the simulated nine-level output voltage waveform of the proposed circuit.

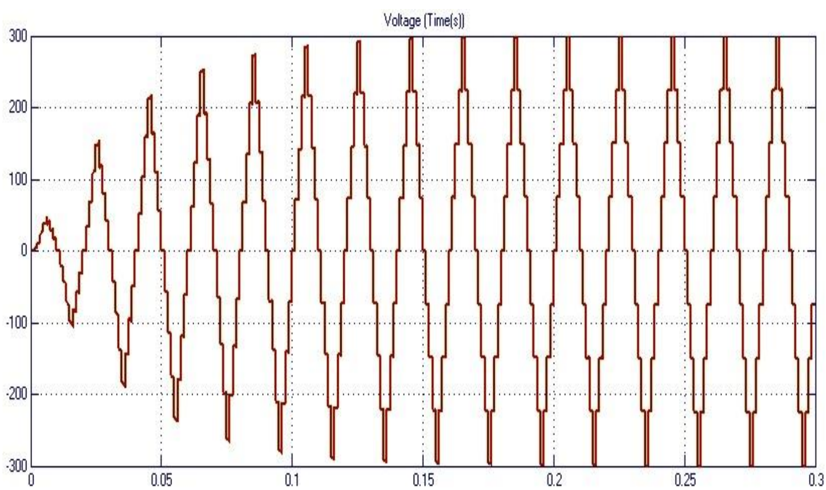

Fig. 8: Output voltage waveform of the simplified nine-level inverter proposed circuit. (Vpv bus = 300 V)

It is clearly visible that the simulated output waveform is very close to the ideal output defined for a simplified nine-level inverter proposed circuit. The nine-levels of voltages are $Vpv = 300V$, $3Vpv/4 = 225V$, $2Vpv/4 = 150V$, $Vpv/4 = 75V$, OV, $-Vpv/4 = -75V$, $-2Vpv/4 = -150V$, $-3Vpv/4 = -225V$, $Vpv = -300V$.

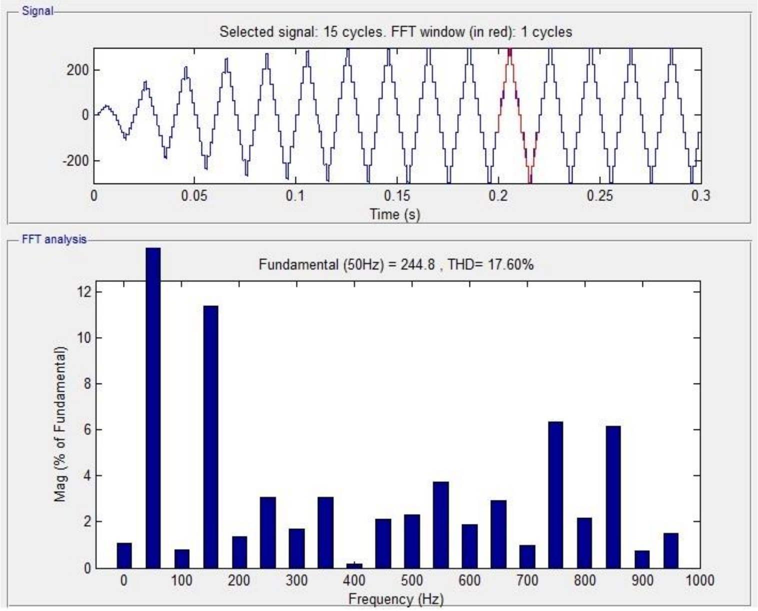

Fig. 9: THD of proposed system

The Total Harmonic Distortion (THD) of the nine- level inverter is observed that 17.60 % and fundamental voltage is 244.8V(50Hz) that has been illustrated in figure 9.

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