SIMULATION OF SINGLE PHASE TRANSFORMER-LESS FIVE-LEVEL INVERTER FOR PV APPLICATIONS

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Abstract:

The transformer-less single-phase five-level Photovoltaic (PV) inverter is presenting in this paper. The Photovoltaic (PV) module is connecting to the proposed topology with different values of irradiation and temperature. The modelling of the PV cell is also representing in this research activity. The output voltage of the PV is stepped up by using DC-DC Boost converter further operation of the topology. The sinusoidal PWM control technique is proposed for this topology. Two reference sinusoidal signals are comparing by the magnitude of the carrier triangular signal for the generation of PWM pulses to the switches. The operating states of the proposed topology are explaining in detail. With the reduced switch inverter topology, the switching, conduction losses are reducing. This proposed topology will be simulated in MATLAB/SIMULINK to produce the output of five-level with the less number of switches.

Keywords: PV Module, Boost DC-DC Converter, Sinusoidal PWM, five-level inverter.

I. Introduction

Generation of electrical energy from fossil fuels causes pollution and releases the hazardous gases which damage the environment. Many Researchers are worked for the alternatives to generate the electric power and they found Renewable energy sources which do not shows any impact on the environment [V]. For the development of renewable energy systems, power electronic circuits are used for the reliable and continuous power supply [VIII]. The sources of renewable energy such as solar, biogas, tidal, wind are widely used for the electric power generation from the past two decades. In renewable energy systems, the usage of Photovoltaic system is growing rapidly because, it is clean, non-pollutant, high efficiency, and long life [III]. The grid-connected PV system is the most popular integrating technique in the renewable energy system [I]. The PV system can be linked to the grid with transformers and without transformers [IX]. The transformer connected PV system is
categorized into two types, low-frequency transformers and high-frequency transformers [IV]. In transformer type inverters, between grid and PV system the galvanic isolation should be made by placing low and high-frequency transformers on Grid and supply-side respectively [X]. The transformer type inverters are making the system bulky, very expensive, complex, and causes high power losses [VII]. For low power, single-phase inverter system requires high power density, low complexity and low cost. The transformer-less PV inverters can overcome the drawbacks of the transformer type inverters [XI]. The transformer-less PV inverters are most preferable to integrating with the grid due to its advantages such as high efficiency, high power, low cost and low complexity [VI]. The galvanic isolation in transformer-less PV inverter between the grid and PV module should be made very carefully. For PV inverters, the parasitic capacitance is obtained between the ground and the PV module [XI]. This parasitic capacitance will produce the high ground leakage currents for high-frequency voltage in the transformer-less grid-connected PV inverter [XII]. The leakage currents are producing high harmonic currents, reducing efficiency, creating personal safety problems and Electromagnetic interference problems in the systems [XIII].

II. Modelling of PV:

A Photovoltaic cell is a semi-conductor device which obtains the electrical energy from the light energy. The Photovoltaic cells are manufactured by using semiconductor materials such as polysilicon, monocrystalline silicon. The usage of PV cells is increasing rapidly due to advantages like low maintenance, no pollution etc. Nowadays, the PV cells are more populated using electrical vehicles, grid-connected system, battery chargers, power systems. In the PV module, the PV cells are connected in series to obtain the electrical energy. The PV module can exhibit the non-linear characteristics due to having the non-linear elements such as diodes, current sources and resistors. Normally, the PV cell has one current source, parallel-connected diode, a resistor in series $R_{ser}$, and resistor in shunt $R_{sh}$ as presented in Fig.1.

The representation of photovoltaic cell to obtain the V-I characteristics is given as eq. (1)

$$I = I_{ph} - I_o \left[ e^{\frac{q(V+I-R_{sh})}{nKT}} - 1 \right] - I_{sh}$$

Where, $I_{ph}$ = Photo current  
$I_o$ = saturation current  
$I_{sh}$ = shunt resistor current  
$q$ = electron charge in Columbs  
$n$ = diode ideality factor  
$k$ = Boltzmann’s constant  
$N_s$ = Number of cells placed in series  
$T$ = effective temperature in Kelvin
The three parameters $I_{ph}$, $I_o$, and $I_{sh}$ have to be determined to understand the performance of the PV cell. The photo current will be calculated as

$$I_{ph} = [I_{sc} + k_i(T - 298)] \frac{G}{1000}$$  

Where, $G$ = solar irradiation ($\text{w/m}^2$)  
$I_{sc}$ = current under short circuit  
$k_i$ = current constant under short circuit

The saturation current is represented as

$$I_o = I_{rs} \left( \frac{T}{T_n} \right)^{3} \left[ \frac{aE_{go}(\frac{1}{T_n} - \frac{1}{T})}{\pi k} \right]$$  

Where,  
$I_{rs}$ = reverse saturation current  
$T_n$ = nominal temperature in Kelvin  
$E_{go}$ = Bandgap energy of semiconductor

The current through shunt resistor $R_{sh}$ is given as

$$I_{sh} = \frac{v + i R_s}{R_{sh}}$$  

The PV module characteristics mainly depend on temperature and solar irradiation. The PV cell characteristics are non-linear, so the MPPT controlis to be designed for the PV applications. The specifications of the PV cell is given in Table.1.
### III. Modelling of DC-DC Boost Converter:

The general function of the DC-DC Boost converter is to step-up the low dc voltage to high dc voltage. The boost converter contains a semiconductor switch like Mosfet, IGBT, input voltage source, diode, energy stored inductor, and the capacitor is given in Fig. 2. The two operating modes of boost converter will understand the performance of the converter.

![Boost DC-DC converter](image)

**State – I:** In this state, the semiconductor switch S will conduct, the input current is passing through the inductor, and the switch S produces the inductor voltage $V_L$ equivalent to the input voltage $V_i$. The inductor voltage in this state is given as

$$v_i = v_L = L \frac{di_L}{dt}$$

The current in the inductor is

$$i_L = \frac{1}{L} \int_{t_0}^{t_{on}} v_i dt$$

$$i_L = \frac{1}{L} v_i t_{on} \tag{5}$$

**State – II:** In this state, the semiconductor switch S will not conduct, the input current $i_L$ is passing through the inductor, diode and the resistor to obtain the output voltage. The output voltage is the combination of the stored energy of the inductor $V_L$ and the supply voltage $V_i$. 

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**Table 1: Specifications**

| Specification                        | Value  |
|--------------------------------------|--------|
| Power rated                          | 200W   |
| Voltage due to maximum power $V_{mp}$| 26.4V  |
| Current due to maximum power $I_{mp}$ | 7.58A  |
| Voltage of open circuit $V_{OC}$      | 32.9V  |
| Current due to short circuit $I_{SC}$ | 8.21A  |
| Number of cells placed in series     | 54     |
| Number of parallel-connected cells   | 1      |
\[ v_o = v_i + L \frac{di_L}{dt} \]

The current in the inductor during the time interval of \( t_{on} - t_{off} \) is

\[ i_L = \int_{t_{on}}^{t_{off}} \left( \frac{v_o - v_i}{L} \right) \, dt \]

\[ i_L = \left( \frac{v_o - v_i}{L} \right) [t_{off} - t_{on}] \tag{6} \]

Comparing Eq (5) and Eq (6),

\[ v_o = \left( \frac{1}{1 - D} \right) v_i \]

where \( D \) is the duty cycle, \( D = 0 \rightarrow 1 \).

**IV. Proposed Topology:**

The Transformer-less single-phase five-level PV inverter is presented in Fig. 3. This topology required less number of switches compared to the classical topologies. The supplementary switch and single full-bridge inverter are utilized in this topology. The PV module is acting as an excitation to the DC-DC Boost converter. The DC-DC Boost converter raises the PV module voltage to the \( \sqrt{2} \) times and acts as input to the reduced switch MLI. The low harmonic sinusoidal current should be injected in the topology. For the generation of sinusoidal current, the Sinusoidal PWM technique works very effectively. The two reference sinusoidal signals are matched by the magnitude of carrier triangular signal to obtain the SPWM pulses. If the reference-1 signal \( V_{ref1} \) is greater than the magnitude of carrier signal \( V_{carrier} \), reference-2 signal \( V_{ref2} \) is compared by the carrier signal \( V_{carrier} \) before it comes to zero.

![Fig. 3: Five level Inverter for PV application](image)

*Fig. 3: Five level Inverter for PV application*
V. Operating Modes of Topology:

The PV arrays are acts an input source voltage and produce the Voltage $V_{array}$, it is raised to $\sqrt{2}$ times of grid voltage by using Boost dc-dc converter. The dc-link capacitor voltage $V_{dc}$ is produced by the boost converter. The topology produces the five-level output voltage, i.e. $-V_{dc}/2$, $-V_{dc}$, 0, $+V_{dc}$, $+V_{dc}/2$. The supplementary circuit is used in this topology, which has four diodes, and single switch $S_1$. Based on the switching pulses, the supplementary circuit will make the part level of dc-link voltages, $-V_{dc}/2$ and $+V_{dc}/2$. The $S_1$, $S_2$, and $S_3$ switches are operating with the carrier frequency, switches $S_4$ and $S_5$ are operating with the fundamental frequency. The $S_2$, $S_3$ switches and $S_4$, $S_5$ switches are operated complementally for the entire operation. The five-level ac output voltage will obtain by the different conducting states of the topology.

In state-1, $S_1$ and $S_5$ switches will conduct as represented in Fig. 4(a). The input current is passed through the capacitor $C_1$, diodes of the supplementary circuit, switch $S_1$, resistor $R$, and switch $S_5$ to produce the positive half level of dc-link voltage $+V_{dc}/2$.

In state-2, $S_2$ and $S_5$ switches are in conduction state is shown in Fig. 4(b). The supplementary circuit is not working in this mode. The input current flow through the $S_1$ switch, resistor $R$, $S_5$ switch to produce the positive output voltage $+V_{dc}$.

| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $V_o$  |
|-------|-------|-------|-------|-------|--------|
| A     | NA    | NA    | NA    | A     | $+V_{dc}/2$ |
| NA    | A     | NA    | NA    | A     | $+V_{dc}$   |
| NA    | NA    | NA    | A     | A     | 0      |
| A     | NA    | NA    | A     | NA    | $-V_{dc}/2$ |
| NA    | NA    | A     | A     | NA    | $-V_{dc}$ |

A:Active; NA: Not Active

In state-3, $S_1$ and $S_4$ switches will conduct as presented in Fig. 4(c). The circuit current is passing over the $S_4$ switch, Resistor $R$, diodes of the supplementary circuit, switch $S_1$, and capacitor $C_2$ to produce negative half level $-V_{dc}/2$ output voltage.

In state-4, $S_3$ and $S_4$ switches are in conduction state as represents in Fig. 4(d). The current in the circuit will flow through the $S_4$, resistor $R$, the switch $S_3$ to make the negative $-V_{dc}$ output voltage. The switching operation of topology is given in Table 2.
VI. Simulation Results:

The single-phasetransformer-lessfive-level PV inverter is practically implemented by using MATLAB/SIMULINK is shown in Fig.5
The photovoltaic (PV) cell with different values of temperatures and irradiation is connected to the proposed topology. The DC-DC Boost converter is placed in between the topology and PV cell to increase the voltage. By using MPPT, the PV cell is performance is controlled. The sinusoidal PWM method is used to provide gate pulses to the switches as shown in Fig.6.

The two reference sinusoidal signals are related by the amplitude of carrier triangular signal which produces the gate pulses to the switches as shown in Fig.7. The supplementary switch and one arm of the inverter work at the high frequency, which is same as carrier frequency, another arm of the inverter operates at the supply frequency 50Hz.
Fig. 7: Switching pulses to the switches $S_1 - S_5$.

The PV cell characteristics with different irradiation values 600 W/m$^2$, 800 W/m$^2$, 1000 W/m$^2$ are shown in Fig. 8. If the insulation decreases, the voltage due to open circuit $V_{OC}$ is decreases and current due to short circuit $I_{SC}$ also drops. The PV power output is decreased, if the solar radiation is decreased, which shows in Fig. 9.
The DC-DC Boost converter is utilized to raise the voltage of the PV cell, the simulation of response voltage is displayed in Fig. 9. The converter voltage first raises to the 460V, then it settles to the steady-state voltage of 250V. The transformer-less single-phase reduced switch five-level PV inverter output voltage is displayed in Fig. 10. The load resistance and capacitor values are 50Ω and 2100μF respectively. For positive voltage output, \( S_1 \) and \( S_5 \) switches are operated for \(+V_{dc}/2\), \( S_2 \) and \( S_5 \) switches are operated for \(+V_{dc}\). For negative voltage output, \( S_1 \) and \( S_4 \) switches are operated for \(-V_{dc}/2\), \( S_4 \) and \( S_3 \) switches are operated for \(-V_{dc}\).

![Fig.9: Simulation response of DC-DC Boost converter.](image)

![Fig.10: Simulation output voltage of five-level inverter.](image)

**VII Conclusion:**

The single-phase Transformer-less five-level PV inverter is simulated in MATLAB/SIMULINK. The mathematical modelling of Photovoltaic (PV) cell, the DC-DC Boost converter is analyzed. The characteristics of the PV cell will exhibit the nonlinear function of the PV cell. The PV cell output is stepped-up by using DC-DC Boost converter. For gating pulses, the two sinusoidal reference signals are matched with the magnitude of carrier triangular signal at the operating frequency. The different operating modes of the proposed topology is explained in detail. With the
obtained five-level output voltage with reduced switches, the cost is less, switching and conduction losses are reduced and improves the system efficiency than the conventional inverter.

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