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Original Research

INSULATED GATE BIPOLAR TRANSISTOR TEMPERATURE CALCULATION USING SIMSCAPE/SIMULINK ENVIRONMENT WITH VARIOUS SWITCHING FREQUENCY

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Abstract: Because of developments in high-power converters, it has become crucial to investigate how effective inverter performance is. consequently, via being aware of the temperature value of the junction for the inverter switch. The rise in the switching frequency of the inverter, as well as the kind of control technique used, all have an impact on the value of junction temperature. The traditional methods for determining the junction temperature are imprecise and challenging to use. Therefore, a novel approach was used in this study to compute the junction temperature in a simple manner utilizing the MATLAB/Simulation SIMSCAPE environment. The junction temperature of the inverter's switches is easily estimated, where the heat conveyed over the layers of the IGBT can be indicated by using the simple thermal model of Foster. Because the semiconductors within the SIMSCAPE environment exhibit boosted design together with a direct thermal port. As a result, the estimation of the junction temperature is more precise and direct. This feature is only openable in the newest categories of the MATLAB program (2019-2023) This paper presents the losses formed in an Insulated Gate Bipolar Transistors, and thermal behavior analysis to represent IGBT's layers. The simulation included the influence of various operating switching frequencies on the temperature value of the junction. The results show that the temperature value of the junction increases as the switching frequency value increases and the Space Vector pulse width modulation technique has a value of junction temperature lower than the Sinusoidal pulse width modulation technique at the same switching frequency.

Keywords: *Conduction losses; switching losses; space vector pulse width modulation; thermal resistance*

1. Introduction

To manage and adapt electrical power, direct current (DC) is converted into alternating current (AC) by power inverters so that it may be utilized in electrical appliances. based on the types of power input and output [1]. Power semiconductor technology is developing quickly, inevitably leading to higher power ratings and smaller sizes, which complicate the thermal management of power electronics converters [2]. A power inverter's primary building components are power semiconductor devices. Insulated Gate Bipolar transistor (IGBTs) modules are extensively used in several significant applications with high power ratings, including electric drives and electric motors [3,4]. Particularly at the high range of power, the important design consideration for the whole converter system is the IGBT modules' thermal properties. Extreme thermal loads and dynamics may rapidly spark reliability issues since the thermal behaviors of semiconductor devices

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have a substantial impact on the dependability of power electronic equipment [5-6]. It's been established that the thermal pressures on semiconductor apparatus may be quantitatively related to the expected dependability and effectiveness of the inverter, enabling a more exact design of the semiconductor components [7-8]. The thermal swing grows when the switching frequency and output current are increased. Lower switching frequencies, on the other hand, result in more losses in a coupled motor that may be present, increasing current harmonics [9]. It is essential to estimate the semiconductor chip junction temperature to get precise measurements and prevent chip burning. The chip temperature must be precisely estimated to develop a trustworthy thermal design for the IGBT module and a heat sink design that influences the overall cost of the converter [6]. There are many methods to simulate the Tj that were formerly in the past, like, the simulation for finite elements and the three-dimensional designing [10]. The most popular approach, a two-part simulation via coupling—introduced a way to predict the temperature value of junction in 3-phase inverters for power modules of IGBT. Through the integration of the Foster and the temperature model [11]. This study indicates that the Tj value of an IGBT can be calculated immediately by using the Environment of SIMSCAPE in MATLAB program/Simulink by structuring a thermal model for impedance found by the manufacturer data of IGBT. This study focused on junction temperature variations with various PWM techniques and the switching frequency variations. The paper is organized in the following steps: Firstly, the IGBT module is studied, and power Losses are calculated. Secondly, Thermal analysis and junction temperature calculation methods of semiconductors, after that, study the Control Strategies of the Inverter. Lastly, a simulation of the proposed method for TJ estimation and a discussion of the results.

2. IGBT (Insulated Gate Bipolar Transistor)

2.1. IGBT Design

The IGBT is a completely semiconductor power-controlled transistor with high switching frequency, easy driving, and protection. Additionally, it has great all-around performance. It is a typical component for power electronic devices and is often seen in various renewable energy inverter systems, such as those that utilize solar and wind energy [12]. The (IGBT) is a hybrid transistor with an input that is a metal-oxide-semiconductor field-effect transistor (MOSFET) and an output that is a bipolar junction transistor (BJT) as shown in Fig. 1. Additionally, it provides the best tradeoff between accuracy and simulation complexity and is simple to parameterize using manufacturer data [13].

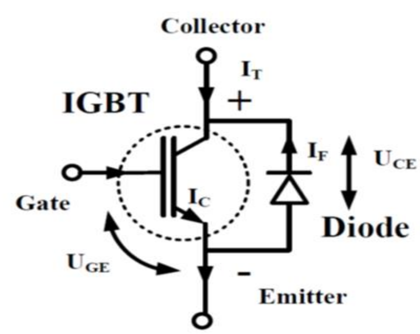

Figure 1. IGBT and anti-parallel diode circuit representation [2].

This paper uses the SIMSCAPE library tools to simulate the thermal behavior of an IGBT power module. The IGBT junction temperature may be obtained straight from the SIMSCAPE library at the last versions MATLAB/Simulink program (2019 to 2023) as illustrated in Fig.2.

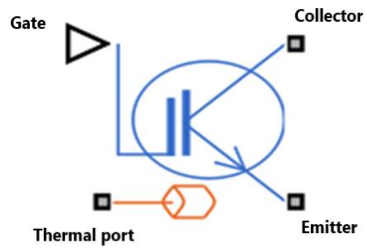

Figure 2. Represents a direct thermal port of an IGBT in the SIMSCAPE library.

2.2. Losses Composition Of IGBT

When the switch-on transition is in the active phase, the collector current IC starts to move from the collector to the emitter. The current (Ic) reaches the load current value (Io), at which point the collector-emitter voltage (Vce) begins to fall. The switch-on operation ends after Vce reaches its low on-state value of Von. Switching-on loss is the term used to describe the energy loss resulting from current levels and high switch voltage during the turn-on crossover period (ts). The opposite procedure takes place during the turn-off transition phase. The voltage between the collector and emitter Vce starts to increase, the current Io switches from the switch to the diode, and Ic falls to zero with a current fall time of tf. The switching-off loss is the energy lost because of the high switch voltage and current levels during the turn-off crossover period ts (OFF). The switch maintains conduction with the on-state voltage Von and the conducting current Io between these two states. Fig.3, illustrates the device's operation and the composition of its losses.

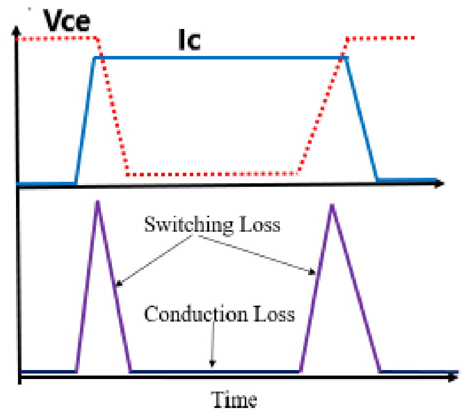

Figure 3. Power losses incurred in an IGBT during the switching and conduction period [16].

2.2.1. Conduction Losses of IGBT.

An IGBT's conduction losses may be computed using the instantaneous current of conducted $i_{_c}(t)$and the associated voltage of collector-emitter $V_{\_ce}(t)$ [2]:

$$P_{cond} = V_{\_ce}(t) \times i_{\_c}(t) \quad (1)$$

2.2.2. Switching Losses of IGBT

During the on/off cycle, the instantaneous power of the IGBT dissipates at p(t) and is also equal to $V_{ce}(t) \times i_c(t)$. Though these actions often occur in a short amount of time, like a few hundred nanoseconds, the energy waste during the switch-on and switch-off procedures is more worrisome. The energy of switching-on (E_on) and the energy of switching-off (E_off) may be expressed using [2]:

$$E_{\_on}(t) = \int_{ton}^{t} V_{\_ce}(t) \times i_{\_c}(t) \times dt \quad (2)$$

$$E_{\_off}(t) = \int_{toff}^{t} V_{\_ce}(t) \times i_{\_c}(t) \times dt \quad (3)$$

3. Thermal Analysis of the IGBT

One of the IGBTs power module features in high-power applications is its ability to withstand heat [10]. Therefore, there is a high need for precise modeling and analysis of the complete power electronics converter from an electrical and thermal perspective. This modeling offers useful data on heat sink efficiency, long-term durability, and semiconductor rating. Both the maximum TJ and the temperature variations ΔTJ also significantly affect the reliability and performance [15]. Where the heat transfer in the semiconductor layers is gradual and the transfer process varies according to the value of the thermal resistance of these layers [1]. see Fig.4 :

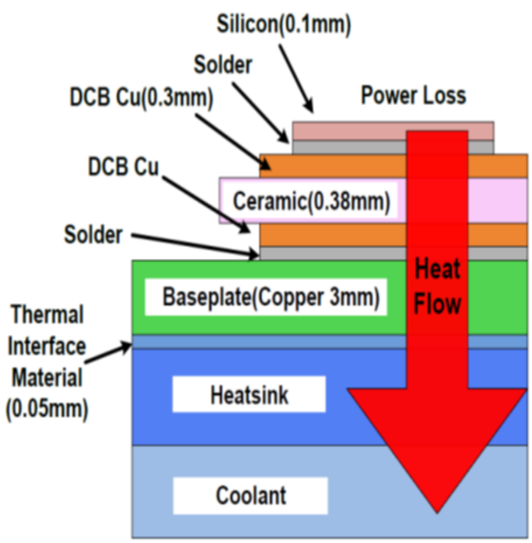

Figure 4. Heat flow through the IGBT layers [1].

3.1. RC Thermal Networks.

A small number of thermal capacitors and resistors may be used to mimic transient thermal impedance curves. For RC networks, the Cauer type and Foster type may often be used. According to the theory of heat transfer.

3.1.1. CAUAR Model.

The internal physical structure of the IGBT layers may be represented by the model of Cauer. A thermal model for the Cauer network model is created, see Fig. 5. The relationship between thermal conductivity and pressure-specific heat capacity and thermal resistance and thermal capacitance is similar to that of electrical characteristics [11]. The mathematical model may be adapted to a thermal impedance curve, or its parameters can be computed using geometrical and thermal parameters, thermal capacitance C_{th} and thermal resistance R_{th} are provided by [17]:

$$R\_{th} = \left(\frac{L}{K}\right) * \left(\frac{d}{A}\right) \quad (4)$$

$$C\_{th} = Cp * \rho * d * A \quad (5)$$

Where Cp is the pressure specific heat capacity, A is the cross-sectional area, d is the thickness of the material, k is the thermal conductivity, and ρ is the density.

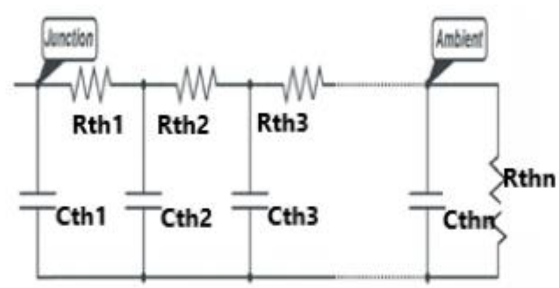

Figure 5. The CAUAR thermal model of the IGBT [21].

3.1.2. Foster Model.

Although the Foster network is simple to use, it cannot accurately depict the internal physical structure of each layer [11]. It is parameters can be simply calculated by apt the model to the curve of thermal impedance. However, the models of Foster are immutable, meaning that nodes within them have no actual physical impact, the model is created by fitting the thermal response curves using the exponential equation below [17]:

$$Z_{th} = \sum_{m=1}^{n} Rth\_m\left(1 - e^{\frac{t}{Rth_m . Cth\_m}}\right) \quad (6)$$

Where, C_{th}- m and R_{th}-m are the thermal capacitance and thermal resistance of the m^{th} RC branches, respectively, and Z_{th} is the thermal impedance. While, the number n represents all the RC branches in the network of RC [17].

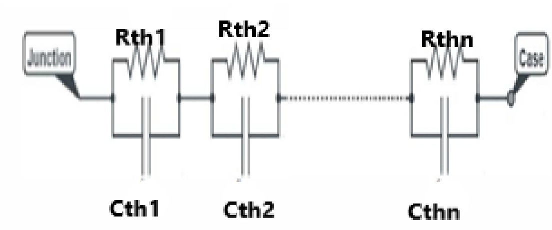

Figure 6. The Foster thermal model from junction to case [21].

3.2. Electro-Thermal Model Implementation.

Thermal modeling acquired importance to save design costs and improve the dependability of electronic power circuits [13]. Consequently, a thorough electro-thermal model necessitates modifications to the thermal performance of IGBTs. The ability to forecast heat production in IGBTs with an electro-thermal analysis is appealing. The dynamic electro-thermal model, in particular the possibility of electric modifications, including resistivity, dielectric constant, dissipation factor, and material characteristics. It's become to use thermal models to determine the TJ under specific power dissipation using the thermal power of the IGBTs as an input [18]. The electro-thermal model is shown in Fig. 7. to account for how the junction temperature affects power losses. The power loss calculation feeds back the predicted TJ, and the effects of thermal coupling are also carried into consideration in the thermal model. The IGBTs and diodes also have differing junction temperatures [2].

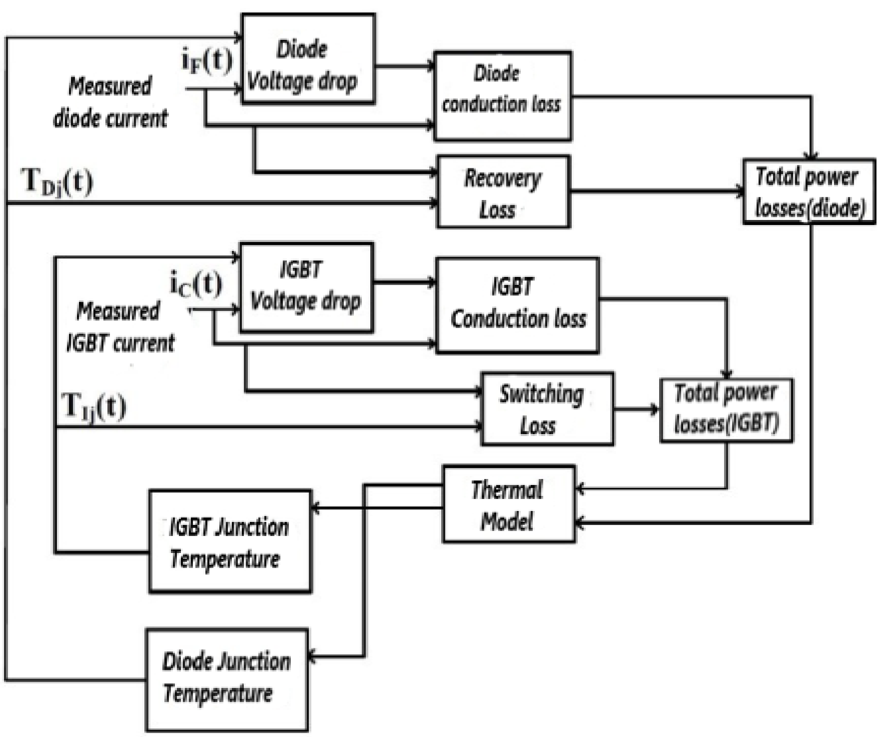

Figure7. Diagram of the electro-thermal model [2].

4. The Control Strategies of the Inverter

The voltage source inverter with a 3-phase (VSI) system is presented in Fig .8. It represents a stable converter used to convert the DC voltage value to an AC voltage value with adjustable frequency and amplitude. Regardless of the inverter type (current or voltage), a control method is needed that is specific to the machine being controlled. The standard performance primarily enables the evaluation and comparison of the various pulse width modulation (PWM) approaches. The inverter switch control signals are used to reduce the impact of the harmonics by controlling the inverter's output frequency and amplitude using the pulse width modulation (PWM) technique. PWM is a broad approach that may be used for a variety of tasks, including decoupling power supplies, analog-to-digital conversions, and variable speed drives [19]. The most often utilized approaches in PWM, are both SVPWM and SPWM [20]. The two control techniques discussed in this research. The simulation of both techniques is carried out using MATLAB/Simulink environment.

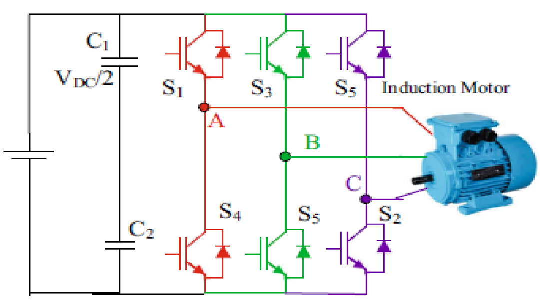

Figure 8. Two-level VSI-fed induction motor [14].

4.1 Sinusoidal PWM.

The sinusoidal PWM method is one of the most widely used and very successful modulation methods for producing a sinusoidal wave. For every leg, three reference sine waves phase-shifted by 120 degrees are used as reference signals. To determine the pulse sizes, this method compares a sinusoidal wave at the necessary fundamental frequency with a triangle wave, sometimes referred to as a carrier wave. In particular, by varying the pulse width of SPWM, the average output voltage waveform is adjusted to resemble a sinusoidal wave [22]. see Fig. 9.

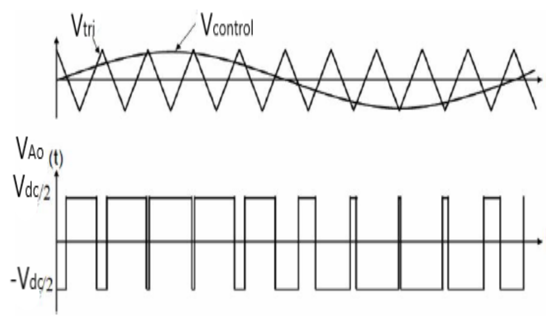

Figure 9. SPWM of three-phase VSI [22].

The voltages at the inverter's output terminal may be determined using the following formulas:

For, $V_{control} \geq V_{tri}$, V_{A0} = V_{dc} / 2

And if, $V_{control} < V_{tri}$, V_{A0} = -V_{dc} / 2

4.2 Space Vector PWM.

Space vector PWM reduces switching actions that are not essential. Compared to identical inverters using traditional pulse width modulation, this results in enhanced output performance, high efficiency, and reliability [20]. The equations of voltage in the reference frame of ABC may be translated using Park's transform to the stationary dq reference frame to construct the PWM Space Vector. This can be defined in the formula [19]:

$$X_{dq} = \begin{pmatrix} 2/3 & -1/3 & -1/3 \\ 0 & \sqrt{3}/3 & -\sqrt{3}/3 \\ 1/3 & 1/3 & 1/3 \end{pmatrix} . X_{abc} \qquad (7)$$

Six sectors make up the DQ reference frame. Sixty degrees is used to split each area evenly [19]. The fundamental vectors are shown in Fig. 10.

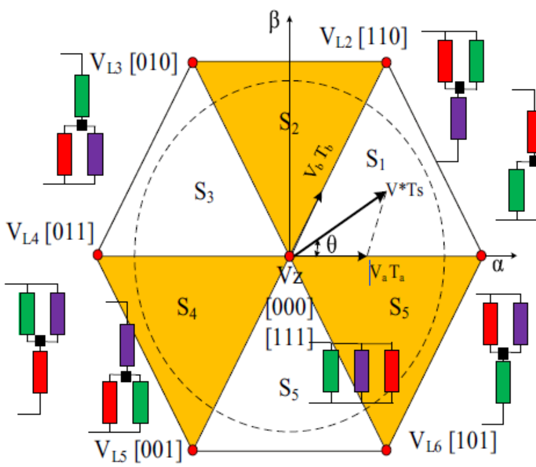

Figure 10. SVPWM of VSI with sectors [14].

5. Simulation Results and Discussion

MATLAB program /Simulink (2022 package) with SIMSCAPE library is used to turn on the simulation. 3-phase with 2-level of VSI together with load represented by an induction motor, see Fig. (11 and 12). The system parameters are: Rated power = 10 KW, Rated speed =1800 rpm, p=4, load torque =40Nm, fundamental frequency= 60 HZ, Dc-link voltage =400V, Ambient temperature = 25 C°, Maximum Junction temperature = 150C°.

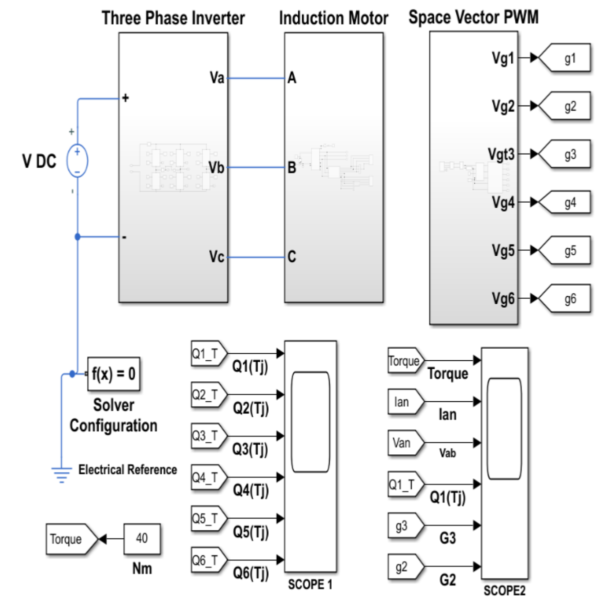

Figure11 The overall scheme diagram of the system.

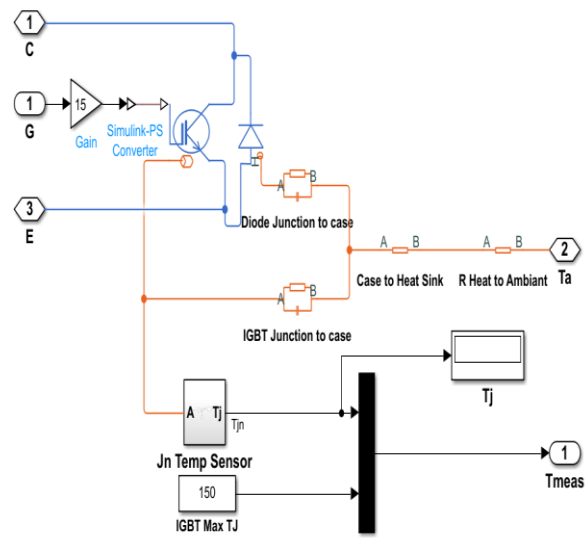

Figure12. An IGBT thermal model

Fig. 12, represents the thermal model of IGBT, from which the junction temperature can be obtained directly without the need to implement the electro-thermal model.

In this work, a variety of switching frequencies are adopted with the PWM space vector technique to track the changes in the junction temperature. Additionally, a particular switching frequency is used with the sinusoidal PWM technique to compare the temperature value of the junction to the temperature value produced by the space vector PWM technique.

Fig. 13 to 17 show the variation in the temperature value of the junction for the IGBT for varies switching frequencies, see Table 1. The maximum permissible value of Tj_{-max} obtained from the industrialist's data sheet is shown in red.

Table 1. F_SW change with TJ at constant load

$F_{\_sw}$ (kHz)	TJ(C)	Torque (Nm)	TJ max
3	67.8	40	150
5	75.11	40	150
7	78.24	40	150
9	83.9	40	150
12	92.74	40	150

Fig.13 demonstrates that the IGBT junction temperature is (67.8) C° with a switching frequency of 3 kHz when the SVPWM technique is utilized.

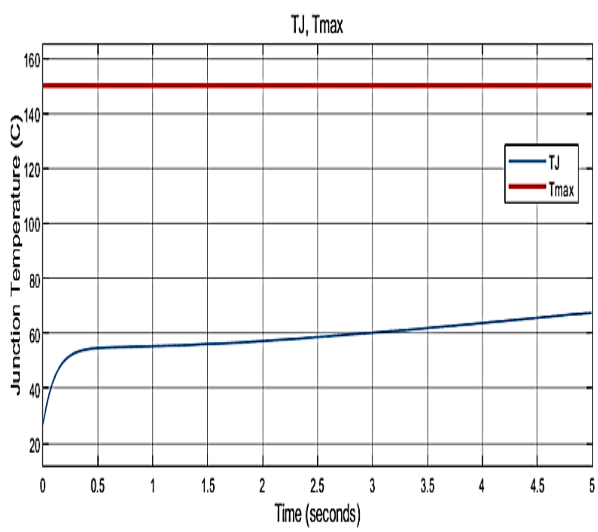

Figure13. Junction temperature at 3 kHz

Fig.14, demonstrates that the IGBT junction temperature is (75.11) C° with a switching frequency of 5 kHz when the SVPWM technique is utilized.

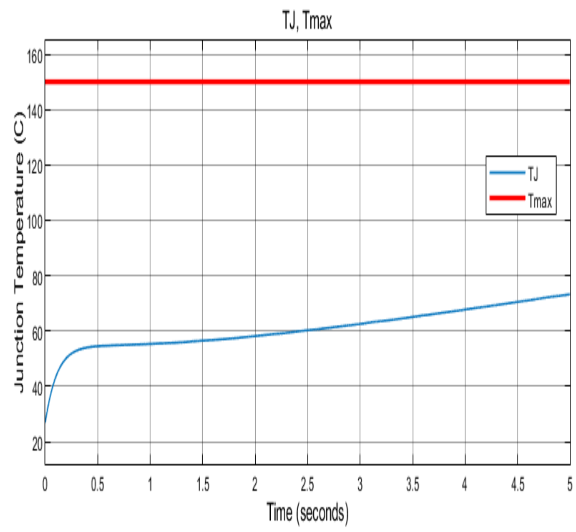

Figure14. Junction temperature at 5 kHz.

Fig.15, shows that the IGBT junction temperature is raised to (78.24) C° at a switching frequency of 7 kHz, using the SVPWM technique.

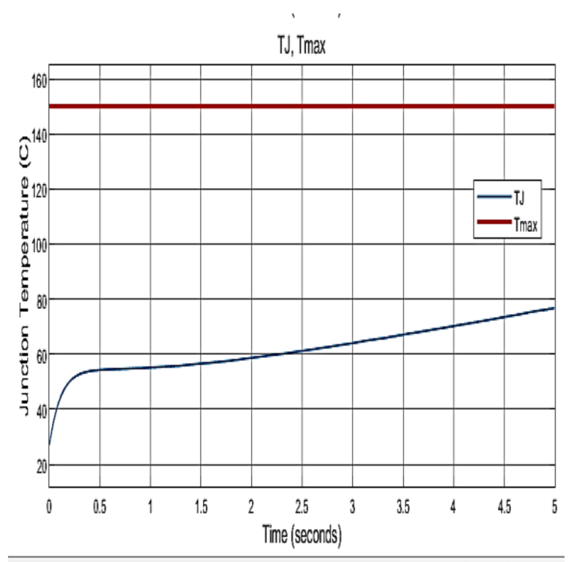

Figure15. Junction temperature at 7 kHz.

Fig.16, depicts that the IGBT junction temperature continues to rise to (83.9) C° at a switching frequency of 9 kHz, using the SVPWM technique.

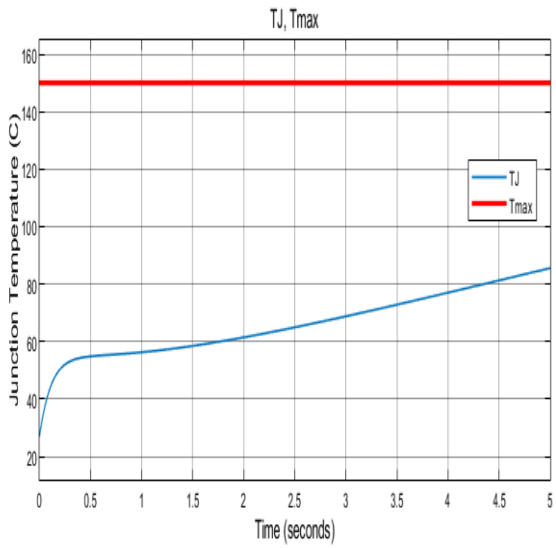

Figure16. Junction temperature at 9kHz.

Fig.17, demonstrates that the IGBT junction temperature is (92.74) C^o at a switching frequency of 12 kHz, using the SVPWM technique.

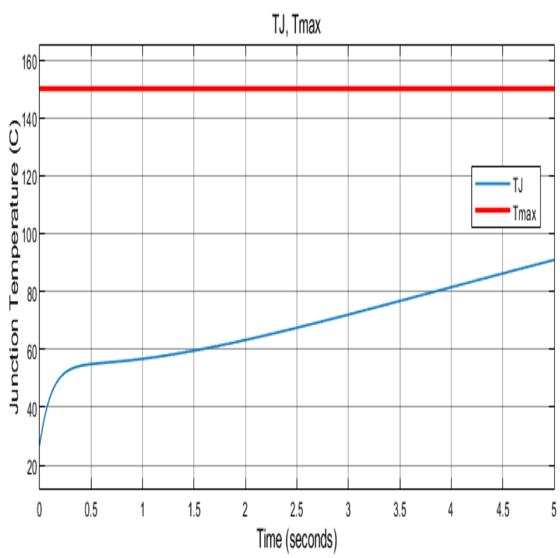

Figure17. Junction temperature at 12kHz.

Fig.18, shows that the IGBT junction temperature is (98.2) C^o at a switching frequency of 12 kHz, using the SPWM technique.

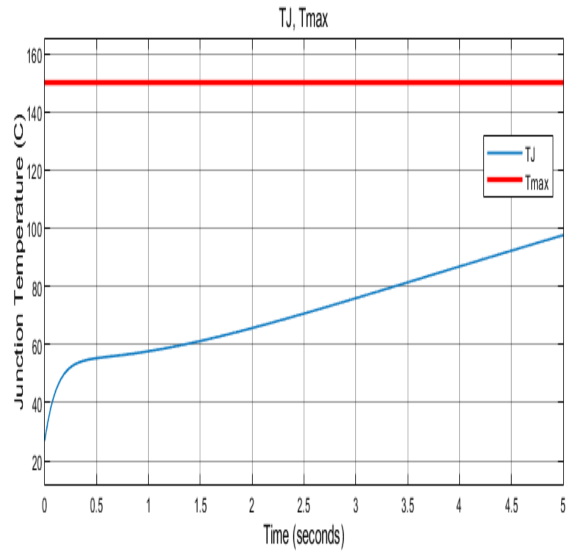

Figure18. Junction temperature at 12kHz using SPWM technique.

Fig.19, shows the phase to neutral current at a torque 40Nm.

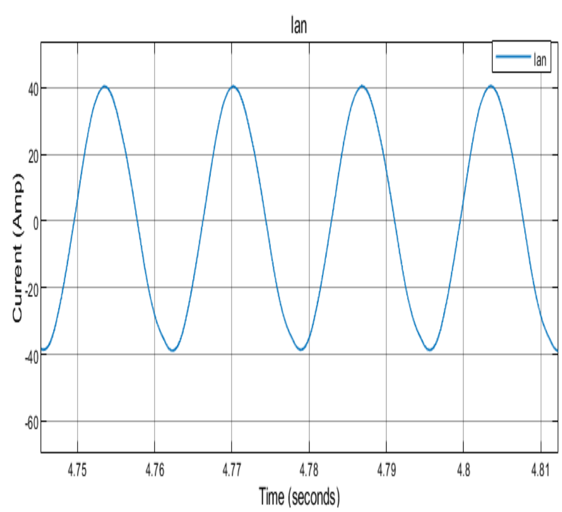

Figure 19 Ian output current.

Fig.20, shows the Line-to-Line Voltage with a 40 Nm torque value.

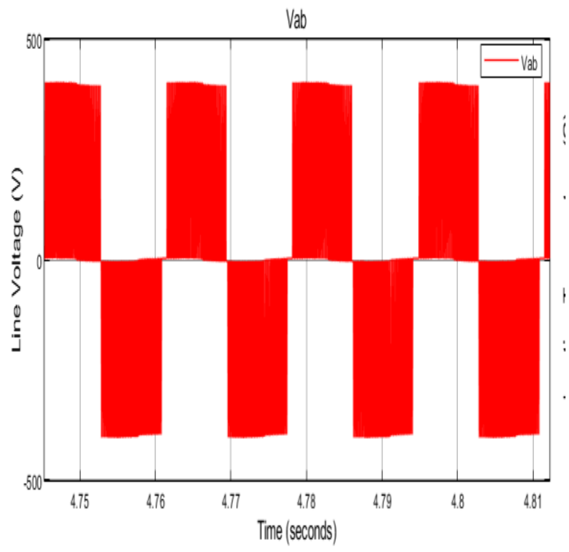

Figure 20 Vab Voltage.

6. Conclusions.

Calculating the temperature value of the junction for the switch of the inverter is substantial since it awards a predictive indication of the efficiency of power converters and their long-term durability. There are several methods for calculating TJ, but most of them are difficult and complex. In this research, the MATLAB/Simulink simulation used the SIMSCAPE environment to determine the TJ value. As a novel method, the development of IGBT in the SIMSCAPE environment gives the possibility to obtain the value of the junction temperature directly and accurately via the IGBT thermal port without the need for computing the power losses. Through this simulation, two types of PWM techniques applied to the inverter (SVPWM and SPWM) were used. Additionally, several values for the switching frequency are taken to confirm the validity of the model. The Analytical results show that the value of the temperature for the junction increases as the value of the switching frequency increases (see Table 1) Moreover, with identical working statuses of the system, the outcomes show., the SVPWM technique is better than the SPWM technique because it gives the least losses at the same switching frequency value, where at switching frequency 12(kHz). TJ recorded (92.74) C° when using the SVPWM technique, while TJ recorded (98.2) C° at the SPWM technique.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Authors Ahmed Sh. Ahmed and Riyadh G. Omar suggested the Work problem. Two authors developed the results. The environment of the SIMSCAPE that was presented in MATLAB/Simulink as a new tool was used to determine the Junction Temperature value of the Inverter's switches in a less complex way. The suggested simulation technique assisted in choosing the right heat sink and saved the duration of time needed for the thermal evaluation of semiconductors.

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