

Temperature control of power semiconductor devices in traction applications

A A Pugachev¹ and N N Strekalov²

¹ Bryansk State Technical University, 7, 50-letiya Otyabrya bul., Bryansk, 241035, Russia

² Moscow State University of Railway Engineering, 9, Obrazcova str., Moscow, 127994, Russia

E-mail: alexander-pugachev@rambler.ru

Abstract. The peculiarity of thermal management of traction frequency converters of a railway rolling stock is highlighted. The topology and the operation principle of the automatic temperature control system of power semiconductor modules of the traction frequency converter are designed and discussed. The features of semiconductors as an object of temperature control are considered; the equivalent circuit of thermal processes in the semiconductors is suggested, the power losses in the two-level voltage source inverters are evaluated and analyzed. The dynamic properties and characteristics of the cooling fan induction motor electric drive with the scalar control are presented. The results of simulation in Matlab are shown for the steady state of thermal processes.

1. Introduction

The power semiconductor module is a main source of heating in up-to-date frequency converters. Its cooling system is designed to provide the needed thermal behaviour limited by the maximum temperature of IGBT and diode junctions [1,2]. This task is the pivotal matter for the traction electric drives in railway applications, where the wide range of loads and speeds is a common condition. The significant currents flowing through the collector and the emitter during the start mode under the heavy freight or fast acceleration lead to the considerable power losses that, in its turn, cause the excessive heating. Otherwise, in the no-load mode, the traction drive could be operated in the mode close to the no-load. These load cycles depend on the profile of the track and, as a result, heating cycles of semiconductor devices vary very widely from almost a cold state to severe overheating. So, the best way to control this type of the condition is to apply an automatic temperature control system. This approach allows us to obtain the required level of air or liquid cooling flow to take away overheating in different modes. It also leads to the possibility of energy saving while the current approaches to the no-load mode. It appears to be an important matter for freight locomotives where the cooling system of the traction frequency converter consume a large amount of energy. For example, the 22 kW induction motor is used in the 2TE25A locomotive for the air cooling of the traction converter, the 55 kW induction motor is used in the VL85 electric locomotive for the same purpose.

The survey of locomotives used in the Russian railway shows that the induction motors of cooling fans are either controlled discretely or not controlled at all [3]. Meanwhile, the greatest effect in solving the problem of increasing the efficiency of cooling systems and providing the required



temperature of semiconductor devices of a frequency converter can be achieved if the cooling systems will be equipped with controlled drive fans, allowing continuous and automatic change of cooling air or liquid depending on the temperature of the IGBT and diode junctions. So, the investigations of thermal behaviour of semiconductor devices used in traction applications and the developments of its control system are still relevant and important. This article presents the topology and the principle of operation of the automatic temperature control system of traction frequency converter semiconductor devices.

2. An automatic temperature control system of semiconductor devices

Despite the fact that there are a number of techniques [4-7] allowing one to reduce junction temperature and its fluctuation by means of changing the frequency switching, this approach does not get wide implementation in the traction drives due to the complex dependences of mechanical processes including adhesion, skid and slipping effects in starting and braking modes and the frequency of the torque and current oscillation. The forced air or liquid convection by means of a fan, a blower or a pump is much preferable in these applications.

The scheme of the automatic temperature control system of semiconductor devices of the frequency converter, feasible for using in a locomotives, is given in Figure 1. It is necessary to analyse properties of each of the units of the scheme (Figure 1) for developing the whole block diagram of the control system. In the present article, the authors proposed the implication of the air fan driven by the induction motor drive with scalar control as the executive regulation device. The dynamic and static performances of the executive regulation device and semiconductor devices as an object of temperature control are investigated and discussed further in the sections below.

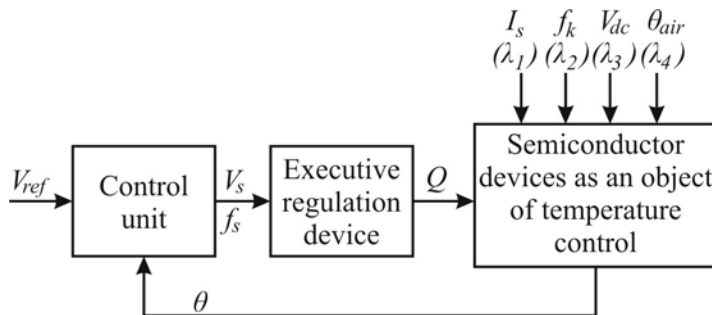


Figure 1. The scheme of the automatic temperature control system:

θ – temperature of semiconductors, V_{ref} – temperature reference, V_s – stator voltage, f_s – stator current frequency, Q – air flow, λ_i – disturbances, I_s – stator current of a traction induction motor, f_k – switching frequency, V_{dc} – DC-link voltage, θ_{air} – air temperature

3. Semiconductor devices as an object of temperature control

The most interesting and difficult thing to be implemented in the suggested scheme is the feedback of the semiconductor temperature. It is obvious that the most thermally stressed part of any semiconductor is its junction and it is almost not available for the direct measurement. So, it is necessary to introduce some indirect techniques to measure or estimate the junction temperature. The technique allowing us to get come solution of this problem bases on the thermal equivalent circuit of the power semiconductor module [4,5]. The thermal equivalent circuit is presented by the multiple circuit of resistances and capacitors connected in series and parallel, the transient characteristics of it are given in the module datasheets as a thermal response in the single step reference or disturbance. The simplified and full thermal equivalent circuits of one leg of the two-level voltage source inverter (Figure 2) are shown in Figure 3.

In Figure 3, Z_{j-c} , Z_{c-hs} , Z_{hs-air} denote the dynamic thermal impedance between the junction and the case, the case and the heatsink, the heatsink and the cooling air, respectively; θ_j , θ_c , θ_{hs} denote the temperature of the junction, the case and the heatsink of the semiconductor module, respectively; θ_{air} denotes the temperature of the cooling air, ΔP denotes the power losses. The power losses in Figure 3 are presented as a current source while the temperature of cooling air is presented as a voltage source. The dynamic thermal impedance can be described as follow:

$$Z_{x-y}(t) = R_{x-y} (1 - e^{-t/\tau_{x-y}}),$$

where R_{x-y} denotes the thermal resistance between conjugated units of x and y ; τ_{x-y} denotes the time constant of the thermal transient mode.

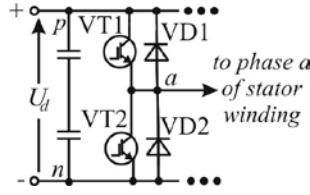


Figure 2. The equivalent circuit of one leg of the two-level inverter

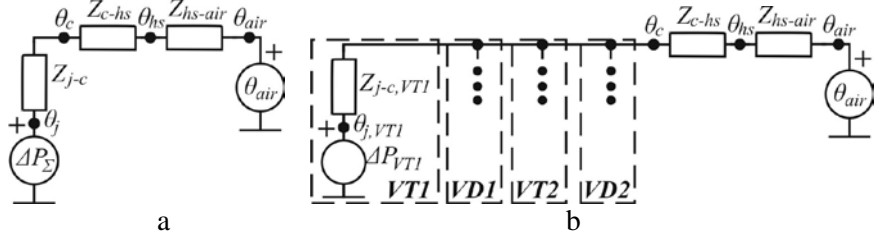


Figure 3. The simplified (a) and full thermal equivalent circuit of one leg of the two-level inverter (Figure 2)

The junction temperature in the steady state can be derived from the simplified equivalent circuit (Figure 3a) as follows:

$$\theta_j = \theta_{air} + \Delta P_{\Sigma} \sum R_{x-y}.$$

The equivalent circuit (Figure 3b) gives more detailed temperature distribution for the semiconductor module consisting of one leg of the two-level inverter (Figure 2). The junction temperature derived from the circuit (Figure 3b) is written as follow:

$$\theta_j = \theta_{air} + \Delta P_{\Sigma} R_{hs-air} + \Delta P_{\Sigma} R_{c-hs} + \Delta P_{VT1} R_{j-c}, \quad (1)$$

where ΔP_{Σ} denotes the total power losses in the semiconductor module; ΔP_{VT1} denotes the power losses in the $VT1$. It is obvious that Figure 3b gives more correct information for the junction temperature evaluation than Figure 3a does. It occurs due to the heat dissipation in the thermal resistance of R_{j-c} caused by only power losses in the considered IGBT.

To use the equivalent circuits properly, it is necessary to take some assumptions for the investigation of temperature and power losses distribution in the semiconductor module. The main ones are as follows: the load current, i.e. the stator current, has the sinusoidal shape, the value of dead time of transistors is neglected, all the phases of voltage source inverter and induction motors are symmetric and even. Power losses in the power switches consist of conduction and switching losses. The conduction losses are mainly caused by the voltage drop on the junction under the forward current. The conduction losses depend on the stator current (as the load of the inverter), the temperature of the junction, the modulation type and its parameters, the power factor of the induction motor stator winding. The switching losses are caused by changing of the opened/closed state of transistors. The value of these losses depends on the load current, DC-link voltage, junction temperature, switching frequency and turn-on and turn-off energy. As some investigations show [6,7], the load current and switching frequency have the main influence on the total power losses.

With the numerical methods applied to the evaluation of electric drive dynamics, the following expressions are used for the power losses over one switching period T_k :

$$\Delta P_{cond,VT} = \frac{1}{2\pi} \int_0^\pi v_{ce} I_{max} \sin(2\pi f_s t) \frac{1+\mu(t)}{2} d(2\pi f_s t) \quad (2)$$

$$\Delta P_{cond,VD} = \frac{1}{2\pi} \int_0^{2\pi} v_{ce} I_{max} |\sin(2\pi f_s t)| \frac{1+\mu(t)}{2} d(2\pi f_s t) \quad (3)$$

$$\Delta P_{sw,VT} = \frac{1}{2\pi} \int_0^\pi (E_{on}(I_s) + E_{off}(I_s)) \frac{V_{dc}}{V_{dc,rat}} \frac{1}{T_k} d(2\pi f_s t) \quad (4)$$

$$\Delta P_{sw,VD} = \frac{1}{2\pi} \int_0^{2\pi} E_{rec}(I_s) \frac{V_{dc}}{V_{dc,rat}} \frac{1}{T_k} d(2\pi f_s t) \quad (5)$$

where $\Delta P_{cond,VT}$, $\Delta P_{cond,VD}$ denote the conduction power losses in IGBT and the diode, respectively; $\Delta P_{sw,VT}$, $\Delta P_{sw,VD}$ denote the switching power losses in IGBT and the diode, respectively; v_{ce} denotes the collector-emitter voltage; E_{on} , E_{off} denote the turn-on and turn-off energy of IGBT, E_{rec} denotes the

recovery energy of the diode; μ denotes the modulation coefficient; the subscript of *rat* denotes the rated value of some parameter.

The dependence of collector-emitter voltage v_{ce} from forward current I_s and junction temperature θ_j is approximated by the following equation [3]:

$$v_{ce}(I_s, \theta_j) = 1.21 + 9.93 \cdot 10^{-3} I_s - 1.88 \cdot 10^{-3} \theta_j - 2.54 \cdot 10^{-5} I_s^2 + 3.22 \cdot 10^{-5} I_s \theta_j. \quad (6)$$

The results of simulation of the electric drive for the power modules with thermal parameters $R_{c,hs,VT} = 0.085^\circ\text{C/W}$, $R_{c,hs,VD} = 0.13^\circ\text{C/W}$, $R_{j-c,VT} = 0.01^\circ\text{C/W}$, $R_{j-c,VD} = 0.015^\circ\text{C/W}$, $R_{hs-air} = 0.031^\circ\text{C/W}$ are shown in Figure 4.

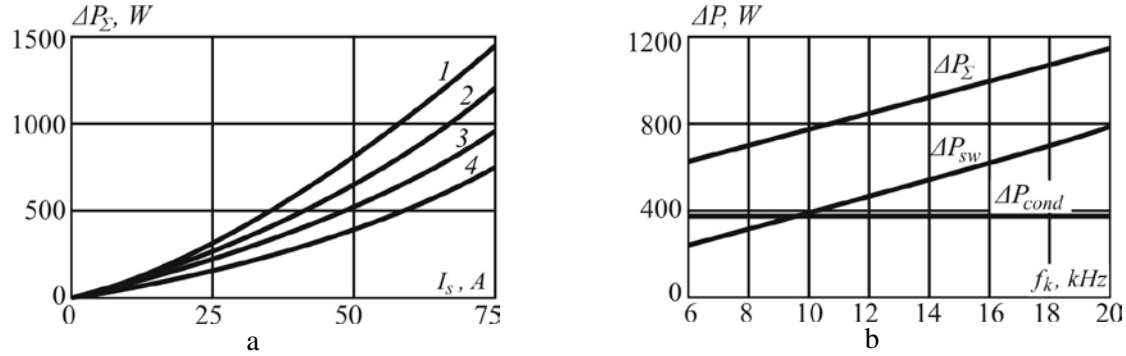


Figure 4. The total power losses vs. the stator current (a) (1 – $f_k = 20$ kHz, 2 – $f_k = 15$ kHz, 3 – $f_k = 10$ kHz, 4 – $f_k = 5$ kHz) and the power losses vs. switching frequency (b) when stator current $I_s = 65$ A

4. The cooling fan with the induction motor drive as an executive regulation device

The implication of the air cooling fan with the induction motor drive is proposed to cool the semiconductors. The most common features of electric drives of cooling fans for locomotives traction electric equipments and motors are highlighted from the survey [8,9] of operation modes of the auxiliary drives and machines. It can be listed as follows: shifting of speed to its lower values causes a considerable reduction of the load torque and the mechanical power on the motor shaft; the long period of time of the operation mode with permanent speed and load torque; the absence of the reverse mode; the absence of overloads, the value of overload may be determined in advance; the start-up time is not limited, the start is preferred to have small start-up time for restricting dynamic overloads. So, it is reasonable to apply a scalar control system of the induction motor because of some specific requirements the electric drive has to satisfy. To design the whole automatic temperature control system, the mathematical model and/or transfer functions of the induction motor and the electric drive have to be known. In this investigation, the well known equations [10] of an induction motor are used:

$$v_{s\alpha} = R_s i_{s\alpha} + \frac{d\lambda_{s\alpha}}{dt} - \omega_k \lambda_{s\beta}, \quad v_{s\beta} = R_s i_{s\beta} + \frac{d\lambda_{s\beta}}{dt} + \omega_k \lambda_{s\alpha}, \quad (7)$$

$$0 = R_r i_{r\alpha} + \frac{d\lambda_{r\alpha}}{dt} - (\omega_k - \omega) \lambda_{r\beta}, \quad 0 = R_r i_{r\beta} + \frac{d\lambda_{r\beta}}{dt} + (\omega_k - \omega) \lambda_{r\alpha}, \quad (8)$$

$$\lambda_{s\alpha} = L_s i_{s\alpha} + L_\mu i_{r\alpha}, \quad \lambda_{s\beta} = L_s i_{s\beta} + L_\mu i_{r\beta}, \quad \lambda_{r\alpha} = L_r i_{r\alpha} + L_\mu i_{s\alpha}, \quad \lambda_{r\beta} = L_r i_{r\beta} + L_\mu i_{s\beta} \quad (9)$$

$$T = \frac{3}{2} p_n (i_{s\beta} \lambda_{s\alpha} - i_{s\alpha} \lambda_{s\beta}) \quad (10)$$

where α, β denote the coordinate axes; $v_{s\alpha}, v_{s\beta}$ denote the corresponding coordinates of the stator voltage; $i_{s\alpha}, i_{s\beta}, i_{r\alpha}, i_{r\beta}$ denote the corresponding coordinates of the stator and rotor currents; $\lambda_{s\alpha}, \lambda_{s\beta}, \lambda_{r\alpha}, \lambda_{r\beta}$ denote the respective coordinates of the stator and rotor flux linkages, R_s, R_r denote the stator and rotor resistances, L_s, L_r, L_μ denote the stator and rotor inductances and magnetizing inductance, respectively; ω_k denotes the speed of the reference; ω denotes the speed of the rotor shaft; T denotes the torque produced by the motor; p_n — the number of pole pairs.

The mechanical movement is described as follows:

$$T - T_L = J d\omega/dt \quad (11)$$

where T_L denotes the load torque, J denotes the moment of inertia.

5. Simulation of the automatic temperature control system

The scheme (Figure 1) adapted by the conducted research to be simulated is shown in Figure 5. To simulate the automatic temperature control system, the Matlab Simulink is used in this investigation. The executive regulation device is described by equations (6) – (11), the thermal behavior of the semiconductor devices is evaluated by equations (1) – (5). The cooling fan is simulated by the proportional gain. The PI-controllers are applied for both temperature (W_θ) and speed (W_ω) controllers to exclude the error in the steady state. As it was mentioned in section 4, the scalar control of the cooling fan induction motor is implemented. The coefficients of k_U and k_ω are chosen so as to provide the square dependence between stator voltage V_s and stator current frequency f_s . The algorithms of sinusoidal pulse-width modulation (PWM) is used to control semiconductors of the voltage source inverter (VSI). The presence of the forced air convection is taken into account by reducing thermal resistance R_{hs-air} by the technique described in [11]. The results of the simulation in the steady state are shown in Figure 6 for $I_s=65A$. The junction of the IGBT is established to be the most thermal stressed unit of the semiconductor module.

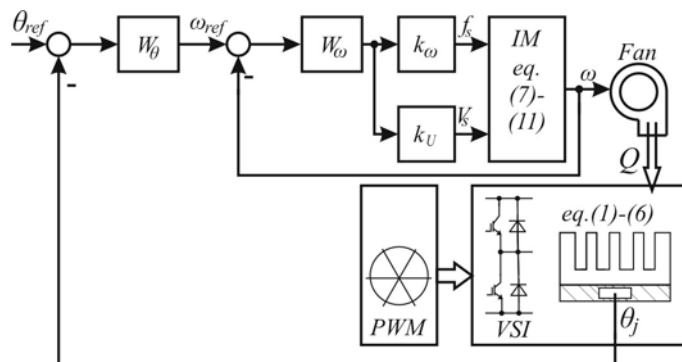


Figure 5. The detailed topology of the scheme (Figure 1) for simulation

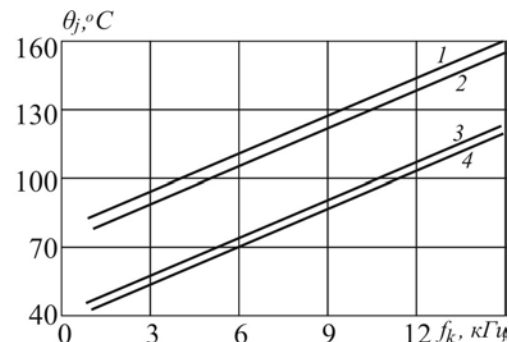


Figure 6. The junction temperature vs. switching frequency (1 – $\theta_{j,VTI}$, 2 – $\theta_{j,VDI}$ during free convection, 3 – $\theta_{j,VTI}$, 4 – $\theta_{j,VDI}$ during forced convection)

6. Conclusion

The investigation presented in the article shows the relevance and the necessity of designing the automatic temperature control system of the semiconductor modules of the traction frequency converter that allows one to get desired thermal behavior of the power switches at any time. The adequacy of the proposed topology and the operation principle of the control system is proved by means of Matlab Simulink. As the results of simulation show, the implementation of the induction motor electric drive for driving the cooling fan and the closed-loop control of junction temperature leads to the reduction of temperatures. Also, the results of simulation show that the most heated unit of the module is the IGBT junction.

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