ARCHIVES OF ELECTRICAL ENGINEERING VOL. 71(3), pp. 615–626 (2022)

DOI 10.24425/aee.2022.141674

Modelling and simulation of sinusoidal pulse width modulation controller for solar photovoltaic inverter to minimize the switching losses and improving the system efficiency

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(Received: 21.08.2021, revised: 12.04.2022)

Abstract: With the extinction of fossil fuels and high increase in power demand, the necessity for renewable energy power generation has increased globally. Solar PV is one such renewable energy power generation, widely used these days in the power sector. The inverters used for power conversion suffer from power losses in the switching elements. This paper aims at the detailed analysis on switching losses in these inverters and also aims at increasing the efficiency of the inverter by reducing losses. Losses in these power electronic switches vary with their types. In this analysis the most widely used semiconductor switches like the insulated gate bipolar transistor (IGBT) and metal oxide semiconductor field effect transistor (MOSFET) are compared. Also using the sinusoidal pulse width modulation (SPWM) technique, improves the system efficiency considerably. Two SPWM-based single-phase inverters with the IGBT and MOSFET are designed and simulated in a MATLAB Simulink environment. The voltage drop and, thereby, the power loss across the switches are compared and analysed. The proposed technique shows that the SPWM inverter with the IGBT has lower power loss than the SPWM inverter with the MOSFET.

Key words: efficiency, IGBT, MOSFET, PV inverter, MATLAB/SIMULINK, SPWM controller, switching loss

1. Introduction

Renewable energy's value has grown dramatically in recent years. Extraction of solar energy for electrical power production is one best utilization of renewable sources. Solar photovoltaic helps convert solar energy into electricity. The output of a solar PV cell is direct current (DC) electricity, which can be stored in batteries and converted to AC for domestic consumption or grid integration. Inverters are used to convert DC power into AC single-phase or three-phase power. An inverter is an electrical converter that converts a PV solar panel's fluctuating DC output into an AC output that may be used to power appliances or fed directly into the electrical grid.

Inverters are classified as voltage source inverters (VSIs) or current source inverters (CSIs) depending on the source. Inverters are categorised as half-bridge or full-bridge inverters, depending on the load. Inverters are categorised as pulse width modulation (PWM), multiple pulse width modulation (MPWM), sinusoidal pulse width modulation (SPWM), and multiple sinusoidal pulse width modulation (MSPWM) based on the pulse generator. Inverters use a variety of switching devices, the most common of which being MOSFET and IGBT switches, each with its own set of advantages and disadvantages.

2. Literature review

Previously, solar PV was mostly employed as a stand-alone power system, with little need for inverters. The use of inverters has expanded dramatically as PV power installations have increased to kW and mW levels. It is commonly recognised that if any time power is converted, there is a loss of power. The efficiency of voltage source inverters is influenced more by power loss owing to switching devices. The conduction and switching losses together contribute to the above-said loss [1]. MOSFET usage leads to more losses in switching processes [2]. The turn-on switching losses are lower in IGBT switches [3]. The IGBT-based voltage source inverter has more switching losses than the current source inverter [4]. MATLAB-Simulink can be used to design, simulate and analyze the inversion with the IGBT-based inverter [5]. The passive driving method causes a large turnoff voltage surge [6]. A soft-switching inverter with low power losses and high efficiency overcomes the drawbacks of a hard-switching inverter [7]. A single-phase inverter design and simulation using sinusoidal pulse width modulation (SPWM) [8] provides a comparison of synchronous pulse width modulation (SPWM) and a pure sine wave inverter with square wave output filters. Also describes how a square wave output filtration-based pure sine wave inverter works in detail. The SPWM approach employs a changing pulse at the power device's gate [9]. For a single-phase H-bridge inverter, two pulse width modulation techniques, namely bipolar sinusoidal pulse width modulation (SPWM) and unipolar SPWM, are typically employed to adjust the magnitude and frequency of the inverter's output voltage [10]. They represent the SPWM technique for harmonic reduction and show how to generate a SPWM switching signal using different simple operational-amplifier (Op-Amp) circuits/analog circuits for the three-phase pulse width modulated (PWM) voltage source inverter (VSI) [11]. The sinusoidal pulse width modulation (SPWM) approach reduces harmonic distortion by bringing the output voltage closer to that of a genuine sine wave and the reduction of harmonics MATLAB Simulink software, and hardware parameters were used to implement the development and model. The installation of a low-pass filter circuit aids in the creation of cleaner sine waveforms with a 0.17 percent THD value [12]. The required reference signal as a feedforward signal for the sinusoidal pulse width modulation (SPWM) control is generated by a sophisticated digital signal processor in traditional grid-connected inverters. However, as the ac mains varies, the reference signal must be recalculated to maintain the required power management. It increases the controller's processing overhead and has become a major roadblock for grid-connected energy storage systems that require power flow regulation [13]. In order to obtain small dimensions and fine sinusoidal output of dc/ac converters, high-resolution sinusoidal pulse-width-modulation (SPWM) switching is beneficial. A new FPGA-based high-definition SPWM (HD-SPWM) architecture is suggested for merging a lower-frequency PWM train with a high-frequency SPWM train in order to suppress inverter output harmonics while attaining high-resolution output [14]. Compared to other four-level classic and advanced inverters, the four-level T-type NNPC inverter has fewer switches and components, making it ideal for high-power medium-voltage applications. Instead of flying capacitors, this topology has been proposed and studied using constant dc sources [15]. A multilevel inverter based on a single-phase cascaded transformer is proposed, with a modified carrier-based level shift sinusoidal pulse width modulation (LS-SPWM) approach. Two bridges with discrete low frequency transformers make up this architecture. The bridges can separately generate quasi-square and pulse width modulated waveforms, and power two transformers with cascaded secondary terminals to achieve a 19-level output voltage waveform across the load [16]. Due to the features such as low harmonic content of the output waveform, multilevel inverters have been widely used in a variety of situations. Multilevel inverters, on the other hand, use a huge number of components, therefore the risk of circuit failure is larger than with traditional inverters. The research object is a T-type three-level inverter, and the open-circuit defect of insulated gate bipolar transistor (IGBT) devices in the inverter is investigated [17]. Among different PWM techniques, space vector modulation (SVM) is discussed despite its popularity [18].

There is a large power loss in the inverter due to the drops across switches. The switching losses are determined not only by the supply voltage, current, and frequency, but also by the switching elements. Low switching losses, on the other hand, lower the requirement for cooling systems. Because of their individual pros and demerits based on application, the MOSFET and IGBT are the most commonly utilised switches for inverters.

2.1. Power loss

Fixed losses, conduction losses, and switching losses are three types of power losses in a converter. Control circuit losses, which include PWM control circuits, are fixed losses. Conduction losses are those caused by a semiconductor switch or diode's resistance and forward voltage drop. Switching losses are the losses incurred when a switch is turned on and off, as well as the losses incurred when a diode is reversed, and they are dependent on both the switching frequency and the output current.

2.2. Fixed loss

There is no defined method for calculating fixed losses in a converter. Fixed losses can be obtained by subtracting the switching losses and the conduction losses from total losses.

2.3. Conduction loss

For the MOSFET and IGBT, the conduction loss depends on their on-resistance and collector-emitter saturation voltage, respectively, whereas for the diode, on its forward voltage drop.

The conduction loss of a former switch can be calculated as follows:

$$P_{\text{con}s} = I_o^2 R_{DS\text{on}} \frac{V_o}{V_{\text{in}}} (W), \tag{1}$$

where: $P_{\text{con}s}$ is the conduction loss, I_o is the output current, $R_{DS\text{on}}$ is the on-state resistance, V_o is the output voltage, V_{in} is the input voltage.

The approximate conduction loss of a diode can be calculated as follows:

$$P_{\text{con}D} = V_F I_{AV} (W), \tag{2}$$

where $P_{\text{con}D}$ is the conduction loss of the diode, V_F is the diode forward voltage, I_{AV} is the diode average current.

2.4. Switching loss calculation

The turning on and turning off contributes to switching loss. The total of it is calculated as follows:

$$P_{SW\text{on}} = \frac{1}{2} V_{\text{in}} I_o t_r f_{SW} (W), \tag{3}$$

$$P_{SW\text{off}} = \frac{1}{2} V_{\text{in}} I_o t_r f_{SW} (W), \tag{4}$$

$$P_{SW\text{tot}} = P_{SW\text{on}} (W) + P_{SW\text{off}}, \tag{5}$$

where $P_{SW\text{on}}$ is the turning on switching loss, $P_{SW\text{off}}$ is the turning off switching loss, $P_{SW\text{tot}}$ is the total switching loss, t_r is the raise time, t_f is the fall time, f_{SW} is the switching frequency.

Gate charge loss is calculated as follows:

$$P_{\text{gate}} = Q_G I_G f_{SW} (W), \tag{6}$$

where P_{gate} is the gate charge power loss, Q_G is the total gate charge, V_G is the gate to source voltage.

3. Methodology

A general PV power system is shown in Fig. 1. Solar PV output is of variable DC depending on irradiance. So, the voltage boost is to be done at the end terminal of PV. The DC power is to be converted to AC before feeding the output to the AC load or connecting it to the grid. So, an inverter is needed, which is an efficient converter. Inverter switches are controlled by a SPWM signal, which can be obtained from the pulse generator (controller). A PV array containing modules of 36 V of open-circuit voltage and 7.8 A of short circuit current is considered here as a source for an inverter. The array consists of 40 strings connected in parallel and each string of 10 modules is connected in series. The test is considered at 800 W/m^2 irradiance and a temperature of 35°C. This PV array produces a voltage of more than 300 V and a current range of more than 250 A.

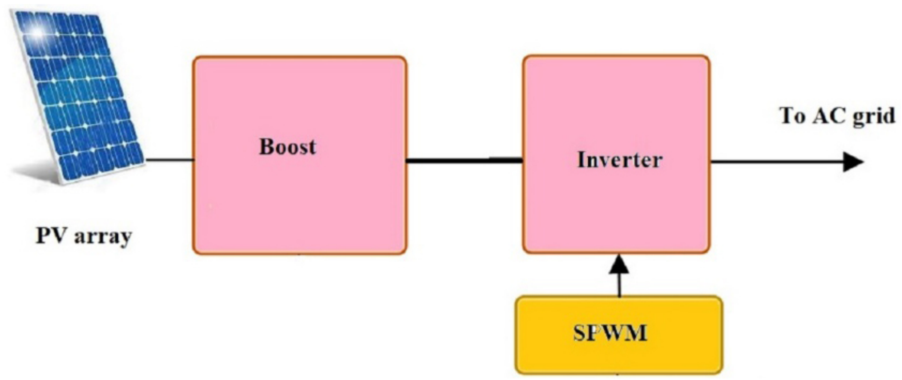

Fig. 1. Block diagram of PV inverter

SPWM is obtained by a controller (either microcontroller or microprocessor) by comparing a sinusoidal wave and a triangular wave. Figure 2 shows the MATLAB/Simulink designed SPWM generator. Also, the pulse wave generated is shown in Fig. 3. The first row is of sinusoidal waveform and triangular waveform. The second and third row are SPWM signals for alternate pairs of switches in inverters.

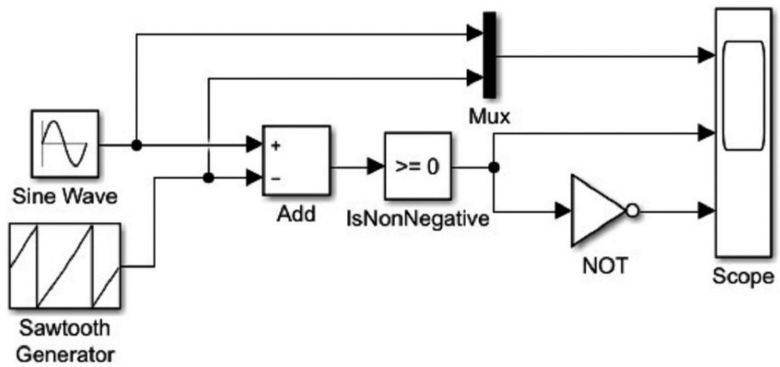

Fig. 2. SPWM pulse generator

Figure 4 shows the inverter design with the MOSFET done in MATLAB-SIMULINK software. The full bridge inverter with the MOSFET is designed and simulated. The inverter switches are controlled by SPWM signals.

Figure 5 shows the inverter design with the IGBT done in MATLAB-SIMULINK software. The full bridge inverter with the IGBT is designed and simulated. The inverter switches are controlled by a SPWM signal.

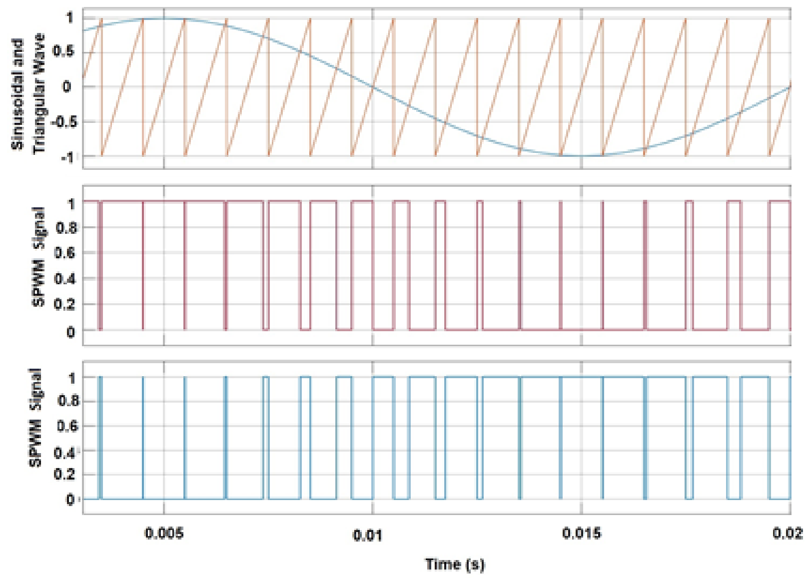

Fig. 3. SPWM signal

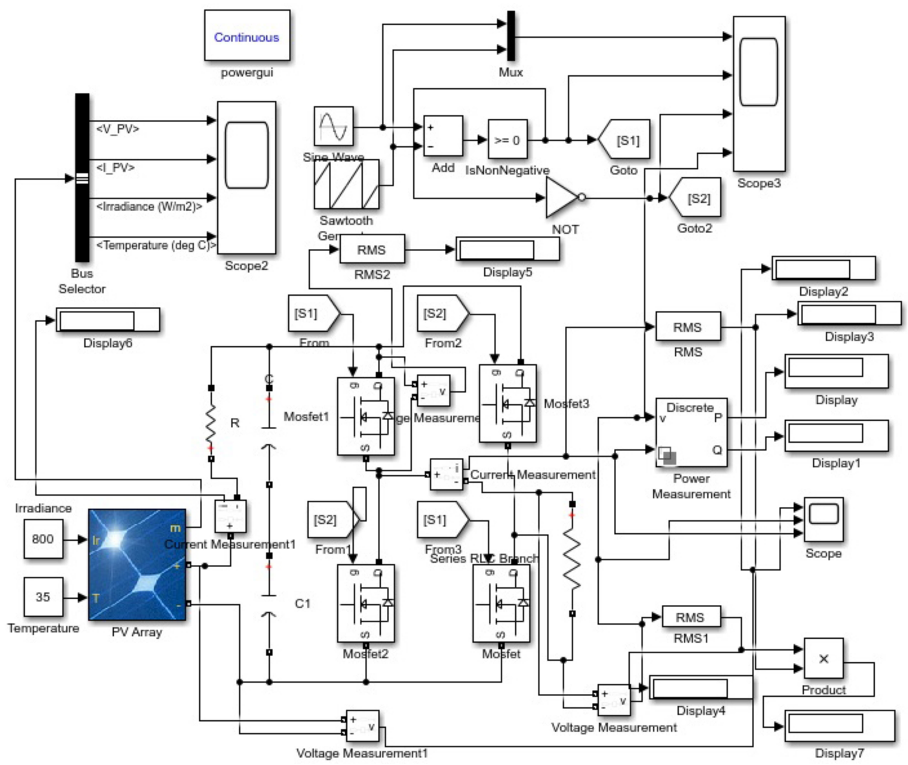

Fig. 4. PV inverter with MOSFET

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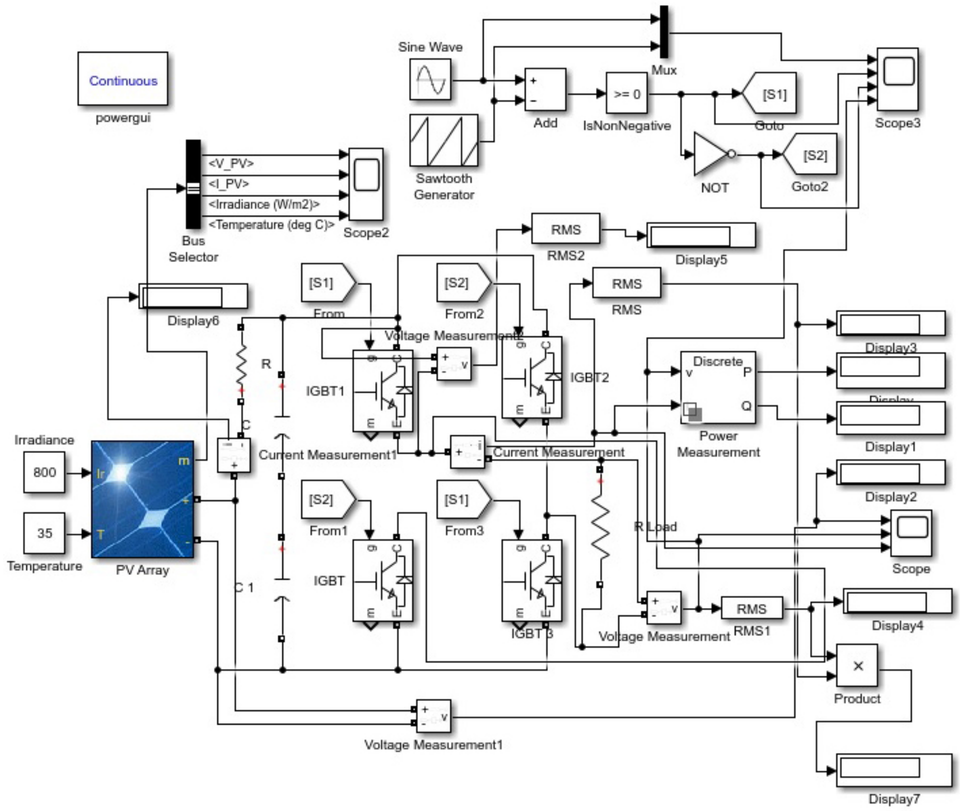

Fig. 5. PV inverter with IGBT

4. Results and discussion

4.1. Simulation output

Two single-phase inverters (two-legged four-switch type), one with the MOSFET and another with the IGBT are simulated separately in MATLAB Simulink and the outputs are compared. The inverter switches are controlled by a sinusoidal pulse width modulated signal. A resistive type of load is connected across the inverter output.

Figures 6 and 7 show input DC voltage and output AC (voltage and current) waveforms of the inverter with the IBGT and MOSFET, respectively.

The difference of output voltages of the SPWM inverter with the MOSFET and IGBT is shown in Fig. 8. Nearly 5–6 V higher output is in the case of the IGBT inverter than that of the MOSFET inverter. As the inverters are simulated separately, voltage drops across each switching devices are measured and compared. Each switching device has a drop due to which power output at the inverter also decreases. The following table gives a detailed comparison of the voltage drop and power loss in the MOSFET and IGBT-based inverters.

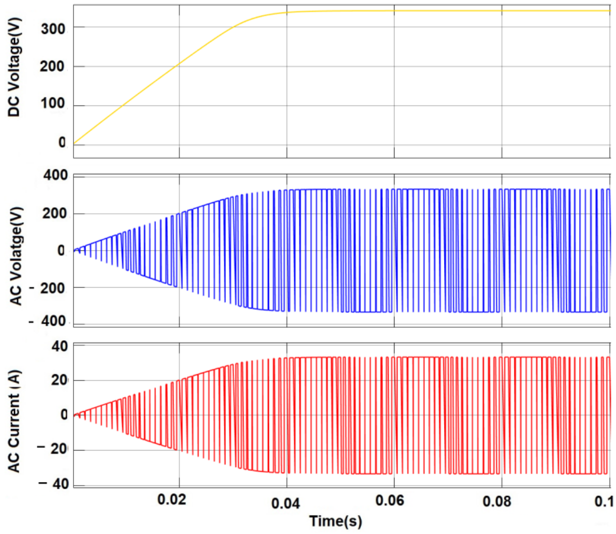

Fig. 6. MOSFET-inverter output

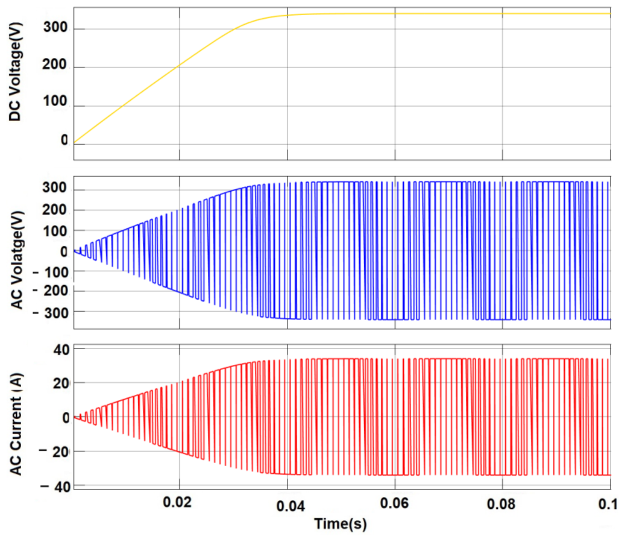

Fig. 7. IGBT- inverter output

From Table 1 it is very much evident that the voltage drop across the MOSFET is greater than that of the IGBT.

Table 2 gives the power difference of inverters with the MOSFET and IGBT at the same irradiance and temperature, nearly 210 W of more power loss in the MOSFET-based SPWM inverter than that of the IGBT-based SPWM inverter.

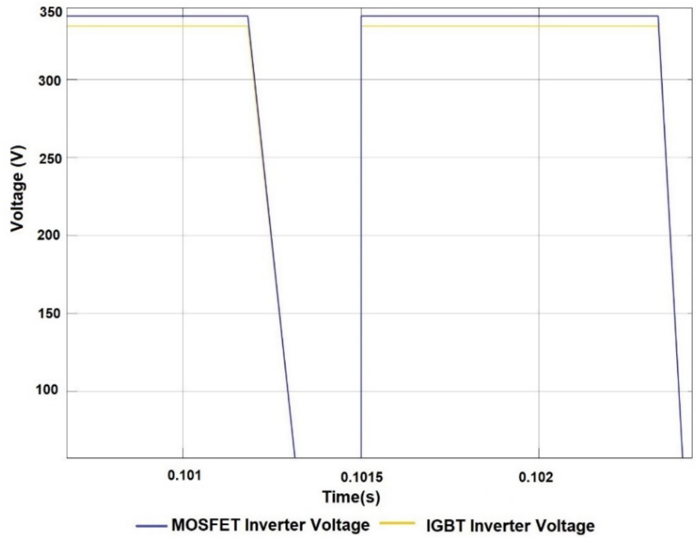

Fig. 8. Inverter output – MOSFET and IGBT voltage comparison

Table 1. MOSFET and IGBT-based SPWM inverter voltage comparison

Switch	V_{IP} **(V)**	V_{OP} **(V)**	V_D **(V)**	**Total** V_D **(V)**
MOSFET	340.9	334.2	3.342	6.684
IGBT	340.8	338.83	1.0347	2.0694

Table 2. MOSFET and IGBT-based SPWM inverter power comparison

Switch	P_{IP} **(W)**	P_{OP} **(W)**	P_{LOSS} **W)**	**Eff (%)**
MOSFET	11392.878	11202.6589	190.2191	98.3
IGBT	11614.463	11446.6805	167.7825	98.6

4.2. Output comparison

Figure 9 shows voltage losses of the inverter with the MOSFET is of nearly 6 V and that of the inverter with the IGBT is 2 V. Figure 10 gives a clear picture of the voltage drop in the individual MOSFET and IGBT switches of an inverter as 3.342 V and 1.0347 V, respectively. The figure also shows the total voltage drop of the inverter at an instant of 6.684 V and 2.0694 V.

Figure 11 shows that the power loss of the inverter with the MOSFET is 190 W and that of the inverter with the IGBT is 168 W. Nearly 22 W more power is lost in the inverter with the MOSFET than with the IGBT. Figure 12 indicates that the inverter with the IGBT is 0.3% more efficient than that with the MOSFET.

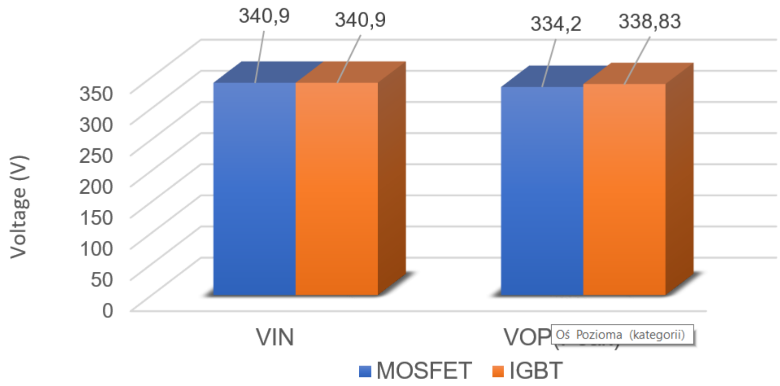

Fig. 9. Inverter input-output voltage

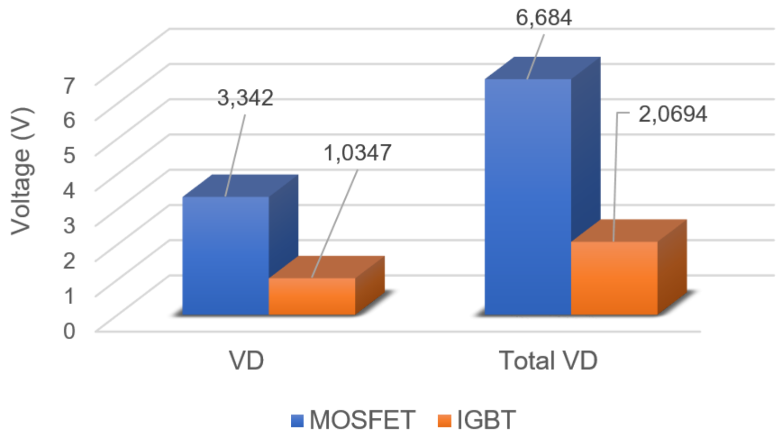

Fig. 10. Voltage drop across the switch

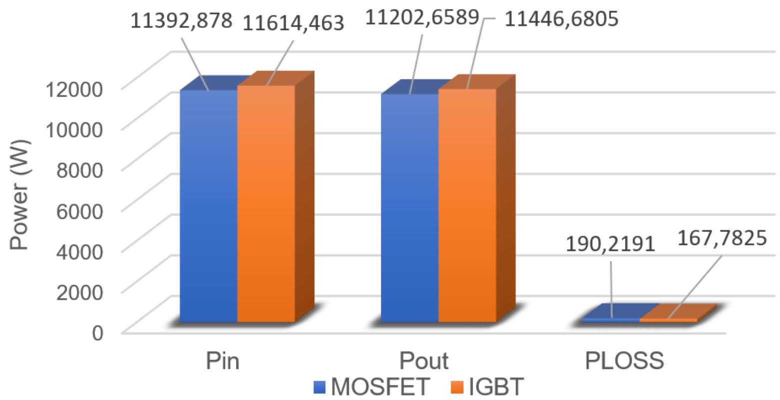

Fig. 11. Inverter – power loss

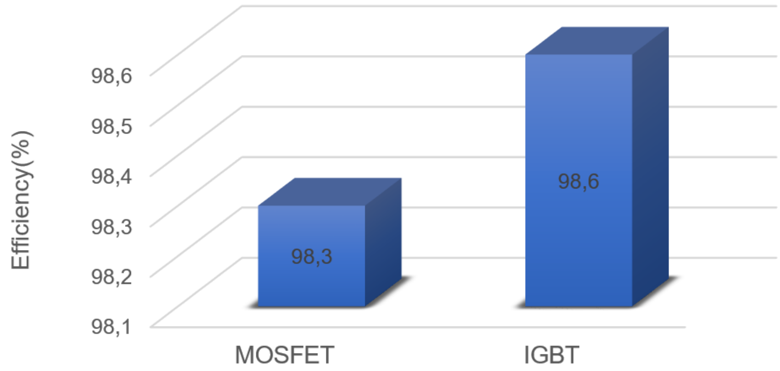

Fig. 12. Inverter efficiency

5. Conclusion

While comparing the MOSFET inverter with the IGBT inverter, it was found that nearly 22 W less power loss occurred in the IGBT-based SPWM inverter than in the MOSFET-based SPWM inverter. The SPWM technique reduced the losses better than the conventional PWM technique. This proposed technique was used to decrease the losses and improve the inverter efficiency by 1–2%. As the voltage drop across the IGBT was less than that of the MOSFET, the temperature rise of the inverter system also decreased to some extent. Temperature reduction leads to less need for cooling the system. The decrease in temperature of the cooling system, as a whole, helps prevent global warming. The results indicate that IGBT-based SPWM inverters contribute to the reduction of size, cost, volume, and ratings of the inverters, as well as to power stability. Three phase inverters with different pulse techniques can be analysed in future.

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