Automation of the design and development stages of semiconductor devices

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Abstract. In the scientific article, automation of optimization of driver control nodes for semiconductor frequency converters feeding mechatronic modules was performed. The selection and justification of the design scheme of the control board nodes examined, the analysis of the possible operating modes of the control boards, the calculation of the system variables (voltage, currents), the calculation and comparison of various control options, and analysis of the results; development of recommendations for the practical use of research results. It was determined that the use of uncontrolled power supplies entails huge losses power allocated to the elements of the amplifier, which requires optimization. The efficiency of the amplifier is also unstable and lies in the range from 15 to 67%; The use of controlled power sources allowed to significantly reduce the power allocated to the elements of the amplifier (2 – 7 times). Also, the efficiency of the amplifier becomes approximately constant and is about 75%; The maximum thermal power dissipation in all modes is 1304 watts for the whole amplifier, including for each module 186 watts; To increase the reliability of the device, we select the safety factor for the power dissipation 3 and calculate the efficiency of the heat removal and recycling system at a thermal power of 600 W.

1. Introduction
Modern mechatronic systems are performed, as a rule, by the criterion of minimum weight and size indicators [1]. Mechatronic devices consist of a power unit and components and controls. Minimization of the mass-dimensional parameters of the controls is determined by the minimum losses in individual nodes and elements [2, 3]. For further integration of elements and control nodes, a significant reduction in heating and, together with it, losses in microcircuits is required, so the task of finding circuit solutions that ensure the best use of circuits is an actual scientific and technical task.

2. Research problem statement
The chosen method of heat removal determines the construction of the central station generating power plant [4]. So, it is necessary to choose the cooling system of the central station generating power plant even at an early design stage, that is, at the stage of a technical proposal or draft design [5]. A slip in the solution of this problem can be announced only at the later stages of design (detailed design study, testing of a prototype, etc.) [6], which can reduce the work of a large group of engineers to ashes, and the creation time of a central station generating power plant will increase (which can be critical) [7].
Needed to know the parameters to select a cooling system: Total power \( P \) of heat generation in the block; Range of change in ambient temperature \( t_{c \text{ max}}, t_{c \text{ min}} \); Limits of change in ambient pressure \( p_{\text{max}}, p_{\text{min}} \); Time of continuous operation of the device \( \tau_{c} \); Permissible operating temperatures of the elements \( t_{i} \); the fill factor of the device \( K_{z}=\sum V_{i}/V \), where \( V_{i} \) is the volume of the \( i \)-th element of the central station generating power plant; \( n \) is the number of elements; \( V \) – volume occupied by the central station generating power plant; Overall dimensions of the case: horizontal - \( L_{1}, L_{2} \), vertical - \( L_{3} \).

3. Mathematical model

These data are not enough for a detailed analysis of the heat load of a central station generating power plant, but they are used for preliminary calculation, estimation and selection of a heat removal method [8]. The latter is a probabilistic nature. It provides an opportunity to estimate the probability of ensuring the thermal load with the selected heat removal method [9]. According to the results of statistical data processing for real constructions, detailed thermal calculations and test data for the models, graphs were built. They characterize the areas of the appropriate use of various cooling methods [10, 11]. These graphs are constructed for the continuous operation of the central station generating power plant and relate two main indicators: \( \vartheta_{s}=f(lgq) \). The first indicator \( \vartheta_{s}=t_{i, \text{ min}}, t_{c} \) is the superheat relative to the environment \( t_{c} \) of the least heat-resistant element, for which the allowable temperature \( t_{i, \text{ min}} \) given in the specification has the minimum value [12].

The second indicator \( q \) is equal to the density of the heat flux passing through the conditional surface area \( A_{p} \) of heat exchange [13]:

\[
q=P\kappa_{p}/A_{p},
\]

(1)

where \( P \) is the total power dissipation; \( \kappa_{p} \) is the air pressure ratio (for atmospheric pressure \( \kappa_{p} = 1 \)).

\[
A_{p}=2[L_{1}, L_{2}+(L_{1}+L_{2})L_{3} K_{z}]
\]

(2)

We will calculate \( \vartheta_{s} \) and \( q \). The dimensions of the used transistors in the TO-247 package are shown in [14], the appearance of the case in [15].

Find the sum of the volumes of the transistors, 20 transistors will be used in the amplifier.

\[
V_{i}=abc=15.6\cdot20\cdot5\cdot20=31200 \text{ mm}^{3}
\]

(3)

Determine the dimensions of the case of electronic equipment (amplifier). \( L_{1}=2/3\cdot480 \text{ mm} \) (taking into account the place occupied by power sources), \( L_{2}=570 \text{ mm} \), \( L_{3}=133 \text{ mm} \).

Find the volume of the amplifier:

\[
K_{z}=\sum V_{i}/V=31200/24259200=1.3\cdot10^{-3}
\]

(4)

The highest operating temperature of the transistor crystal is \( t_{j, \text{ max}}=150 ^{\circ} \text{C} \), but the recommended one is no more than \( t_{j}=110 ^{\circ} \text{C} \) [16]. The thermal resistance of the crystal body \( R_{t, j,c}=0.83 \text{ K/W} \) [17]. The maximum power \( P_{t}=4174W \) dissipated on the entire amplifier with unmanaged power sources [18]. The amplifier has a modular design and the number of modules is 7, and the number of transistors used in each module is 20, we find the maximum power dissipated on one transistor:

\[
P_{t, \text{tr}}=4174/(7\cdot20)=29.8 \text{ W}
\]

(5)

We give the formula of thermal resistance

\[
R_{t}=(T_{2}-T_{1})/P,
\]

(6)

where \( R_{t} \) is thermal resistance, \( T_{2} \) is the temperature of the beginning of the section, \( T_{1} \) is the temperature of the end of the section.

Therefore, the transistor case temperature is \( t_{\text{case}}=110-0.83\cdot30=85.1 ^{\circ} \text{C} \).

Maximum ambient temperature \( t_{c, \text{ max}}=40 ^{\circ} \text{C} \). \( T_{i}=t_{\text{case}} \).

Find the nominal first indicator \( \vartheta_{s} \), required to select the heat removal system.
\( \Theta_c = t_i - t_c_{\text{max}} = 85.1 - 40 = 45.1 \, ^\circ C \)  
\[ \text{(7)} \]

\( A_p = 2[2/3 \cdot 480 \cdot 570 + (2/3 \cdot 480 + 570) \cdot 133 \cdot 1.3 \cdot [10] ^{\langle -3 \rangle}] = 0.365 \, \text{m}^2 \)  
\[ \text{(8)} \]

Find the second indicator \( q \):

\[ Q = (596.29 \cdot 1) / (0.365) = 1633.67 \, \text{W/m}^2 \]  
\[ \text{lg} q = \text{lg} [1633.67 = 3.21] \]  
\[ \text{(10)} \]

Based on the data presented [19], you need to choose the method of forced air cooling. This method is best suited for the developed power amplifier, since the use of liquid cooling would be difficult and impose additional financial costs [20].

**4. Selection of the type of radiator**

Since in the previous subsection we received a forced air-cooling method, it is first necessary to select the type of radiator. Possible types of radiators are presented in [21].

[22] shows schematically a radiator 1 with a device 2 fixed on it - a transistor in the TO-247 case [23, 24], inside which there is a power source \( P \) that warms the device’s working area (the p-n junction region) and its body up to temperatures \( t_i \) and \( t_e \) at the place of attachment of the device to the radiator, temperature \( t_r \), and the average temperature of the base of the radiator \( t_c \).

To determine the type of radiator you need to know the parameters: The maximum permissible operating temperature of the transistor \( t_c = t_j = 110 \, ^\circ C \); Power dissipated by the device \( P = 29.8 \, \text{W} \); Temperature \( t_c_{\text{max}} = 40 \, ^\circ C \) of the environment; Thermal resistance \( R_{j-c} = 0.83 \, \text{K/W} \) of the device between the crystal and the body; The method of mounting the device to the radiator, which is characterized by thermal resistance \( R_{k} \); Air cooling method (free, forced).

\[ T_p - t_c_{\text{max}} = (t_p - t_c) + (t_i - t_c) + (t_i - t_c_{\text{max}}) \]  
\[ t_i - t_c_{\text{max}} = (t_i - t_c) + P (R_{j-c} + R_{k}) \]  
\[ \beta = (t_i - t_c_{\text{max}}) / (t_i - t_c) = R_{k} \sqrt{A/A_p} \]  
\[ \text{(11)} \]
\[ \text{(12)} \]
\[ \text{(13)} \]

where \( \beta \) is a dimensionless quantity connecting the average temperature \( t_s \) of the base of the radiator and the temperature \( t_i \) and at the place of the device attachment to the radiator; \( B \) and \( \sqrt{A/A_p} \) are the similarity numbers on which \( \beta \) depends; \( A_p \) и \( A_i \) - areas of the base of the radiator and the device.

\[ B = (\alpha_1 + \alpha_2) A_p / (\delta \lambda) \]

where \( \alpha_1 \) and \( \alpha_2 \) are heat transfer coefficients from one and the other sides of the radiator; \( \delta \) is the thickness of the base of the radiator; \( \lambda \) - thermal conductivity of the material of the radiator.

All the necessary parameters [25] are known except for the thermal resistance \( R_{k} \), the contact of the device with the radiator. Since the transistor housings need to be electrically insulated from each other, it is necessary to use a heat-conducting electrically insulating gasket [26]. NOMAKON gaskets [27] are widely used. Consequently, the thermal resistance will be determined by the thermal resistance of the gasket used. We use the necessary information on the manufacturer’s website.

The specific thermal resistance of the gasket \( R_{p-g} = 0.97 \, \text{(K/cm}^2\text{)/W} \).

Determine the thermal resistance per area of the transistor mounting [28] with a radiator:

\[ S_k = 15.6 \times 2010^{-2} = 3.12 \, \text{cm}^2 \]  
\[ \text{(14)} \]

\[ R_{k} = R_{p-g} / S_k = 0.97 / 3.12 = 0.31 \, \text{K/W} = R_{k} \]  
\[ \text{(15)} \]

According to the formula 16, we determine the temperature \( t_i \) in the place of mounting of the transistor:

\[ T_i - t_c_{\text{max}} = (110 - 40) - 29.8 (0.83 + 3.31) = 36.028 \, ^\circ C \]  
\[ \text{(16)} \]
In the approximation, we take $\beta = 1.2$ and find:

$$t_s - t_c_{\text{max}} = \frac{36,028}{1.2} = 30.02 \, ^\circ C$$ \hspace{1em} (17)

Set the conditional area of the radiator base:

$$S_p = 25010^3 \cdot 300 \cdot 10^{-3} = 75 \cdot 10^{-3} \, m^2$$ \hspace{1em} (18)

Find the heat flux density for 20 transistors:

$$q = \frac{P}{S_p} = \frac{596.3}{75 \cdot 10^{-3}} = 8 \cdot 10^3$$ \hspace{1em} (19)

The graphs indicate: a1 – b1, a2 – b2, a3 – b3 – lamellar in [29], ribbed, pin radiators with free convection; a4 – b4 - plate: a5 – b5 - ribbed: a6 – b6 - loop-wire: a7 – b7 - louvered: a8 – b8 - pin radiators with forced air movement with velocities $u = (2 \div 5) \, m / s$.

According to [30] we determine the type of radiator and clarify the cooling conditions. With the obtained values, we find ourselves in the graph a5 - this is the graph of a ribbed radiator with forced air cooling.

All further calculations to assess the effectiveness of the heat removal system will be performed in the software environment of SolidWorks Flow Simulation [31].

5. Simulation of the heat removal and disposal system

The main element of the constructive system of heat removal and utilization is an aluminum radiator from the AB9030 profile [32].

In the process of choosing a technical implementation, several options were considered. The results of the data modeling options for the design of the heat removal system are presented below: radiator length 200 mm, number of fans 2, type of fans JF0925-1H [33], number of power transistors 12, total power allocated to transistors 240 W, ambient temperature 40°C.

Materials: radiator - aluminum, case - stainless steel, transistor case - plastic, transistor plate - copper. When calculating, it is assumed that external fans operate on injection. When calculating the given level grid 5. [34, 35] shows the volumetric model for which the analysis of thermal conditions was carried out. Experimental study of the heat removal and disposal system

A distributed resistive heater circuit was used to create a thermal power of 600 W. It is shown in Figure 1.

Thermograms obtained at different times after switching on the distributed resistive heater are shown in Figures 2 - 4. The graph of the dependence of the superheat temperature of a resistive heater on time shows in Figure 5.

![Figure 1. The scheme of the distributed resistive heater.](image1)

![Figure 2. The scheme of turning on of the distributed resistive heater.](image2)
6. Conclusions
The calculation and simulation of the heat removal and heat recovery system allows to draw the following conclusions: When designing a heat removal and heat recovery system, it is advisable to carry out preliminary calculations to select the optimal method of heat removal; Simulation of the system of heat removal and utilization allows to significantly reduce the time of its development and allows to take into account various factors (ambient temperature, pressure, material properties, fan parameters), which are usually not considered in the analytical calculation. Also, the simulation of the heat removal and utilization system allows to reduce financial costs, since there is no need to create intermediate test layouts; If it is necessary to observe the nature of the warm-up of the heat removal system and heat recovery from time, it is possible to model a non-stationary task, but this type of simulation requires a lot of machine time. In the absence of such a need, there is the possibility of modeling a stationary problem, which quickly allows us to estimate the efficiency of the heat removal and disposal system; According to the results of the simulation, a system of heat removal and utilization was developed, which successfully confirmed the removal and utilization of the necessary power.

References
[1] Ivanov D V, Katsyuba O A and Grigorovskiy B K 2017 *Russian Electrical Engineering* **88**(3) 123-6
[2] Zasov V A, Zheleznov D V, Mitrofanov A N and Belonogov A S 2017 *Russian Electrical Engineering* **88**(3) 115-9
[3] Kamenskikh A N, Stepchenkov Y A and Tyurin S F 2015 *Russian Electrical Engineering* **86**(11) 646-50
[4] Shcherbakov A V, Goncharov A L, Kozhechenko A S, Rubtsov V P and Dragunov V K 2016 *Russian Electrical Engineering* **87**(8) 487-92
[5] Gordeev I P, Garanin M A and Tarasov E M 2017 *Russian Electrical Engineering* **88**(3) 135-9
[6] Yakushev A Y, Sereda A G, Vasilenko M N, Bulavskii P E and Belozerov V L 2017 *Russian Electrical Engineering* **88**(10) 643-8
[7] Gryzlov A A, Grigor’ev M A and Imanova A A 2017 *Russian Electrical Engineering* **88**(4) 193-6
[8] Beloglovskaia A A 2016 *Russian Electrical Engineering* **87**(8) 476-80
[9] Voronin P A, Rashitov P A, Astashev M G and Remizevich T V 2015 *Russian Electrical Engineering* **86**(12) 697-99
[10] Shakirov M A 2017 *Russian Electrical Engineering* **88**(5) 289-95
[11] Gorozhankin A N, Grigor’ev M A, Zhuravlev A M and Sychev D A 2015 *Russian Electrical Engineering* **86**(12) 67-99
[12] Dergachev P A, Kulaev Y V, Kurbatov P A and Kurbatova E P 2016 *Russian Electrical Engineering* **87**(6) 356-62
[13] Belousov E V, Grigor’ev M A and Gryzlov A A 2017 *Russian Electrical Engineering* **88**(4) 185-8
[14] Gulyaev I V, Dar’ enkov A B, Kuzmenkov A N and Titov V G 2017 *Russian Electrical Engineering* **88**(6) 342-6
[15] Tarasov E M, Zheleznov D V, Isaicheva A G and Kopeikin S V 2015 *Russian Electrical Engineering* **86**(3) 99-104
[16] Usynin Y S, Grigor’ev M A and Shishkov A N 2015 *Russian Electrical Engineering* **86**(12) 700-2
[17] Rubtsov V P, Goryachikh E V and Shcherbakov A V 2015 *Russian Electrical Engineering* **86**(7) 403-6
[18] Mikheev G M, Ivanova T G, Konstantinov D I and Turdiev A K 2017 *Russian Electrical Engineering* **88**(7) 423-9
[19] Goncharov A L, Dragunov V K, Shcherbakov A V, Portnov M A and Chulkov I S 2015 *Russian Electrical Engineering* **86**(10) 594-7
[20] Afenchenko R V, Barskii V A, Kurdyumov D S and Malyar A V 2015 *Russian Electrical Engineering* **86**(10) 567-70
[21] Chaplygin E E, Astashev M G and Rasuli K V 2016 *Russian Electrical Engineering* **87**(11) 635-40
[22] Belykh I A, Grigor’ev M A and Belousov E V 2017 *Russian Electrical Engineering* **88**(4) 205-8
[23] Grigor’ev M A, Naumovich N I and Belousov E V 2015 *Russian Electrical Engineering* **86**(12) 731-4
[24] Shcherbakov A V, Pogrebisskii M Y, Dragunov V K et al 2017 *Russian Electrical Engineering* **87**(9) 541-8
[25] Grigor’ev M A 2017 *Russian Electrical Engineering* **88**(4) 189-92
[26] Zinchenko A V and Chernoussova L V 2015 *Russian Electrical Engineering* **86**(8) 448-52
[27] Khokhlov Y I, Safonov V I and Lonzer G P V 2016 *Russian Electrical Engineering* **87**(3) 145-9
[28] Pudovikov O E and Tun A Z 2016 *Russian Electrical Engineering* **87**(9) 536-40
[29] Grigor’ev M A, Sychev D A, Zhuravlev A M et al 2015 *Russian Electrical Engineering* **86**(12) 728-30
[30] Shpiganovich A N, Shpiganovich A A and Pushnitsa K A 2017 *Russian Electrical Engineering* **88**(6) 378-80
[31] Efianov D V, Groshiev G M and Malikov O B 2016 *Russian Electrical Engineering* **87**(5) 286-8
[32] Grigor’ev M A 2015 *Russian Electrical Engineering* **86**(12) 694-6
[33] Wang X.H. and Tian L. 2017 *Russian Electrical Engineering* **88**(2) 91-7
[34] Nikitin A B, Panachev A Y and Vasilenko M N 2016 *Russian Electrical Engineering* **87**(5)
241-3

[35] Khayatov E S and Grigor’ev M A 2017 *Russian Electrical Engineering* **88(4)** 197-200