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Simulation of Leakage current and THD Compensation in a Large PV system

Mohamed Youssef Tarnini[1], Nabil Abdel-Karim[2] and Khaled Chahine[3]

[1, 2, 3] Beirut Arab University, Electrical and Computer Department,
Power and Machines Program, Debbieh, Lebanon.

[1]Orcid ID: 0000-0001-7726-4598 and ResearcherID: C-7393-2016

Abstract

In the recent years the applications of solar energy and photovoltaic panels PV were increasing rapidly in order to minimize the consumption of traditional fuels and hence decrease the overall KWh generation cost, also to minimize the CO_2 emission that is harmful to the environment. The application of large PV panels with transformer-less inverter leads to the so-called discharging current problems associated with natural capacitance between different panels and the ground. Moreover, the presence of the capacitance between different layers of the same panel adds more complexity to the problem. This paper focuses on the performance of a modified H5 bridge for such problems. The proposed single phase solution minimizes the overall natural capacitance and hence attenuating the impact of the harmful leakage current below standard limits with a fast response and low price. Also, the proposed solution is associated with an effective filter in order to increase the effectiveness of such systems. The simulation of uncontrolled and fully controlled with suitable filter was performed in order to validate the proposed method.

Keywords: Leakage currents; PV panels; renewable energy sources and THD.

INTRODUCTION

When a PV system is connected to the grid, safety standards should be met during operation for reliability, power quality and protection. Transformer-less photovoltaic inverters (TPVI) are increasing rapidly in the world markets due to their higher efficiency, small size, lower cost and lighter weight compared to their counterpart transformer based PV inverters [1].

Nevertheless, the elimination of transformers leads to a direct galvanic connection between the PV panels and the grid, thus creating a leakage current due to the formation of parasitic capacitance between the layers of PV panels and the PV-ground system. The THD noise problem also increases due to elimination of the isolation represented by traditional transformers or due to the formation of leakage capacitance currents [2]. High-frequency currents can cause often electromagnetic noise that may affect the operation of some sensitive electronic devices. The higher the frequency of the distribution transformer, the poorer the voltage quality across the equivalent impedances of the grid. Finally, both problems of leakage current and THD lead to serious safety issues, especially for the applications when the leakage current or THD exceeds the standard limits [3].

This paper, shows the simulation work of unprotected H4 and protected H5 single phase transformer-less models for a PV grid connected system with a suitable filter to study the behavior of the leakage currents for both cases and to show the validity of this method in minimizing the leakage current to meet VDE-0126-1-1 German standard and A8-2014 IEEE which limits the leakage current to 30-mA.

The proposed method deals with an inverter design implementation to reduce the leakage current by means of decoupling (or isolating) the AC from DC side during zero states via establishing proper switch configurations.

In general, to guarantee the safety of operation and protection of the overall PV installation, and to prevent harmful effects resulting from the flow of leakage current, the load THD current and the leakage current should be limited to values set by the international standards such as German and IEEE standards [6].

MATHEMATICAL MODEL OF UNPROTECTED SYSTEM

Fig. 1 shows a typical single phase transformer-less PV system. The dangerous effect of the leakage current traveling to the grid is represented by the amount of RMS value and by the THD. The electric equivalent model of Fig. 1 is shown in Fig. 2 for analysis purpose. In this application, the THD is limited to 5% as per IEEE standard and is given by:

$$THD = \frac{\sqrt{\sum_{n=2}^{\max} I_n}}{I_{fundamin\,tal}} \tag{1}$$

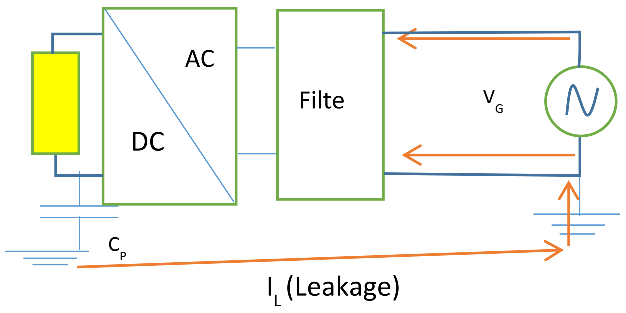

Figure 1: Leakage ground current path in a transformer-less PV inverter

In order to simplify the analysis, the above circuit is converted into its common mode (CM) and deferential mode (DM) models. In Fig. 2, Z_G is the ground impedance, Z_P and Z_N are the line and neutral impedances of the electrical line between the medium voltage/ low voltage transformer and the Point of connection of the PV system respectively, whereas L_P and L_N are the decoupling inductors between the grid and the inverter. C_{PV} is the equivalent parasitic capacitances to ground of the PV system, V_{A0} and V_{B0} are the voltages generated by the front-end inverter, the Differential-Mode current IDM, and the common-mode current ICM are generated by the photovoltaic inverter.

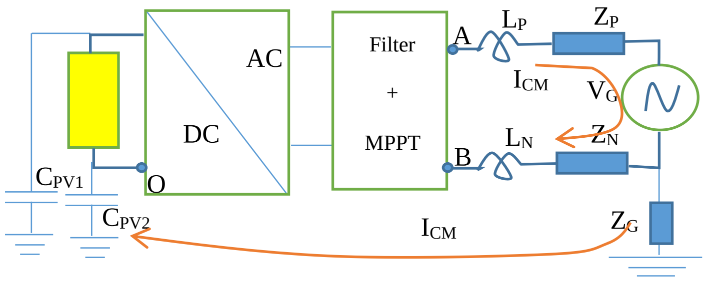

Figure 2: Single phase transformer-less PV system

The grid impedance Z_P and Z_N have a tendency to limit the leakage current, therefore the critical case or the maximum value of the leakage occurs when $Z_P = Z_N = 0$. In this case, a simplified version of Fig.2 is depicted by Fig. 3 where the common mode voltage VCM and differential mode voltage VDM can be expressed as [7]

$$u_{CM} = \frac{u_{AO} + u_{BO}}{2} \quad (2)$$

$$u_{DM} = u_{AB} = u_{AN} - u_{BN} \quad (3)$$

$$u_{AO} = u_{CM} + \frac{u_{DM}}{2} \quad (4)$$

$$u_{AO} = u_{CM} - \frac{u_{DM}}{2} \quad (5)$$

And the leakage current can be calculated as:

$$I_{CM} = \frac{SC_{PV}}{1 + sC_{PV} Z_G(s) + s^2 C_{PV} L_{PN}} \left[\frac{L_N u_{AO}(s) + L_P u_{BO}(s)}{L_P + L_N}\right] \quad (6)$$

Substitute (4) and (5) in (6) to get (7)

$$I_{CM} = \frac{SC_{PV}}{1 + sC_{PV} Z_G(s) + s^2 C_{PV} L_{PN}} V_{TCM}(s) \quad (7)$$

Where $L_{PN} = \frac{L_P L_N}{L_P + L_N}$ and V_{TCM} is the total common-mode voltage.

$$V_{TCM}(s) = u_{CM}(s) + \frac{L_N - L_P}{2(L_P + L_N)} u_{DM}(s) \quad (8)$$

For most applications, the value of L_N is approximately equal to L_P or they can be equated by using an additional inductance to cancel the effect of differential mode voltage u_{DM}. In this case, the current is directly affected by the common mode voltage u_{CM} and given by:

$$I_{CM} = C_{PV}\left(\frac{dV_{CM}}{dt}\right) \quad (9)$$

According to (9) if the CMV, u_{CM} , is constant then the value of the leakage current is decreased [5]

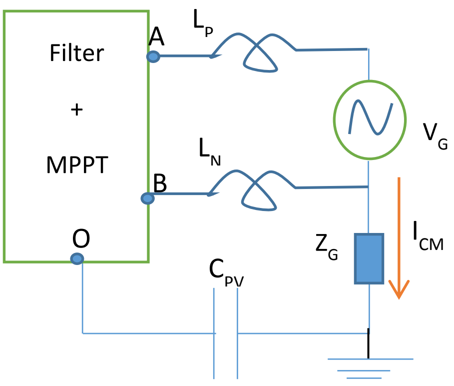

Figure 3: Common mode model of the transformer-less PV system

Moreover, from eq. (7), (8) and (9) the unprotected system is simulated using Matlab/Simulink in order to show the behavior of such system with the maximum power point tracking (MPPT) for different irradiation levels and to measure the leakage current due to the presence of the parasitic capacitance. Here, the MPPT algorithm is based on the incremental conductance method [8]

MATLAB/SIMULINK BLOCK OF THE UNPROTECTED SYSTEM

In order to demonstrate the harmful effect of the leakage current, a Matlab/Simulink block is simulated for a 100-KW PV array connected to a utility grid through a single-phase transformer-less inverter as shown in Fig. 4. The PV source array is made up from 66 parallel strings where each string has 5 series-connected modules, at constant temperature of 25^0c. The module characteristics are shown in Fig. 5. The main components of the block are:

1- Boost Converter to set the voltage output from the PV source for MPPT purpose.

2- Transformer-less Inverter that acts as a variable part in our simulation, The circuit is simulated for a single-phase uncontrolled bridge with PWM generator. Then with modified H5 bridge with its filter to show the validity of the proposed system in reducing the leakage current.

3- Load and utility grid: The output of the iinverter is connected to the utility grid. The grid is modeled using a typical pole-mounted transformer and an ideal AC source of 14.4 kV-rms.

4- Parasitic Capacitance: The circuit is modeled by 2 PV arrays connected to two capacitors Cp through the ground as shown in Fig. 4.

The output Power and voltage of PV array for a given irradiance with MPPT are 100.7 kW, 273.5 V at 1000 W/m^2 and 25^0C irradiance. Accordingly, the output power becomes around 25-kW when the irradiance is decreased to 250W/m^2.

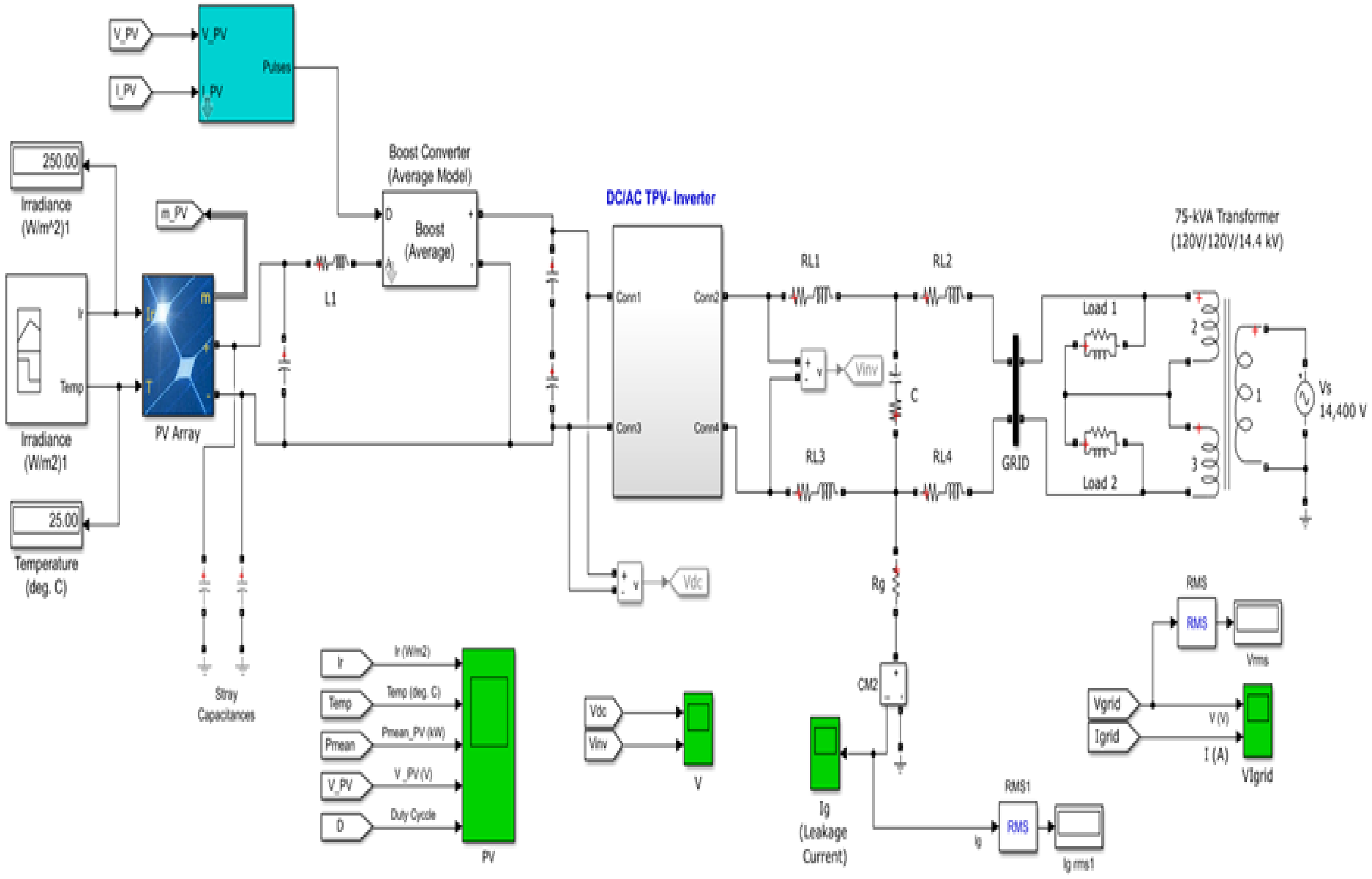

Figure 4: Matlab/Simulink Model of Transformer-less Inverter system

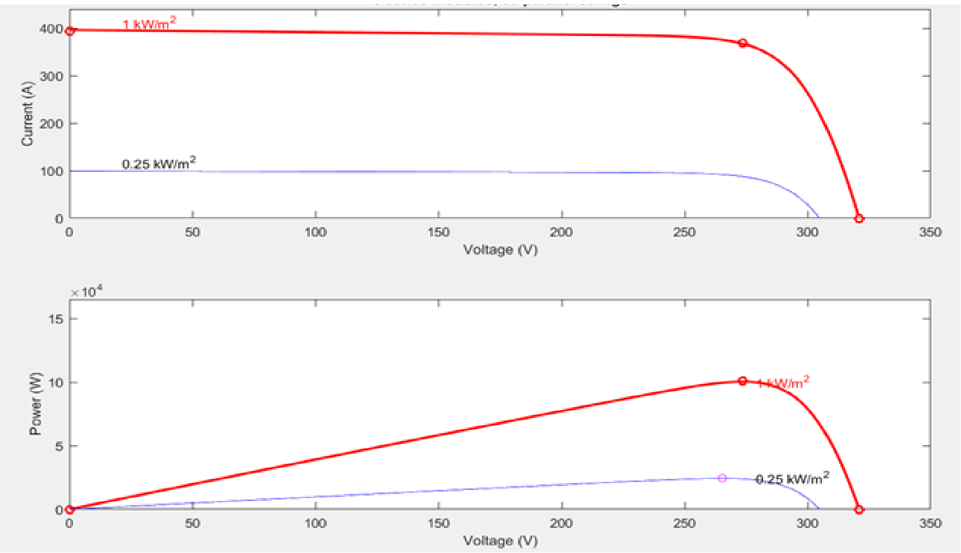

Figure 5: I_V & P_V characteristics for PV array

Fig. 5 shows the power and the voltage of the PV system at constant temperature and different values of irradiance. According to Table (1), the value of the leakage is exceeding the acceptable values limits by all standards. it's high value is harmful for the system and human being.

Fig. 7 shows the variation of the voltage and current of the grid versus time. The harmonic contents is acceptable and the THD is around 7% indicating that the filter after the inverter (4 switches only) in Fig. 4 is working correctly.

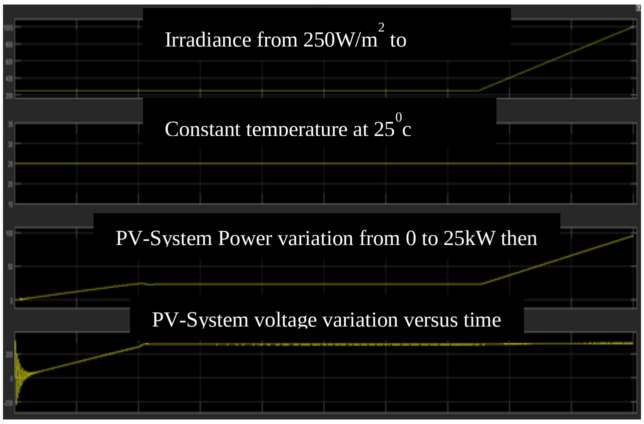

Figure 6: Irradiance power, temperature, output PV power and voltage

Table 1 illustrates the direct effect between Cp and the RMS value of leakage current measured at the grid. As C_P increases the leakage current increases too. In this simulation, we use 2 stray capacitances each of value Cp = 1nF.

Table 1: leakage current

Unprotected bridge Inverter	
Capacitance C_P in μF	***Leakage current Ig (A)***
0.001	0.95
0.01	0.71
0.1	3.55

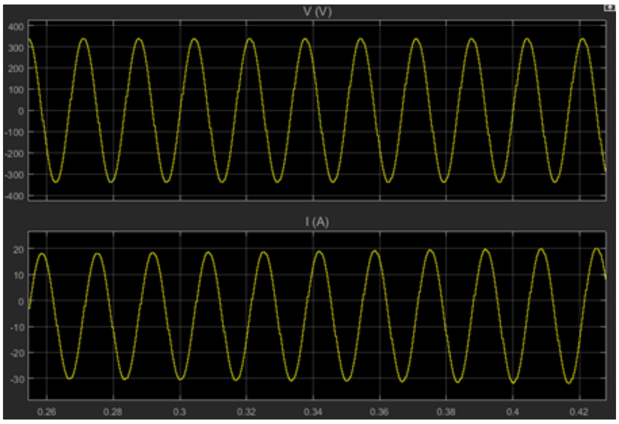

Figure 7: Variation of grid voltage and current versus time

IV. MODEL AND SIMULATION OF H5 SWITCHING

A. *General switching sub-circut model technique*

This technique has several advantages; it offers low DC bus voltage requirements, low leakage current, and high efficiency characteristics. Moreover, the dead time is not required as the switches on a DC bus short-circuiting path are not in conduction state in the same PWM cycle [4].

Fig. 9 shows the energized switches and its corresponding equivalent circuit.

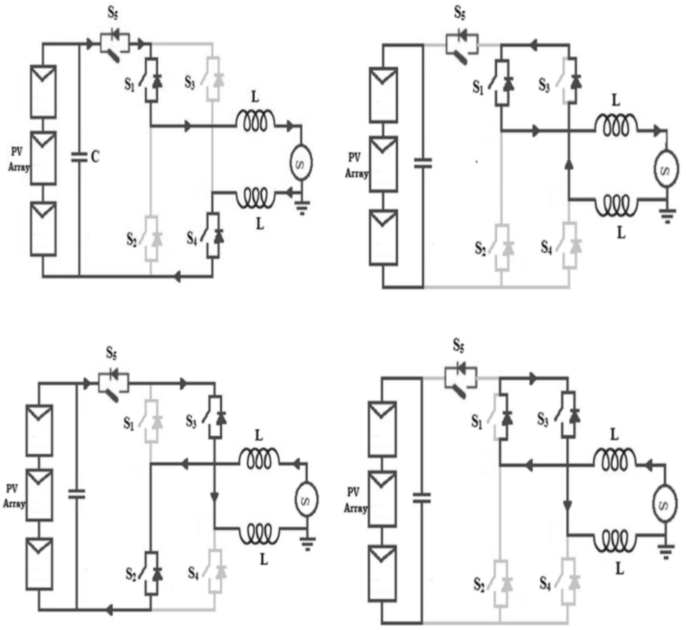

Figure 8: Equivalent circuits during energized switching

B. *PWM Switching Configuration*

- At Cp=1nF the leakage current oscillates around positive and negative 1.5-A with an RMS value of 0.95-A that cause a serious problem to the circuit.
- In this study, we propose a modified H5 bridge inverter for the leakage current solution. The H5 system is buildup of 5 switches and the switching scheme plays the main role in leakage current solution in addition to the effective proposed filter as shown in Fig. 10
- We set S1 to open mode in the positive cycle while S4 is closed, and S3 is open in the negative half cycle while S2 is operating as shown in Fig. 8
- S5 is operating with S4 in positive cycle mode and with S2 in negative half cycle mode, cutting off the circuit at zero operating mode to ensure decoupling of the circuit
- The switches in H5 apply the switching configuration shown in Fig. 9

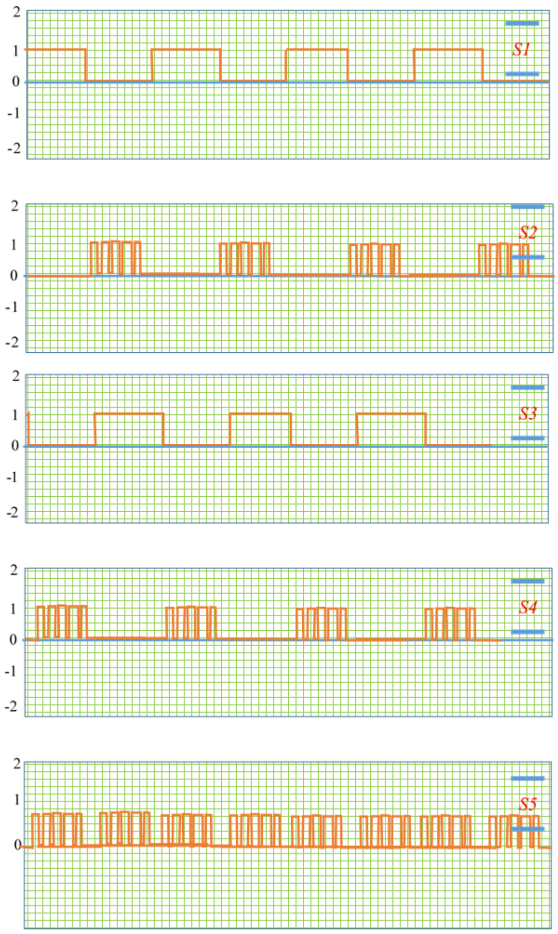

Figure 9: Swiching configuration of the 5 switches

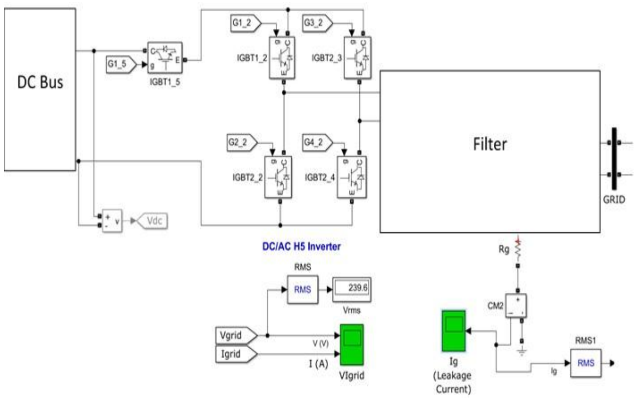

Figure 10: Overall system with filter

C. *Filter Circuit*

For the simulation two coils are used instead of one coil with two capacitors as shown in Fig. 4. The Magnetic coupling will split the filter coil into two coils in parallel with same number of turns but in an anti-phase connection for a better filtering process.

D. Simulation Result of Protected System

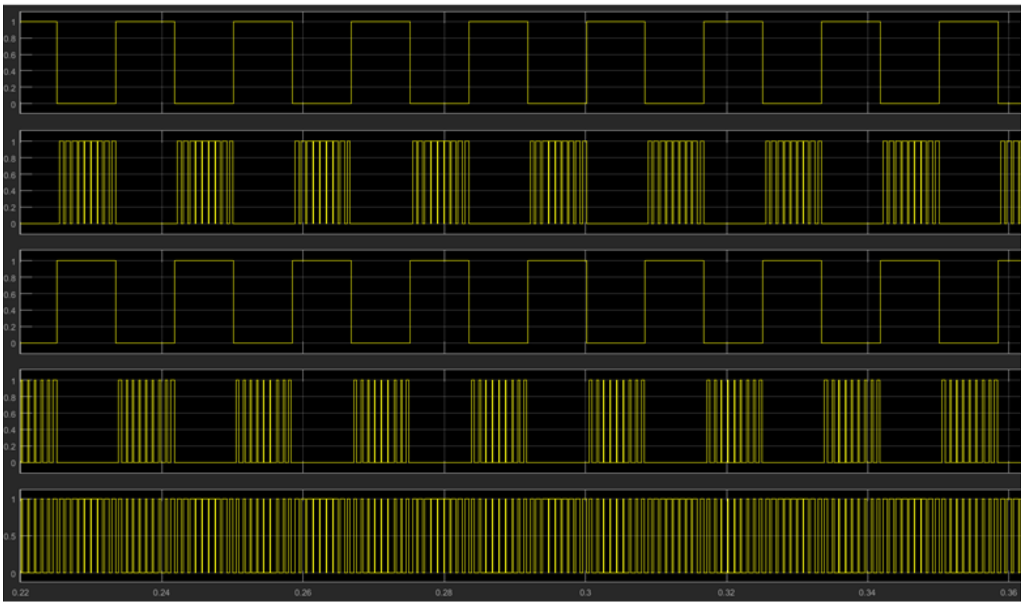

Figure 11: Switching configuration of H5 bridg

Fig. 11 shows the output results of the proposed system. The switching gate control circuit achieving the switching configuration is derived from reference and carrier signal, as shown in Fig. 12

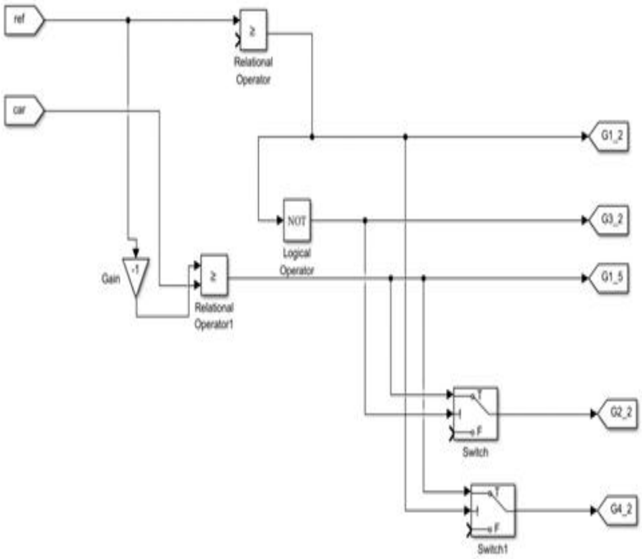

Figure 12: Gate control switching circuit

CONCLUSION

An improved grid-connected inverter topology for transformer-less PV systems is presented in this paper. The unipolar SPWM and double-frequency SPWM control strategies are both implemented with three-level output in the inverter. With this configuration, the common-mode leakage current is not present since the elimination conditions are met. Furthermore, the switching voltage of all commutating switches is half of the input DC voltage and the switching losses are reduced greatly. The high efficiency and convenient thermal design are achieved thanks to the decoupling of two additional switches S5 and S6. Moreover, by adopting the double-frequency SPWM, the higher frequency and lower current ripples are achieved. Consequently, the higher quality and lower THD of the grid-connected current are obtained, or the smaller filter inductors are employed and the copper losses and core losses are reduced accordingly. Finally, a large scale simulation system was built, to show the validity of the modified system.

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