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RESEARCH OF THERMAL PROCESSES OF AN IGBT MODULE-BASED INVERTER

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Purpose. *Study of thermal processes of an inverter based on an IGBT module for used in a frequency converter to control the operation of an asynchronous motor.*

Methodology. *Analytical and computational methods to analyse thermal processes of an inverter based on an IGBT module.*

Findings. *The study of thermal processes of the SKM200GB12T4 inverter based on the IGBT module was performed using the SemiSel program. A mathematical model of the cooling process of the SKM200GB12T4 inverter was developed. The dependence of the dynamic thermal impedance Zth(s-a) on time, which is described by an exponential function, was obtained. The value of the time constant for this dependence, which characterizes the rate of change in the cooler temperature, i.e. the quality of its operation, has been calculated. The thermal time constant τ = 1.44 s indicates the time required to reach a temperature difference of approximately 63% of its stationary value. This low value reflects the effective cooling due to the high air flow velocity (7 m/s) and air flow rate (426.43 m³/h), which is critically important for maintaining the IGBT junction temperature below 175 °C during overload.*

The values of the inverter temperature maxima during overload were obtained. For an overload of 10.94 seconds, the maximum temperature for IGBT transistors is 120.85 °C, and for diodes – 123.4 °C. The case temperature Tc = 71.21 °C and the radiator temperature Ts = 63.56 °C remain the same for transistors and diodes and do not exceed the maximum operating temperature of the module due to the stability of the cooling system. However, overheating can increase with prolonged loading, resulting in the degradation of semiconductor devices.

The temperature and power variation processes at nominal load and in overload mode for one period have been studied using the SemiSel program. The temperature change graphs reflect the stability of the temperature at various points, such as the transitions of IGBT transistors and reverse diodes, due to effective thermal control. The power graph indicates cyclical changes in losses, with peaks in the phases where current and voltage are maximum. These data confirm the suitability of the module for use in control circuits.

Originality. *Based on the graphical analysis of the kinetic dependencies of temperature and inverter power, a mathematical model of the cooling process of the SKM200GB12T4 inverter was developed, that describes the dependence of the dynamic thermal impedance Zth(s-a) on time. The thermal time constant for this dependence, which characterises the rate of change of the cooler temperature, was calculated.*

Practical value. *The results of the study of the thermal characteristics of the SKM200GB12T4 inverter can be used to optimize the operating modes of the frequency converter for controlling the operation of an asynchronous motor.*

Keywords: thermal processes; inverter; IGBT module; frequency converter.

I. INTRODUTION

The control system with a frequency-controlled drive is the simplest and most economical from a technical point of view. An integral part of a regulated electric drive is a controlled power converter, which provides smooth speed control of electric motors by converting fixed values of voltage and frequency of the network into variable values [1].

The number of revolutions of the motor is proportional to the frequency of its supply. If the electric motor is powered from a 50 Hz network, then its number of revolutions will be maximum and constant. When the electric motor is powered from a frequency converter (adjustable output frequency 0-50 Hz), its number of revolutions can vary from zero to the maximum value.

When changing the engine speed, it is possible to control the power consumption and energy losses.

In addition, the use of frequency converters allows you to reduce reactive power consumption and starting currents, which has a positive effect on the service life of technological equipment and energy infrastructure.

Modern electronic switches based on IGBT transistors, due to their positive properties, are used to create power keys of inverters in the production of frequency converters for electric drives [2] – [3].

Today, frequency converters using a power

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transistor module based on IGBT transistors, which consists of a set of insulated gate bipolar transistors and reverse current diodes, are widely used.

The study of thermal processes of an inverter based on an IGBT module for use in a frequency converter is important to ensure its reliable operation in high power systems, such as traction inverters. This process involves the evaluation and analysis of thermal parameters (thermal resistance, temperature and power) to prevent overheating and increase efficiency.

II. ANALYSIS OF LAST RESEARCHES

The data sheet for the SKM200GB12T4 power transistor module [4], available on the Semikron Danfoss website (Semikron Danfoss), presents the basic thermal parameters required for calculations. These include: junction-to-case thermal resistance ($R_{th(j\text{-}c)}$); case-to-heat sink thermal resistance ($R_{th(c\text{-}s)}$). These parameters are critical for estimating the temperature rise from the transistor junction to the environment [5].

In the article [6], an analysis of the most commonly used IGBT modules for voltages from 600 V to 6500 V is made and a methodology for determining the quality criteria of modules for a given voltage, current and frequency is developed.

The article [7] describes the use of the RC (resistance-capacitance) approach to predict the junction temperature of modules mounted on a liquid cooled heatsink. Finite element modelling (FEM) is used for detailed thermal analysis, taking into account the thermal interaction between modules and the influence of heatsink materials. A comparison of single and dual phase cooling systems is presented. Different thermal interface materials (TIMs) are evaluated, indicating the reduction in junction temperature. These methods can be adapted to the SKM200GB12T4 module, especially in the context of traction applications, where thermal modelling accuracy is important.

Article [8] describes a thermal resistance model and an equivalent thermal circuit for IGBT modules, including the calculation of transistor and diode losses using the pulse width modulation (SVPWM) method.

Article [9] emphasises the importance of calculating the junction temperature for multi-chip devices and suggests that the calculations should be separated for each chip, taking into account differences in thermal resistance.

In [10], the power loss of the IGBT module under nominal operating conditions was theoretically estimated. The temperature field of the heat sink under typical operating conditions was simulated by ICEPAK, and the heatsink was parameterised. The simulation results show that under the condition of forced cooling and heat dissipation, the optimised heat sink meets the heat dissipation requirements of the motor controller.

In [12], thermal management studies for IGBT modules are reviewed. The thermal resistances of IGBT modules are studied. It is stated that the junction-to-case thermal resistance usually decreases inversely with the total thermal power. In addition, IGBT cooling solutions are also considered, and the performance of different solutions is compared. A fast and efficient method for IGBT thermal management is proposed depending on the junction-to-case thermal resistance requirements and the equivalent heat transfer coefficient of the test samples.

In [13], experimental methods for determining the thermal characteristics of IGBT power modules are reported. Three different systems were used: the first performs a “temporary” characteristic to monitor the most significant device parameters during normal operation or stress tests; the second performs a complete and dynamic thermal characterization; finally, an infrared optical analysis was performed to verify the results.

In [14], different thermal models of the IGBT power module are presented and compared. A three-dimensional finite element method (FEM) model is simulated in COMSOL. And then a thermal model with lumped parameters is derived taking into account various aspects (heat propagation and thermal coupling).

In the book [15] the author describes experimental and numerical methods, tools used in a typical thermal design process. Information is provided on some advanced methods of cooling electronic devices.

An analysis of research and publications devoted to the thermal characteristics of power transistor modules based on IGBT transistors allows us to consider the development and improvement of control circuits using IGBT transistors as relevant.

III. FORMULATION OF THE WORK PURPOSE

The purpose of this work is to study the thermal processes of the SKM200GB12T4 inverter based on the IGBT module for use in a frequency converter in an electric circuit to control an asynchronous motor.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

We investigated the thermal characteristics of the SKM200GB12T4 inverter based on IGBT transistors and reverse diodes (Fig. 1).

The simulation and calculations of the inverter were carried out using the SemiSel program, which is available on the manufacturer's website [1]. The SemiSel program is used to simulate and analyse the operation of electronic devices, such as the SKM200GB12T4 inverter module manufactured by Semikron. Typical values for calculating the inverter in the SemiSel program are given in Table 1.

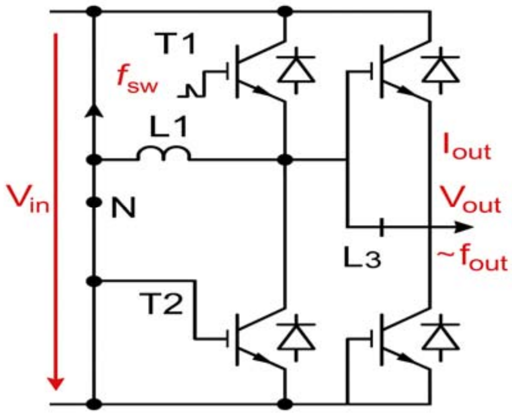

Figure 1. SKM200GB12T4 inverter diagram

Table 1. Typical values for calculating an inverter in the SemiSel program

Input voltage (V_{in})	650 V
Output current (I_{out})	86,4 A_{rms}
Power factor (cos φ)	0,866
Switching frequency (f_{sw})	5 kHz
Additional losses per heat sink ($P+_{HS}$)	0 W
Overload current (I_{over})	130 A_{rms}
Minimum output frequency ($f_{out(min)}$)	2 Hz
Duration (t_{over})	10 s
Output voltage (V_{out})	380 V_{rms}
Output power (P_{out})	40,1 kW
Output frequency (f_{out})	50 Hz
Modulation (M) Sinus triangle PWM	M PWM
Overload factor	1,5
Minimum output voltage ($V_{out(min)}$)	51,7 V_{rms}

Fig. 2 shows graphs of the dependence of voltage, current, and frequency on time during overloads of the SKM200GB12T4 module.

Analysis of the voltage, current and frequency curves during overloads (Fig. 2) indicates that at the moment of switching on and off, the change in these quantities follows a linear law. After an initial increase in current and a decrease in voltage and frequency, they reach the set value and the module operates in the operating mode. The physical process by which these quantities change during power-up is related to the dynamics of the charge and discharge of the gate node, as well as to the distribution of the electric field in the IGBT structure, which affects the switching speed and heat dissipation. It has been demonstrated that when the module is deactivated, there is an increase in both voltage and frequency, whilst concurrently there is a decrease in current. The rate of current decrease is related to the slow recombination of minority carriers in the drift region. This effect increases turn-off time and switching losses.

Typical values for calculating the thermal characteristics of the SKM200GB12T4 inverter in the SemiSel program are given in Table 2.

Table 2. Typical values for calculating the thermal characteristics of the inverter in the SemiSel program

	T	*D*
I_{ref}	200 A	200 A
V_{ref}	600 V	600 V
$T_{j\ opt}$	150 °C	150 °C
$T_{j\ max}$	175 °C	175 °C
$V_{f@25°C,\ Iref}$	1,8 V	2,2 V
$V_{f@Tjopt,\ Iref}$	2,2 V	2,12 V
R_{gOn}	4,75 Ohm	
R_{gOff}	4,75 Ohm	4,75 Ohm
E_{on}	21 mJ	
E_{off}	20 mJ	13 mJ
$R_{th(j\text{-}c)}$	0,14 K/W	0,26 K/W
$R_{th(c\text{-}s)}$	0,045 K/W	0,057 K/W

The use of the SemiSel program allowed us to determine the main thermal characteristics of the cooling system of the SKM200GB12T4 inverter. The radiator parameters are given in Table 3.

The mathematical model of cooling processes for the SKM200GB12T4 inverter is based on Newton’s law of cooling and the radiator parameters from Table 3. Convective heat transfer is carried out by transferring heat from a heated body to a cooling gas. The heat transfer process is described by Newton's law of cooling [16]:

$$dQ = \alpha \Delta T S dt, \tag{1}$$

where dQ - the amount of heat transferred from a heated body to a cooling medium; α is the heat transfer coefficient; S is the area of the cooling surface; ΔT is the temperature excess of the heated body over the ambient temperature.

The heat transfer rate P is given by:

$$P = \frac{dQ}{dt} = \alpha \Delta T S, \tag{2}$$

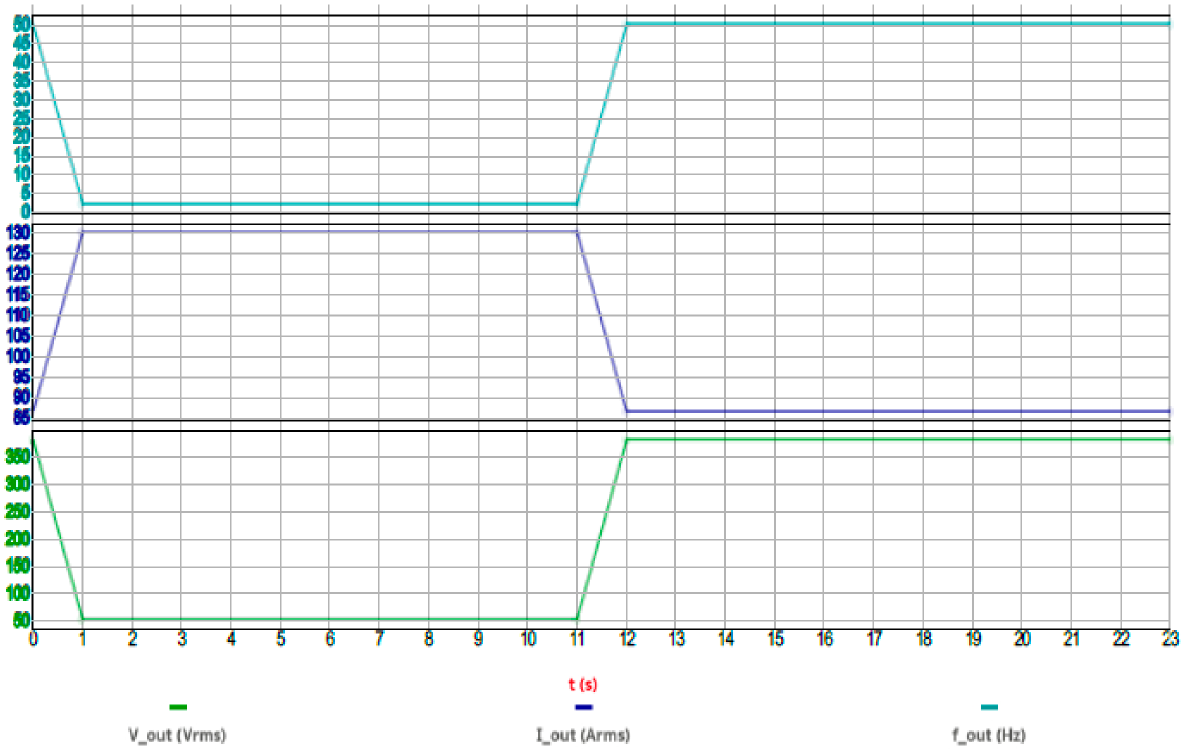

Figure 2. Graphs of voltage, current, frequency versus time during overloads of the SKM200GB12T4 module

Table 3. Basic thermal characteristics for the inverter cooling system

Cooling method	Air cooling
Mounting surface width	345.34 mm
Mounting surface length	244.14 mm
Fin length	70 mm
Coolant speed	7 м/c
Coolant flow rate	426.43 m^3/h
Distance between products	5 mm
Coolant temperature	40 °C
$R_{th(s\text{-}a)}$, steady state	0.0352 K/W

The change in the temperature excess during heating of the body is described by an exponential law:

$$\Delta T = \frac{P}{\alpha S}(1 - e^{-\frac{t}{\tau}}) = \Delta T_s(1 - e^{-\frac{t}{\tau}}), \quad (3)$$

where ΔT_s is the set temperature excess; τ is the thermal time constant.

The thermal time constant of a body is defined as follows:

$$\tau = \frac{cm}{\alpha S}, \quad (4)$$

where c is the specific heat capacity of the body, m is the mass of the body, α is the heat transfer coefficient, S is the cooling surface area.

The value of the thermal time constant characterizes the rate of change in body temperature; it depends on the ratio between the heat capacity of the body c*m and the heat transfer conditions α*S. Increases in cooling intensity, owing to elevated heat dissipation (increasing α), result in a reduction of the thermal time constant.

The thermal resistance is defined as

$$R_{th(s-a)} = \frac{\Delta T}{P}. \quad (5)$$

The thermal resistance is related to the heat transfer coefficient:

$$R_{th(s-a)} = \frac{1}{\alpha S}. \quad (6)$$

Transforming formula (3) taking into account (5) and (6), we obtain:

$$R_{th} = \frac{1}{\alpha S}(1 - e^{-\frac{t}{\tau}}) = R_{ths}(1 - e^{-\frac{t}{\tau}}), \quad (7)$$

where R_{th} is the thermal resistance of convection; R_{ths} is the value of the thermal resistance of convection that has been established.

Fig. 3 indicates the dependence of the dynamic thermal impedance $Z_{th(s-a)}$ on time, obtained using the SemiSel program.

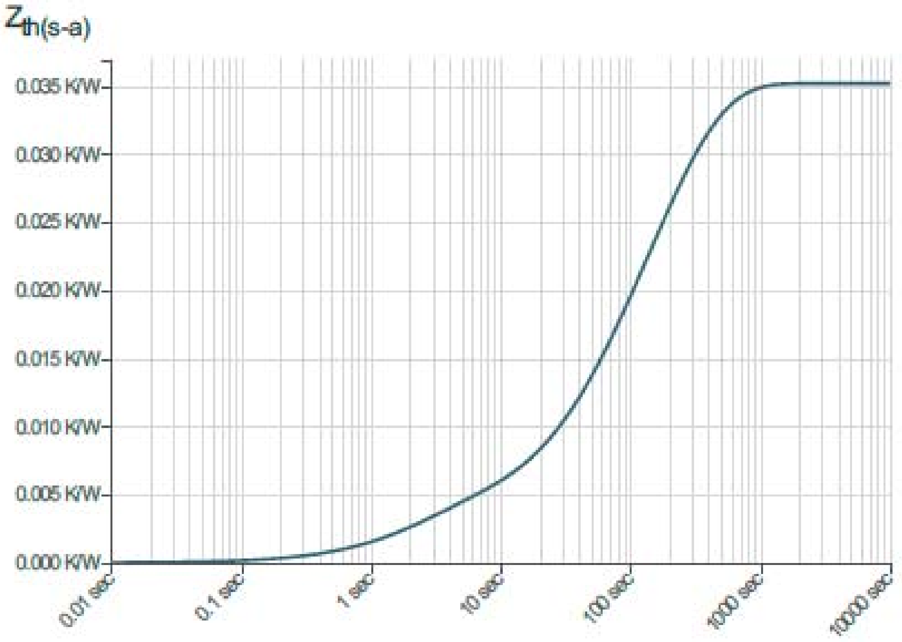

Figure 3. Dependence of dynamic thermal impedance $Z_{th(s-a)}$ on time

The parameter $Z_{th(s-a)}$ is interpreted as the dynamic thermal impedance at transient regimes, which is used in the analysis of the thermal characteristics of electronic components or cooling systems. The units K/W indicate the ratio of temperature change to power, which is characteristic of thermal resistance.

The dependence graph of dynamic thermal impedance $Z_{th(s-a)}$ on time utilises a logarithmic scale on the time axis, which allows you to cover a wide range of values (from 0.01 to 10,000 seconds), which is not always obvious when analysing such data. The value of $Z_{th(s-a)}$ increases to a value of 0.032 at 400 seconds, and after this time the growth slows down, gradually approaching a plateau of approximately 0.035 K/W.

The graph illustrates an exponential growth pattern, with an initial value and a gradual approach to the limiting value, which corresponds to formula (7). The initial value of 0.005 K/W can reflect the instantaneous thermal resistance, while the limit value of 0.035 K/W can be considered as the stationary thermal resistance that results after a significant duration.

Mathematical analysis allowed us to obtain a regression formula that describes the graph of the dependence of the parameter $Z_{th(s-a)}$ on time, as illustrated in Fig. 3. The dynamic thermal impedance $Z_{th(s-a)}(t)$ is determined by formula (8) with initial value $Z_{th(s-a)}(0)$ = 0.005 K/W and steady-state value $Z_{th(s-a)}(\infty)$ = 0.035 K/W:

$$Z_{th}(t) = 0.005 + 0.03(1 - e^{-\frac{t}{1.44}}). \quad (8)$$

The value of the thermal time constant is τ = 1.44 s. At $t = \tau$ the exponent in equation (3) becomes $e^{-\frac{t}{\tau}} = e^{-1} \approx 0.3679$. So, we obtain $\Delta T = \Delta T_s(1 - e^{-1}) = \Delta T_s(1 - 0.3679) = \Delta T_s \cdot 0.6321.$ This means, that when the time equals the thermal time constant $t = \tau$, the temperature difference reaches approximately 63% of its final steady-state value ΔT_s.

Thus, the thermal time constant indicates the time required to achieve a temperature difference of ≈ 63% of its stationary value. This low value reflects effective cooling due to the high air flow velocity (7 m/s) and air flow rate (426.43 m³/h), which is critically important for maintaining the IGBT junction temperature below 175 °C during overload.

The radiator uses air cooling with a steady-state thermal resistance $R_{th(s-a)}$ = 0.0352 K/W. Radiator area S = 345.34 mm ·244.14 mm = 0.08436 m².
Thus, the heat transfer coefficient is:

$$\alpha = \frac{1}{R_{th(s-a)}S} \approx 336.7 \ \Omega/\mu^2\text{K}. \quad (9)$$

The results of the calculation of the cooling system in the SemiSel program are shown in figures: 4, 5, 6, 7, 8.

As illustrated in Figure 4, the results of the calculation of temperature and power for the inverter at nominal load are presented.

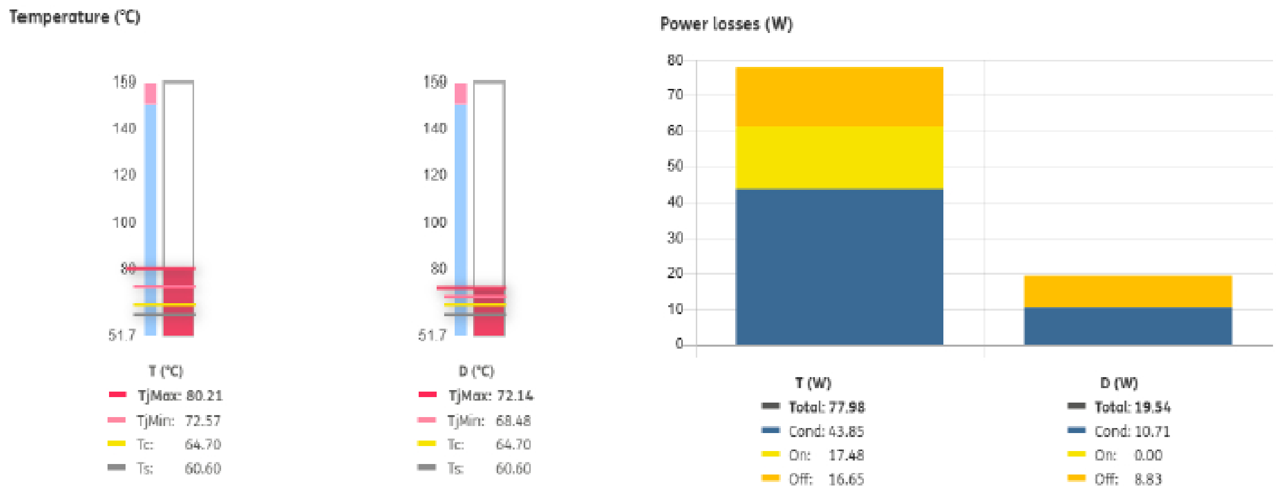

Figure 4. Results of calculating the temperature and power of the inverter at rated load

Research has demonstrated that the total losses are 585 W, which requires effective heat dissipation for reliable operation of the module. The losses in IGBT transistors are higher than in diodes, which is typical for such systems.

The simulation displays the maximum operating junction temperature for the transistor ($T_{j\ max}$) as 80.21 °C, and the minimum ($T_{j\ min}$) as 72.57 °C. The case temperature (T_c) is 64.7 °C, and the heat sink temperature (T_s) is 60.6 °C. These values indicate how effectively heat is removed from the module, preventing overheating. The higher junction temperature is explained by the fact that this is where the main conversion of energy to heat occurs.

The maximum operating junction temperature ($T_{j\ max}$) of the diode is 72.14 °C, while its the minimum ($T_{j\ min}$) is 68.48 °C, the case temperature (T_c) is 64.7 °C, and the heat sink temperature (T_s) is 60.6 °C.

These temperature values indicate that the cooling system is effectively removing heat, thereby maintaining the junction temperature of the transistor and diode below the maximum allowable level (typically 150 °C for such modules).

The total system losses are 585 W, and the efficiency is 98.83%. The losses in IGBT transistors per device (87.98 W: losses in conduction mode 43.85 W, when turned on 17.48 W, when turned off 16.65 W) and diodes per device (19.54 W: losses when turned on - 0.00 W, and when turned off - 8.83 W). It is imperative that these losses are distributed by the cooling system in order to ensure that the temperature remains within safe limits.

The simulation results demonstrate that the cooling system of the SKM200GB12T4 module is is capable of maintaining safe temperatures at its rated load, with a dissipation of 585 W of heat.

Fig. 5 illustrates the results of calculating the temperature and power of single output period for the IGBT transistors of the inverter at its rated load.

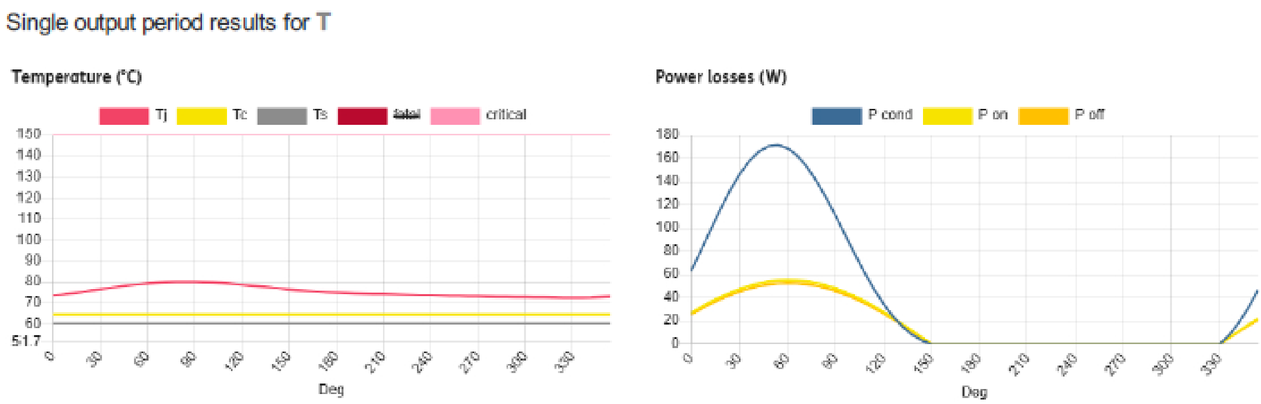

Figure 5. Results of calculating temperature and power of one output period for transistors (T) at nominal load

The graphs presented herein consist of two primary components: the first component illustrates the temperature of the various components, whilst the second component illustrates the power losses over a period corresponding to a full AC cycle.

The first graph illustrates the temperatures of key parts of the system. The junction temperature (T_j) fluctuates slightly, remaining below 75 °C, and does not reach the critical threshold of 150 °C, indicating safe operation.

It is evident that the case temperatures (T_c) remain stable at approximately 66 °C, and the heat sink temperatures (Ts) remain stable at around 60 °C.

The maintenance of stable temperatures is indicative of effective control of diode heat dissipation, with the cooling system playing a pivotal role in preventing overheating, a critical factor in ensuring the device's durability.

The second graph illustrates three categories of losses. The conduction losses (P_{cond}) exhibit a sinusoidal pattern, reaching a maximum of approximately 53 W at 110 degrees, which is concomitant with the peak current.

The on-state losses (P_{off}) reach a maximum of approximately 25 W at 60 degrees, indicating a substantial energy expenditure during the switching process. The off-state losses (P_{on}) are practically zero.

The graphs indicate that the cooling system for the diodes of the SKM200GB12T4 module at nominal load works effectively, keeping all temperatures within safe limits. However, the high off-state losses (P_{off}) are an important aspect that may require optimization for long-term reliability, particularly in scenarios involving heavy duty operations.

Fig. 6 illustrates the results of the calculation of the maximum temperature for the inverter under overload.

The analysis of the results indicates that the maximum and minimum temperatures of the transistor (T = 120.85 °C) are the same. The maximum and minimum temperatures of the diode (T = 123.4 °C) of the SKM200GB12T4 module are also the same.

For an overload of 10.94 seconds, the maximum temperature for the transistors is 120.85 °C, and for the diodes is 123.4 °C.

Other temperatures, case temperature T_c =71.21 °C and the heat sink temperature T_s =63.56 °C remain the same for transistors and diodes and do not exceed the maximum operating temperature of the module due to the stability of the cooling system. However, with longer load times, overheating may increase, which will cause degradation of semiconductor devices. This is a confirmation of the effectiveness of the cooling system to ensure the reliability of the module.

Fig. 7 illustrates the results of calculating the temperature and power of single output period for the IGBT transistors of the inverter during overload.

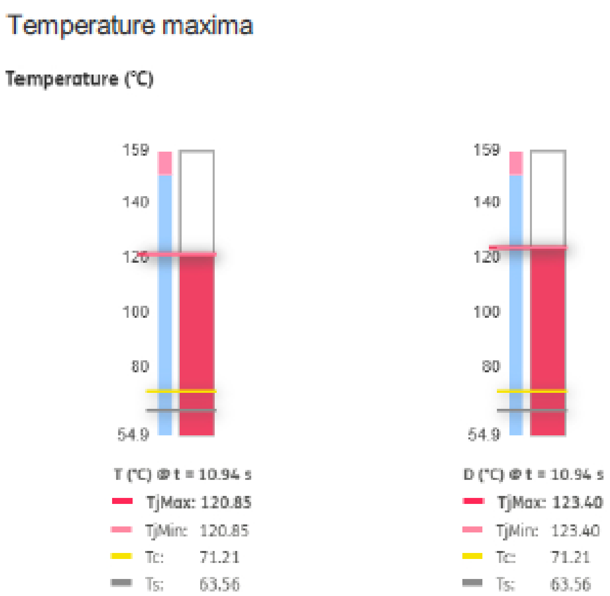

Figure 6. Inverter temperature peaks during overload

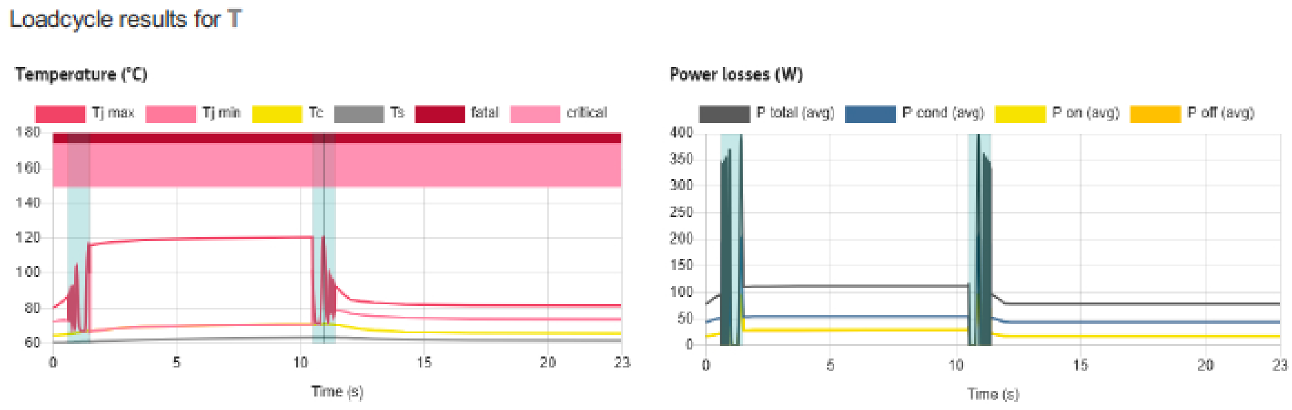

Figure 7. Results of calculating the temperature and power of one output period for IGBT transistors of the inverter (T) during overload

These graphs illustrate the response of the SKM200GB12T4 module reacts to overload when operating with an asynchronous motor.

The junction temperature reaches approximately 120 °C during periods of peak operation, remaining within safe limits (maximum 150 °C). The temperature graph demonstrates that the junction temperature (T_{jmax} and T_{jmin}) reaches peaks of approximately 105 °C at the 2nd and 120 °C at the 11th second of the test. This is due to the increased current that the motor consumes during overload, which increases power losses and heating of the IGBT module.

The case temperature (T_c) and the heat sink temperature (T_s) also increase, but remain below the limit (peaks around 65 °C).

The critical range (above 150 °) indicates the zone where the module experiences stress but remains operational, while the fatal threshold (175 °C) is the limit beyond which failure is possible.

The power loss increases sharply during overload, reaching 400 W. The power loss (P_{total}) peaks at 400 W at 2 and 11 seconds, corresponding to the temperature peaks. The bulk of the loss is the loss (P_{cond}, about 180 W) that occurs when the IGBT conducts under high load.

Switching losses (P_{on} around 25 W and P_{off} around 25 W) are lower, indicating that conduction losses are the primary influence in this test.

The peak values of temperature and power loss reflect the moments when the motor requires a greater current flow, thereby leading to an increase in the module's temperature.

Thus, the temperature of the IGBT transistors remains below 150 ° C, thereby confirming that the module is operating within safe limits. The low heatsink temperature (≈ 63 °C) indicates that the cooling system is effectively removing heat, thereby preventing the accumulation of excess heat and the subsequent occurrence of overheating.

The graphs in Fig. 7 demonstrate that the SKM200GB12T4 module effectively copes with loads, remaining within safe temperature limits thanks to thermal management.

Fig. 8 illustrates the results of calculating the temperature and power of single output period for the inverter diodes under overload.

Studies demonstrate that the overload graphs for the SKM200GB12T4 module diodes illustrate its capacity to withstand short-term overloads while remaining within safe temperature limits.

The junction temperature reaches 123 °C, which is far from the critical range, and does not exceed it.

Power losses of 225 W are primarily attributable to conduction losses, with a lesser contribution from switching losses.

Temperature graphs demonstrate how the maximum junction temperature ($T_{j\ max}$) peaks at approximately 110 °C at 2 seconds and around 120 °C at 12 seconds, indicating significant thermal stress during overload. The case and heatsink temperatures remain stable (approximately 70 °C and 65 °C, respectively). The module does not fall into the critical range (150 °C – 175 °C), and does not exceed the fatal threshold (175 °C).

The power loss graphs demonstrate that the total losses reach 225 W at overload peaks, with the main contribution of conduction losses (50 W), while switching losses (20 W at turn-on and 0 W at turn-off) play a smaller role. It can be deduced from the evidence presented that the primary function is contingent upon the magnitude of the current that is flowing through the module.

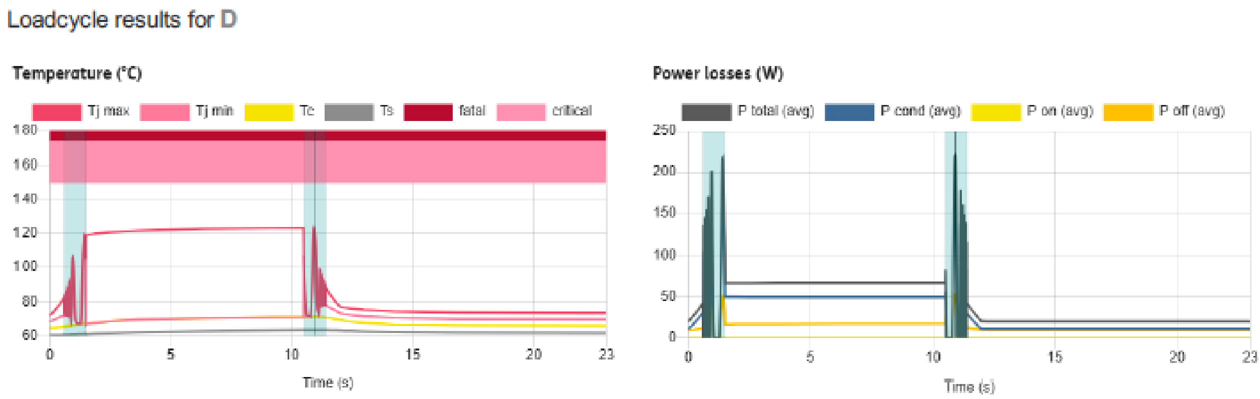

Figure 8. Results of calculating the temperature and power of one output period for the inverter diodes (*D*) during overload

Consequently, the simulation utilising the SemiSel program furnishes comprehensive data on the thermal and power characteristics of the SKM200GB12T4 module at both nominal load and overload conditions.

V. CONCLUSION

1. Based on the study of the kinetic dependences of temperature and power of the inverter, a mathematical model of the cooling process of the SKM200GB12T4 inverter was developed.

2. The utilisation of the SemiSel program for the SKM200GB12T14 inverter facilitated the acquisition of the dynamic thermal impedance $Z_{th(s\text{-}a)}$ as a function of time, which was found to be described by an exponential function.

3. The value of the thermal time constant for the dependence of the dynamic thermal impedance $Z_{th(s\text{-}a)}$ on time was calculated. The value of the thermal constant τ = 1.44 s characterises a sufficient speed of the cooling system, which ensures safe operation of the SKM200GB12T4 inverter.

4. The thermal processes of the SKM200GB12T4 inverter based on the IGBT module were studied using the SemiSel program. Based on the data obtained, an analysis of the processes of temperature and power changes at nominal load and in overload operation mode for one period was carried out. The temperature change graphs demonstrate the stability of the temperature at various points, such as the junctions of IGBT transistors and reverse diodes, due to effective thermal control. The power graph displays cyclic changes in losses, with peaks in the phases where the current and voltage are at their maximum. The findings of this study corroborate the hypothesis that the module is suitable for utilisation in control circuits.

5. The values of the inverter temperature peaks during overload are obtained. For an overload of 10.55 seconds, the maximum temperature for IGBT transistors is 112.72 °C, and for diodes - 124.18 °C. The case temperature T_c and the heat sink temperature T_s remain the same for transistors and diodes and do not exceed the maximum operating temperature of the module due to the stability of the cooling system.

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ДОСЛІДЖЕННЯ ТЕПЛОВИХ ПРОЦЕСІВ ІНВЕРТОРА НА БАЗІ IGBT МОДУЛЯ

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Мета роботи. *Дослідження теплових процесів інвертора на базі IGBT модуля для застосування в перетворювачі частоти для керування роботою асинхронним двигуном.*

Методи дослідження. *Аналітико-розрахункові методи для аналізу теплових процесів інвертора на базі IGBT модуля.*

Отримані результати. *Дослідження теплових процесів інвертора SKM200GB12T4 на базі IGBT модуля було виконано за допомогою програми SemiSel. Розроблено математичну модель процесу охолодження інвертора SKM200GB12T4. Отримано залежність динамічного теплового імпедансу $Z_{th(s\text{-}a)}$ від часу, яка описується експоненціальною функцією. Розраховано значення сталої часу для цієї залежності, яка характеризує швидкість зміни температури охолоджувача, тобто якість його роботи. Теплова стала часу τ = 1,44 с показує час, необхідний для досягнення різниці температур ≈ 63% від її стаціонарного значення. Таке низьке значення теплової сталої відображає ефективне охолодження завдяки високій швидкості повітряного потоку (7 м/с) та витраті повітря (426,43 м³/год), що є критично важливим для підтримки температури переходу IGBT нижче 175 °С під час перевантаження.*

Отримано значення температурних максимумів інвертора при перевантаженні. Для перевантаження за 10,94 секунд максимальна температура для IGBT транзисторів становить 120.85 °С, а для діодів – 123.4 °С. Температура корпусу T_c = 71.21 °С та температура радіатора T_s = 63.56 °С залишаються однаковими для транзисторів та діодів і не перевищують граничну температуру роботи модуля завдяки стабільності системи охолодження. Але при більшому часі навантаження перегрів може зростати, що буде спричиняти деградацію напівпровідникових приладів.

Проведено дослідження процесів зміни температури і потужності при номінальному навантаженні і в *режимі роботи при перевантаженні для одного періоду за допомогою програми SemiSel. Графіки зміни температури відображає стабільність температури в різних точках, таких як переходи IGBT транзисторів і зворотних діодів, завдяки ефективному тепловому контролю. Графік потужності показує циклічні зміни втрат, з піками у фазах, де струм і напруга максимальні. Ці дані підтверджують придатність модуля для використання в схемах управління.*

Наукова новизна. *На основі графічного аналізу кінетичних залежностей температури і потужності інвертора розроблено математичну модель процесу охолодження інвертора SKM200GB12T4, яка описує залежність динамічного теплового імпедансу* $Zth_{(s\text{-}a)}$ *від часу. Розрахована теплова стала часу для цієї залежності, яка характеризує швидкість зміни температури охолоджувача.*

Практична цінність. *Результати дослідження теплових характеристик інвертора SKM200GB12T4 можуть бути застосовані для оптимізації режимів роботи частотного перетворювача для керування роботою асинхронного двигуна.*

Ключові слова:* *теплові процеси; інвертор; IGBT модуль; перетворювач частоти.