Efficiency Analysis of Single-Phase Photovoltaic Transformer-less Inverters

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Abstract. This paper presents an efficiency analysis of five single-phase transformer-less inverters for photovoltaic applications (Full H-Bridge, Half H-Bridge, H5, HERIC and NPC inverters) implemented with different topologies of switches. Silicon (Si) and Silicon Carbide (SiC) diodes have been considered combined with two kinds of IGBTs. Simulation results have been obtained for each of the systems in different operating conditions by using PLECS software. Power losses and European Efficiency (EE) have been calculated for all the topologies by including the real characteristics of the switches in the thermal models provided by the software.

Keywords

Transformer-less PV inverter, IGBTs, Silicon diodes, Silicon Carbide Diodes, European Efficiency.

1. Introduction

Renewable energy sources and mostly photovoltaic (PV) applications are nowadays experiencing a fast and continuous development. From the scientific point of view, the effort over the last years has gone into increasing the efficiency of PV cells and bringing down the manufacturing costs. Taken into account that the efficiency of the PV panels currently available on the market is only 15-20%, a crucial aspect in these kinds of applications is to design efficient power electronics systems to exploit the most of the produced energy. The main component of these systems is the PV inverter, representing the 25% of the whole system cost [1].

Inverters used in PV systems can be grouped into two main categories: the isolated and the non-isolated inverters. The former, in order to create a galvanic isolation between the input and the output include a transformer (mandatory in some countries) that limits the whole system performances in terms of efficiency, weight, size and cost. On the contrary, transformer-less inverters do not present any isolation and are characterized by little size, lower cost and higher efficiency (more than 2% higher). Nevertheless, the lack of transformers leads to leakage currents that can be harmful to the human body, as well as for the whole conversion system integrity. This can

be considered their main drawback [4].

The goal of this paper is to evaluate the efficiency of different topologies of single-phase transformer-less PV inverters, implemented with different kinds of switches. Silicon (Si) and Silicon Carbide (SiC) diodes have been considered combined with two different IGBTs available on the market. Simulation results have been obtained for each of the systems in different operating conditions by using PLECS software.

A block diagram of the simulated systems is shown in Figure 1.

Figure 1. Block diagram of the simulated systems

The LC filter components considered for all the topologies have been designed using reference [3].

Power losses and European Efficiency (EE) have been calculated for all the topologies considering the real characteristics of the switches by including parameters of datasheets in the thermal models provided by the software.

Hereinafter, Section II introduces the concept of European Efficiency, while Section III describes the different tested inverter topologies. Section IV describes how the different simulations have been performed while Section V presents the obtained results. Conclusions are drawn in Section VI.

2. European Efficiency

The efficiency of a power converter is defined by the following equation:

$$\eta = \frac{P_{dc} - \text{losses}}{P_{dc}} \quad (1)$$

where P_{dc} is the DC input power. In the considered systems the losses are mainly due to the internal power dissipation of the switches (IGBTs and diodes in our case).

Since in the real applications, PV systems are installed in a wide range of solar sources, in order to take into account the different levels of efficiency at different levels of input power, a different factor is commonly used, the so-called *European efficiency* (EE) [9]. This parameter is a weighted conversion efficiency index and is defined as:

$$\eta_{EUA0} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%} \quad (2)$$

where $\eta_{i\%}$ is the conversion efficiency at $i\%$ of inverter input power. The typical EE of PV power converters is in the range 95-98%.

3. PV Inverter Topologies

This section presents a short description of the different inverter topologies tested in the simulations.

A. Full H-Bridge Inverter

The full H-bridge converter considered in this paper presents a DC decoupling scheme [7] which adds two extra switches and two extra diodes to common H-Bridge topology. IGBTs T5-T6 are switched at high frequency, while switches T1-T4 are switched with the grid frequency and in anti-parallel to T2, T3, depending on whether the reference voltage is in the positive or negative half period.

Figure 2. Full DC decoupled H-Bridge Inverter

B. Half H-Bridge Inverter

The Half H-bridge topology is formed by 2 IGBTs and a capacitive divider connected to the PV array (Fig. 3).

Figure3. Half H-Bridge Inverter

The connection of the grid neutral wire to the capacitive divider midpoint ensures an almost constant common

mode voltage, thus preventing leakage current through the parasitic capacitance of the PV module.

C. NPC Inverter

The operation of Neutral point clamp (NPC) topology (Fig.4) can be described as follow: during the positive half cycle, T2 remains ON, T1 commutates at switching frequency and T3 and T4 are OFF; in more detail, when T1 is ON the current flows through T1 and T2 toward the grid (current increasing), while when T1 is OFF, the current flows through D5 and T2 (current decreasing). During the negative half cycle, T3 remains ON, whereas T4 commutates at switching frequency and T1 and T2 are OFF; when T4 is ON current flows through T3 and T4 toward the grid (current increasing). Moreover, when T4 is OFF, the current flows through T3 and D6 (current decreasing) [8].

Figure 4. NPC Inverter

D. HERIC

HERIC (Highly Efficient and Reliable Inverter Concept) topology is another structure that avoids a fluctuating potential on the DC terminals of the PV generators by means of disconnecting the converter from the grid (Fig.5).

Figure 5. HERIC topology

During the positive half cycle T6 remains connected, whereas T1 and T4 commutate at switching frequency. When T1 and T4 are ON, current flows from the PV panels to grid, while they switch OFF, the current flows through T6 and D1 (freewheeling state). On the other hand, when the negative cycle is coming, S6 goes OFF and S5 goes ON, whereas T3 and T2 commutate at switching frequency. In more detail when T3 and T2 are ON, the current flows from the PV panel towards the

load, thus when T3 and T2 turn off, the current flows through T5 and D2 [8].

E. H-5 Inverter

Compared to the full H-bridge, this topology presents an additional transistor, and that is the reason for its name. The H5 topology is patented by SMA [10] and it is based on the same concept as the HERIC topology, i.e. to disconnect the PV panels from the grid during current freewheeling periods, thus having an almost constant common mode voltage. In Fig. 7 it is shown the H-5 topology, that uses a full-bridge consisting of the four switches T1, T2, T3 and T4, and the DC-bypass T5 switch. The switches T1 and T2 are operated at grid frequency, whereas T3, T4 and T5 are operated at high frequency. During current free-wheeling period, T5 is open, disconnecting PV panels from the inverter full H-bridge. The free-wheeling path is closed by the transistor T1 and the inverse diode of T3 for the positive half-cycle of the electrical grid, and by the transistor T3 and the inverse diode of T1 for the negative half-cycle [11].

Figure 6. H-5 Inverter

4. Switches model for power losses calculation

In any semiconductor device operating in switch-mode, power losses can be classified in three main categories [12]:

- conduction losses;
- switching losses;
- blocking (leakage) losses, usually neglected.

A. IGBT conduction losses

IGBT conduction losses are related to the energy lost in the switch during the on-state, depending on the voltage across it and the handled current.

The method used by PLECS to calculate the IGBT conduction losses consists in modeling the IGBT as a DC voltage source, which represents the on-state zero-current collector-emitter voltage (v_{CE0}), connected in series with a resistance representing the collector-emitter on-state resistance (r_c):

$$v_{CE}(i_c) = v_{CE0} + r_c \cdot i_c \quad [V] \quad (3)$$

The average conduction losses of the IGBT are so computed as:

$$P_{cond} = \frac{1}{T_{sw}} \cdot \int_0^{T_{sw}} (v_{CE} \cdot i_c(t)) dt \quad [W] \quad (4)$$

$$P_{cond} = \frac{1}{T_{sw}} \cdot \int_0^{T_{sw}} (v_{CE0} \cdot i_c(t) + r_c \cdot i_c(t)^2) dt \\ = v_{CE0} \cdot I_{Cav} + r_c \cdot I_{Crms}^2 \quad [W] \quad (5)$$

where T_{sw} is the switching period, I_{Cav} is the handled average collector current and I_{Crms} is its rms value. In order to execute the calculation, PLECS requires the collector-emitter on voltage vs collector current curve (varying with the temperature) from the datasheet of the component.

B. IGBT switching losses

IGBT switching losses represent the energy losses which occur during the switching transient, as the operating switch state is changed from on to off and vice versa. They depend on the voltage across the switch, the current through it and the switching time. The mathematical equation used by PLECS to evaluate the IGBT switching losses can be expressed as:

$$P_{sw} = f_{sw} \cdot (\int_{t_1}^{t_1+t_{swon}} i_s \cdot v_s dt + \int_{t_2}^{t_2+t_{swoff}} i_s \cdot v_s dt) \quad [W] \quad (6)$$

where f_{sw} is the switching frequency, t_1 represents the moment when the IGBT starts to turn on, t_2 represents the time moment when the switch starts to turn off, t_{swon} represents the time needed for the switch to turn on, t_{swoff} represents the time needed for the switch to turn off, i_s is the instantaneous current through the IGBT and v_s is the instantaneous voltage across the switch.

C. Diode Losses

Diode switching and conduction losses are calculated by PLECS following the same approach described previously for the IGBTs.

5. Simulation Results

The following Table 1 shows all the parameters used in the simulations.

Table 1 – Simulation parameters

Simulation step size	Ts = 1e-5
Switching frequency	fs = 10 kHz
DC voltage	Vdc = 300 V
output voltage frequency	f = 50 Hz
Resistor (Load)	R = 15.5 Ω
Inductances	L=3.4 mH
Capacitance	C=22 μF
IGBTs	STGW35NB60S
IGBTs	STGP20NC60V
Si Diodes	STTH15R06D
SiC Diodes	STPSC1006D

In all the schemes, a resistive load of 15.5 Ω absorbing 18Arms has been connected at the inverters output.

In all the simulations two different IGBTs (STGW35NB60S and STGP20NC60V) and two different diodes (STPSC1006D SiC diode, STTH15R06D Si diode) have been considered. Parameters required by PLECS model have been extracted from the components'

datasheets. The following Figures 17, 18, 19, 20, 21 show the obtained results for the H-bridge, HERIC, H5, NPC and Half-bridge topologies respectively.

Figure 7. Full H-bridge losses

Figure 8. Half H-Bridge losses

Figure 8. HERIC losses

Figure 9. H5 losses

Figure 10. NPC losses

The first two columns of the histograms represent the total losses in the IGBTs, while the last ones report the

losses within the Si diode and the SiC diode.

The total power losses in the different inverters are shown in Figure 12 and Figure 13, considering the two different diodes for each of the IGBTs.

Figure 12. Total losses comparison between Si and SiC diodes using the STGW35NB60S-IGBT

Figure 13. Total losses comparison between Si and SiC diodes using the STGW20NC60V-IGBT

Efficiency related to the input power for all the considered converters is shown in the following figures. The different versions data shown in the tables have to be meant as follows:

- Version 1: STGW35NB60S IGBT + Si diode
- Version 2: STGW35NB60S IGBT + SiC diode
- Version 3: STGW20NC60V + Si diode
- Version 4: STGW20NC60V + SiC diode

Figure 14. Full H-Bridge Efficiency for the 4 different combinations of IGBTs and diodes

Version 1	Version 2	Version 3	Version 4
98%	98,1%	98,3%	98,4%

Table 2. Full H-Bridge European Efficiency for the 4 different combinations of IGBTs and diodes

Figure 15. Half H-Bridge Efficiency for the 4 different combinations of IGBTs and diodes

Version 1	Version 2	Version 3	Version 4
98,3%	98,3%	99,3%	99,4%

Table 3. Half H-Bridge European Efficiency for the 4 different combinations of IGBTs and diodes

Figure 16. HERIC Efficiency for the 4 different combinations of IGBTs and diodes

Version 1	Version 2	Version 3	Version 4
98,5%	98,6%	99,7%	99%

Table 4. HERIC European Efficiency for the 4 different combinations of IGBTs and diodes

Figure 17. H-5 Efficiency for the 4 different combinations of IGBTs and diodes

Version 1	Version 2	Version 3	Version 4
98,2%	98,3%	99,6%	98,7%

Table 5. H5 European Efficiency for the 4 different combinations of IGBTs and diodes

Figure 18. NPC Efficiency for the 4 different combinations of IGBTs and diodes

Version 1	Version 2	Version 3	Version 4
98,5%	98,6%	98,9%	99%

Table 6: NPC European Efficiency for the 4 different combinations of IGBTs and diodes

6. Conclusions

An efficiency analysis of five single-phase transformer-less inverters for PV applications has been performed considering different topologies of switches. Simulation results show the theoretical efficiency achievable in each converter by using the SiC diodes and how strong is the impact related to the use of this expensive components, combined with two different IGBTs currently available on the market. For all the converters the European Efficiency has been calculated in all the combinations IGBTs-diodes.

Further investigations will be performed in the future by implementing and testing real prototypes for each of the topologies.

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