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Model of PV inverter in H4 and H5 topologies for power loss analysis

***Abstract**. The PV, H4 inverters without transformers have many advantages like: high reliability and efficiency, low size and weight. However leakage currents arise at such topology, therefore, it is important to eliminate this unfavorable phenomenon. One of several methods is to use an inverter topology with an increased number of semiconductor switches, which allows the elimination of leakage currents. The aim of this paper is to reveal a through calculation of semiconductor losses of H4 and H5 power inverters used in different renewable energy sources. Power losses have been calculated by including the characteristics of the switches in the thermal models provided by the simulation software.*

***Streszczenie.** Beztransformatorowe falowniki PV, w topologii H4 mają wiele zalet, takich jak: wysoka niezawodność i sprawność, niewielkie rozmiary i ciężar. Jednak w takiej topologii pojawiają się prądy upływu, dlatego ważne jest, aby wyeliminować to niekorzystne zjawisko. Jedną z kilku metod jest użycie topologii przetwornicy z większą liczbą przełączników półprzewodnikowych, co pozwala wyeliminować te prądy. Celem pracy jest przedstawienie obliczeń strat elementów półprzewodnikowych przetwornic mocy H4 i H5, stosowanych w różnych odnawialnych źródłach energii. Straty energii zostały obliczone przez uwzględnienie charakterystyk łączników w modelach termicznych dostępnych w programie symulacyjnym. (**Model przetwornicy PV w topologii H4 i H5 do analizy strat mocy**).*

Keywords: PV inverters; semi conductor elements power loss calculation; power electronics transformerless converters.
Słowa kluczowe: falowniki PV; obliczanie strat mocy elementów półprzewodników; beztransformatorowe przekształtniki energoelektroniczne.

Introduction

In many applications of renewable energy high performance power electronics converters are desirable for coupling low voltage power supplies to loads operating at significantly higher voltage levels [1]-[2]. Low input voltages result in high currents flowing through the components of the inverter, resulting in increased power losses, proportional to the square of the current [3].

Energy losses can reduce system efficiency so much that achieving a target output power becomes impossible, so limiting losses often determines practical implementation of converter. There are topologies of inverters with and without galvanic isolation. Transformer converters increases the cost and the power losses, so the efficiency of the system is reduced [4]. Hence, transformer-less inverters are nowadays one of the most popular power electronic devices used to connect green energy sources to the electrical grid [5]–[6]. Many control mechanisms have been proposed to regulate the inverter output current that is injected into the utility grid [7]-[8].

This paper compares simulation results of two converters mainly in terms of power losses of semiconductor components. Compared topologies of H4 and H5 galvanic resistors were compared.Simulation results have been obtained by using PSIM software [9].

Power electronics semiconductor losses

This part presents the models to find out the power losses of each presented power electronics converter. Power losses affect the efficiency of the inverter, the heat sink dimensions and cooling method. This note describes the theory behind the calculation and show how to calculate the power losses for the IGBT and Diode respectively. The modelling process will be detailed in the following.

IGBT module total losses

The considered power electronics module consists of an IGBT transistor and an anti-parallel diode. There are three kinds of losses in Insulated Gate Bipolar Transistor (IGBT transistor) and anti-parallel diode: blocking (leakage) losses, static losses also called conduction losses, and the transient losses known as switching losses [10]. Total transistor losses are given by:

$$P_{TTot} = P_{TTot} + P_{Tsw} + P_{Tleak} \tag{1}$$

where: P_{TTot} are the total transistor losses, P_{Tcon} are the conduction transistor losses and P_{Tleak} are the IGBT losses in blocking state.

The average value of total losses for the anti-parallel diode is:

$$P_{ADTot} = P_{ADcon} + P_{ADsw} + P_{ADleak} \tag{2}$$

So the total switch losses P_{STot} are given by:

$$P_{STot} = P_{TTot} + P_{ADTot} \tag{3}$$

IGBT module leakage losses

Leakage losses are produced by a low leakage current when the semiconductor is in blocking state.

$$P_{Tleak} = U_{CE} I_{CES} \tag{4}$$

Where, U_{CE} is the blocking voltage applied and I_{CES} is the maximum collector-emitter leakage current.

The manufactures of power semiconductor indicates that value of leakage current at certain blocking voltage and temperature are very low. So in general in comparison to other IGBT's and anti-parallel diode losses, leakage losses are low and can be neglected. Therefore, total power losses can be described by the formula:

$$P_{STot} = P_{Scon} + P_{Ssw} \tag{5}$$

IGBT module static losses

Conduction losses are occurred in the semiconductor duty cycle. The calculation of IGBT conduction losses mainly depends on required load current average I_{cAV} and RMS I_{cRMS} values, the transistor voltage u_{ce0} and a collector-emitter on-state resistance r_C.

$$P_{Tcon} = u_{ce0} I_{cAV} + r_c I_{cRMS}^2 \tag{6}$$

If the average diode current is I_{ADAV}, and the RMS diode current is I_{ADRMS}, the average diode conduction losses are:

(7) $$P_{ADcon} = u_{AD0} I_{ADAV} + r_{AD} I_{ADRMS}^2$$

Exact voltage, current and resistance parameter values for power loss calculation has been given in semiconductor data sheets. So the switch conduction losses P_{Scon} are equal:

(8) $$P_{Scon} = P_{Tcon} + P_{ADcon}$$

IGBT module transient losses

The switching losses of the transistor are calculated by formula:

(9) $$P_{Tsw} = (E_{Ton} + E_{Toff})\, f_{sw}$$

Power electronics semiconductors are designed to be used in switching states, so IGBTs switching time periods are short. The ratio of switching energies (the turn-on energy E_{Ton} and the turn-off energy E_{Toff}) and the switching frequency f_{sw} determine power losses during these switching periods. The loss calculation for device integrated the anti-parallel diode is the same as was presented above, however due to the small amount of turn-off energy, the following relationship is assumed:

(10) $$P_{ADsw} = E_{ADon}\, f_{sw}$$

So, the switch transient losses P_{Ssw}:

(11) $$P_{Ssw} = P_{Tcsw} + P_{ADsw}$$

Power Diode total losses

Diode conduction and switching losses are calculated following the same approach described previously for the switch consisting of IGBTs and anti-parallel diode. The power diode conduction losses are:

(12) $$P_{Dcon} = u_{D0} I_{DAV} + r_D I_{DRMS}^2$$

As mentioned in the previous subsection, we also count the switching losses:

(13) $$P_{Dsw} = E_{Don}\, f_{sw}$$

The currents I_{AV} and I_{RMS} are determined by load and application condition. That expressions can be calculated using the appropriate equations.

Single Phase Transformer-less Inverter Topologies

This section presents a short description of the two topologies that have been selected based on their main features, among which is the low number of semiconductors, which by nature can reduce power losses and costs. First, the one phase, H-bridge topology was analysed which consists of 4 semiconductors only. Second considered circuit was the H5 inverter comprising 5 semiconductor devices included in this analysis.

H4 inverter topology

H4 topology is widely used and can be used in both DC-DC and DC-AC converters. This topology can also be implement as half H-bridge (HHB) or full H-bridge (FHB) circuit. The full H-bridge version was shown in the figure 1. In transformerless inverter topologies, a galvanic connection between the ground of the grid and the PV module exists. As a result, a common-mode resonant circuit appears consisting of the stray capacitor between the PV modules and the ground.

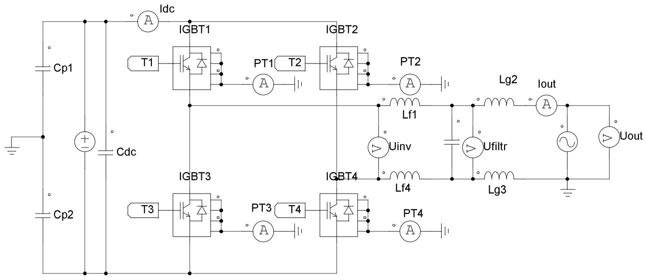


Fig. 1. The simulation circuit with full H-bridge inverter FHB.

There are three modulation techniques: unipolar, bipolar and hybrid modulation, which can be used for single phase full bride H4 (FHB) transformerless PV inverter. In case of bipolar modulation two-level voltage is generated. Switch pair IGBT1/ IGBT4 and IGBT2/ IGBT3 are switched at high frequency complementarily. Thus AC voltage can be generated, no zero output voltage state is possible. The advantage of this modulation strategy is very low leakage current and electromagnetic interference if the topology is implement in transformer-less architecture. The disadvantages are current ripple, the voltage variation across the filter producing higher magnetic core losses, lower efficiency because two switches are always simultaneously conducting every switching period. Second modulation strategies has been used is unipolar switching modulation technique. In case of unipolar modulation and hybrid modulation, three- level voltage is generated. Switch pair IGBT1/ IGBT4 and IGBT2/ IGBT3 are switched at high frequency with mirrored reference signals. The inverter output voltage is changing from positive peak value to zero and then to negative peak values. Advantages of this topology are lower filtering requirement, the voltage across the filter is unipolar, so core losses are lower and efficiency is higher due to the no losses during zero voltage states. Many inverter topologies have been introduced, which have advantages of both unipolar and bipolar modulation techniques: high efficiency and low leakage current.

H5 inverter topology

When full H-bridge transformer less converter is used, as a undesirable result a common-mode voltage appears. A varying common-mode voltage can generate a leakage current, flowing by circuit consisting of the stray capacitor between DC source and the ground.

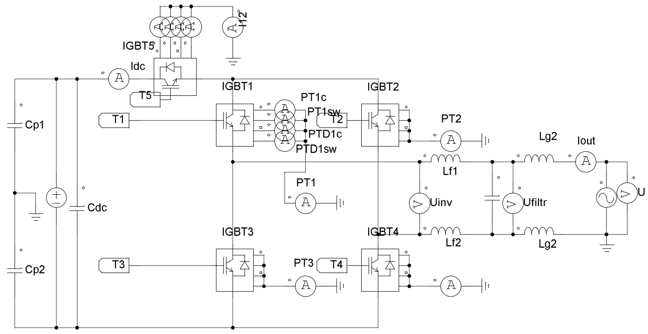


Fig. 2. H5 inverter topology

Compared to the FHB presented in Fig.1, H5 is made up by adding an extra switch IGBT5 between the DC circuit and full H-bridge. This H5 inverter topology was shown in Fig. 2. The switches IGBT1-4 are not complementary commutated, two switches are high frequency and two are low frequency operated. When the switches IGBT3 and IGBT4 are operated with high switching frequency the IGBT1 and IGBT2 are turned on complementary. Than current flows through IGBT1, IGBT4, and IGBT5. The zero voltage vectors are achieved when IGBT4, and IGBT5 are turned off, the current paths flows through IGBT1 and IGBT3. Thus the leakage current is minimized .Because of current flows through three switches, H5 has higher conduction losses then full H-bridge topology. The SPWM switching signals for H5 topology are presented in Fig. 3.

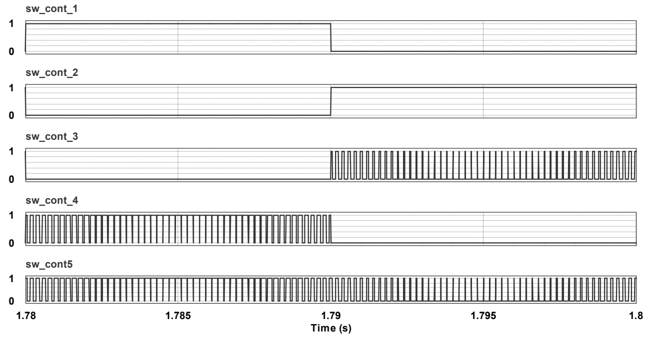
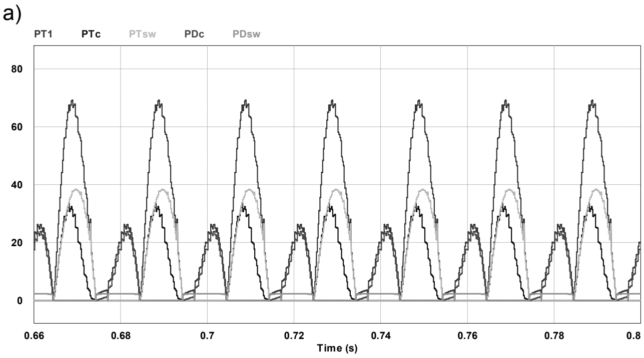


Fig. 3. H5 inverter switching control signals

Power loss analysis

Simulation tests were performed in the PSIM program. The IGBT MH1000HA-24H transistor thermal model was used for the study.

a)



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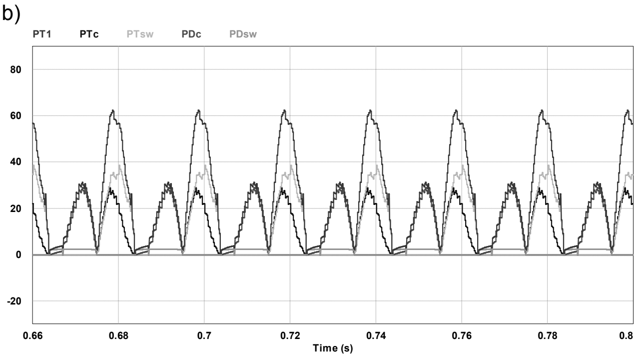
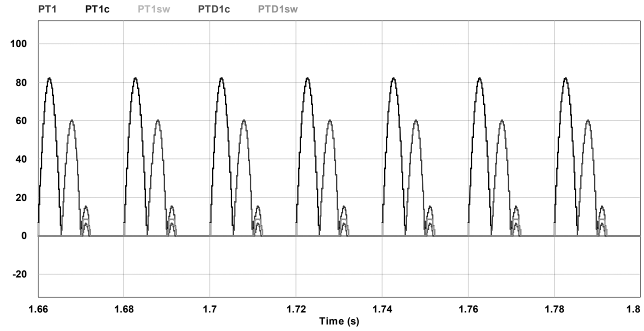


Fig. 4. H4 inverter power losses distribution with a) bipolar-, b) unipolar- modulation. PT1 switch total losses; PTc— transistor conduction losses; PTsw— transistor switching losses; PDc— anti-parallel diode conduction losses; PDsw— anti-parallel diode switching losses.

Simulation tests were performed for the following parameters. The DC circuit voltage was set at 350 V for both H4 and H5 inverters. The converters loads is the grid with L_g=1.8mH, the voltage U_{max}=325V and the frequency f=50Hz. The RMS value of grid's current is I_{out}=100 A.

a)



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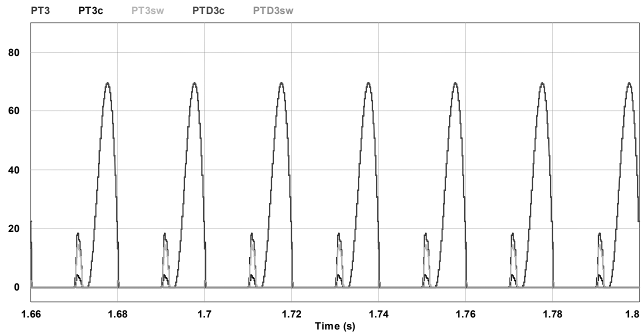

c)

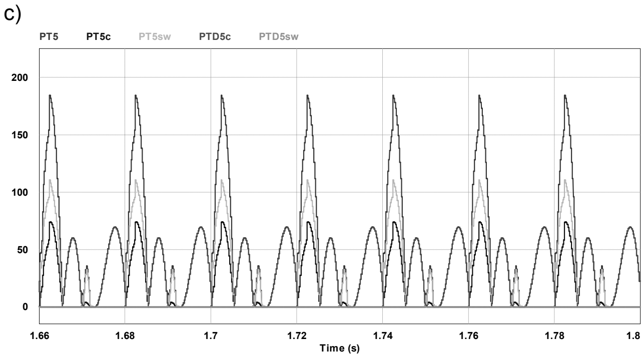

Fig. 5. H5 inverter with— Power Losses distribution of switches a) IGBT1, b) IGBT3 c) IGBT3, where: PT1, PT2, PT3 respectively are a total losses of switches; PT1c, PT3c, PT5c —conduction losses of transistors 1, 3 and 5; PT1sw, PT3sw, PT5sw —switching losses of transistors 1, 3 and 5; PTD1c, PTD3c, PTD5c —conduction losses of anti-parallel diode 1, 3 and 5; PTD1sw, PTD3sw, PTD5sw —switching losses of anti-parallel diode 1, 3 and 5

Use the thermal model from the PSIM library allows to calculate the power loss of semiconductor devices. Thermal models of semiconductor devices include both static and dynamic properties such as conductor voltage drop or dynamic resistance. The instantaneous power losses are shown in Fig. 4 – Fig. 5. Simulations have been made for several instances, calculation of switching losses and total losses of all semiconductor components in different topologies.

The same diagram presented in Fig. 1 was used to determine the topology of the H4 inverter with bipolar and unipolar switching modulation. The simulation was shown in Fig. 4a and 4b. The conclusions drawn from the analysis used in this work is that transformer-less full bridge inverter topology with unipolar switching technique has lower power losses than the same configuration but implementing bipolar switching. The Fig. 5a to 5c presents of H5 inverter simulation results. The simulation research was done using the IGBT thermal models available in the PSIM library. As shown in Figure 5, the higher power losses were recorded for transistor IGBT1 because of its high switching frequency. The switch IGBT3 has a lower switching frequency, so and accordingly lower losses. Due to the longest conduction times and high switching frequencies, the highest power loss was recorded on IGBT5.

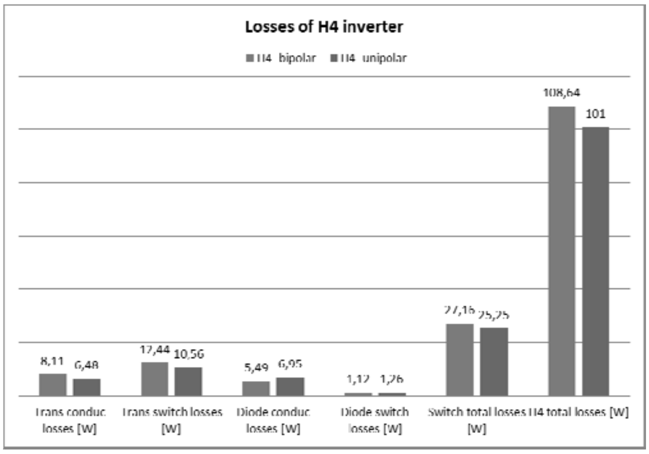

Fig. 6. The power losses of H4 inverter with bipolar and unipolar modulation technique

The power loss have been illustrated by the instantaneous power with high maximum value, but the mean values are lower. Therefore, in the following Fig.6-Fig.7, the average values of the active power of the selected semiconductors for the discussed H4 and H5 topologies of converters were presented. Figure 6 shows the power losses for only one transistor because of other semiconductors have identical values due to the symmetrical load of the rest of transistors. In case of H5 topology due to unsymmetrical transistor load, three different semiconductor switches were analyzed.

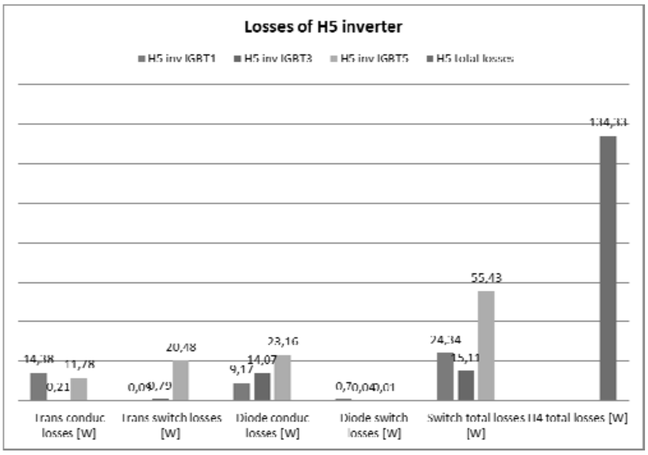

Fig. 7. The v power losses of H5 inverter

As was shown in Fig. 7, the higher power losses over each discussed converter topology has H5 inverter shown in Fig. 2.

Summary

The power loss analysis of transformer-less inverters for renewable applications has been performed considering parameters of switches. The main advantages of these systems are the small power losses as shown in the paper, low cost and small size. The analysis of the characteristics of those transformer-less converters, was done. Simulation results shown the differences in loss dissipation achievable in each converter. Thermal Module a real semiconductor device model from PSIM was used. The important is to know the power dissipated by each transistor to make the right design and ensure reliable operation of semiconductors. For all discussed converters the power losses has been calculated in the combinations: IGBTs - anti-parallel diodes.The analyzed topologies have high efficiency and low power dissipation so these topologies, are suitable for high-performance renewable energy systems. Further investigations will be performed in the future by implementing and testing real prototypes for each of discussed topologies.

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