ANALYSIS OF THERMAL PROCESSES IN A CONTROLLED ASYNCHRONOUS MOTOR

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Abstract

This article examines the reliability and risks associated with technical systems involved in the conversion of mechanical energy to electrical energy, focusing on the thermal dynamics of electric machines. It explores the processes of heat generation due to energy losses, primarily heat dissipation, and the effects of temperature increases on the longevity and performance of the machine. The cooling systems essential for managing heat transfer and minimizing overheating are analyzed, considering factors such as heat conduction, convection, and radiation, as well as the role of electrohydraulic and aerodynamic systems in optimizing heat exchange. Special attention is given to the impact of temperature fluctuations on the insulation materials of electric machines, with an emphasis on how overheating accelerates insulation degradation and reduces machine lifespan. The paper further discusses the intricate relationship between cooling efficiency, machine power, and the economic implications of designing effective thermal management systems. Moreover, the challenges of selecting and optimizing cooling strategies in electric machine design are highlighted, considering both technical and economic factors. Lastly, the study delves into ventilation calculations necessary to ensure efficient airflow and cooling, using practical equations and methods for determining pressure loss and fan performance, underscoring the complexity and importance of achieving optimal temperature conditions for long-term, reliable machine operation.

Key words: Thermal processes, controlled asynchronous motor, cooling systems, energy losses, insulation degradation, ventilation, power output

I. Introduction

The conversion of mechanical energy into electrical energy and vice versa is accompanied by losses, in which part of the converted energy is converted into heat. The thermal energy of the losses heats the electric machine, is transferred to the surrounding environment, dissipates and is lost without returning. The more intensive the output of heat losses in an electric machine, the more power it is possible to obtain from it for a given overall dimensions of the machine.

Electromechanical conversion of energy is based on many physical laws, the main of which are electromagnetism and mechanics. However, for normal operation, it is impossible to design engines without electrohydraulic and aerodynamic calculations, since these processes are based on the laws of thermo, aero and hydrodynamics.

The transfer of heat from the place of separation to the surrounding environment, that is, heat exchange or heat transfer, is the temperature increase achieved by the parts of the machine relative to the temperature of the surrounding environment. Heat transfer is carried out mainly by three methods: heat conduction, convection and radiation. In electric machines, heat flows sometimes travel along complex paths from the heat source to the surrounding environment through intermediate masses - solid, gaseous or liquid. This is due to the complexity of the design of the electric machine, since it consists of heterogeneous elements, and is also realized by the use of special cooling systems to improve heat transfer. In such systems, the cooling medium or heat carrier moves, carrying out convective heat transfer. The driving elements as a source of motion: fan, pump or compressor are taken depending on the type and pressure of the medium.

The more heat energy the cooling system can remove from the machine at the permissible temperature of the heated parts, the greater the losses can be allowed and, accordingly, the greater the power load on the machine. Thus, the cooling system has a significant impact on the use of the machine in terms of power. The efficiency of the cooling of the machine is determined by the efficiency of heat exchange between its active parts and the surrounding environment.

One of the main requirements for the cooling system is that it should ensure that the heating of important systems and parts of the machine (windings, bearings, etc.) is within the permissible limit: this is necessary for the long-term and reliable operation of the machine. On the other hand, the cooling system must be effective, so that the costs incurred for its preparation and the operating costs associated with its good performance should be within the acceptable range. The design and calculation of the cooling system, verification of its efficiency by calculating the heating temperature of the main parts of the machine - one of the main important parts of the design process of electric machines, the heating test of the test sample of the machine - is a necessary condition for acceptance. Hydrogasdynamics and, in particular, its engineering hydraulics and the theory of fans can be taken as the theoretical basis for the design of the cooling system. Hydraulic methods are adopted to calculate the flow of liquids and gases, so that their compression and thermodynamic conditions are not taken into account.

The conditions for the transfer of heat flows, heat exchange with the surrounding environment and the formation of temperature fields on this basis are an element of the study of heat transfer theory, which forms the basis of thermal calculations of various electrical machines.

The high temperature of heating of electric machines affects the durability of insulation of coils, pads, collector-brush junction and other elements. High heating temperatures cause temperature wear of the insulation of the windings, which leads to an irreversible decrease in electrical and mechanical strength. According to Montzinger's rule, an increase in temperature of 8^0S - 10^0S reduces the life of the insulation by 2 times. This rule makes it possible to determine the required service life of the machine based on the permissible value of the temperature of the insulation. It is taken into account that the local temperature increase can also cause the insulation to break down in a certain place. In the process of operating the machine, accidents and overloading are also encountered, during which a short-term high temperature regime is observed. The transition process due to temperature in the working process is one of the influencing factors for the normal operation of the machine. For example, it is shown as an example that 5 sec. If the short-circuited insulation cools at a rate of 30^0S/min, its effect on wear is equal to the result of 3 years of normal operation. Thermo-mechanical stresses can also have a significant effect on the work of insulation in circuit-insulation constructions. These are caused by heating of materials and especially rapid changes in temperature - heat shocks during short circuits, start-ups, etc. can be.

II. Formulation of the problem

The indicated situations force to choose the allowable temperature of the insulation with a certain caution, taking into account the experience of operating the machines. In this case, different types of insulating materials and their combinations are divided into classes according to their heat resistance.

The heat resistance classes of insulation A, E, B, F, H have allowable temperatures $V_{bb} = 105^0$S, 120^0S, 130^0S, 155^0S, 180^0S. For electrical machines, the main indicator of heating is the temperature increase of the machine elements relative to the temperature of the surrounding environment - $\Delta\theta$. For normal climatic conditions, the temperature of the surrounding environment is taken to be $\nu_e = 40^0$S. The allowable temperature increase $\Delta\theta_{bb}$ of insulating materials is related to the allowable value of the outer limit, which is determined by the following expression (1):

$$\Delta\theta_{bb} = \nu_k - \nu_e - \Delta\theta_r \quad (1)$$

where $\Delta\theta_r$ is a reserve taking into account the inviscidity of the heat considered for the element of the machine's design.

According to state standards, the following Δθe values are considered for the windings of electric machines: $\Delta\theta_{bbe}$=60⁰S, 75⁰S, 80⁰S, 100⁰S, 125⁰S and, accordingly, the change according to the thermometer $\Delta\theta_{bb}$T=50⁰S, 65⁰S, 75⁰S, 85⁰S, 105⁰S. Of course, as a rule, the values cannot be increased even at ν_e<40⁰S. When designing, an additional constructive reserve can be taken: $\Delta\theta_{bb}$≈5%÷10% (due to errors in thermal calculations and technological errors that arose during the preparation of experimental samples) Uninsulated short-circuited windings and cores that are not in direct contact with insulation and are not directly connected must have a temperature that is not dangerous for the materials in contact with them. For oscillating bearings, the temperature should not exceed 100⁰S, and for sliding bearings - 80⁰S.

The wide range of rotation frequencies and power of electric machines requires a variety of cooling systems, changing requirements for them and operating conditions. With an increase in the power of the machine, the process of increasing the heat flux is inevitable. As a result, the density of the heat flux in the heat transfer areas and insulation layers increases, which is prevented by increasing the cooling efficiency as the machine power increases [1].

A large number of micromachines operate without any special cooling system. Starting from a few tens of watts of power, the use of a fan is required. At a power of several tens of kilovolts and higher, special ventilation channels are already being used.To protect against the negative effects of the surrounding environment (dust, moisture, etc.), most machine designs are equipped with an external blowing system with internal ventilation. This system is a primary requirement of the designed machine, which works with a speed control program in various cases.

In the modern design process of electric machines, the issues of choosing a cooling system, its calculation and optimization often arise as a complex issue. A broad knowledge base is necessary to overcome these issues.

The cooling system remains one of the important issues for increasing the technical and economic indicators of many types of electric machines. How effective this issue is is clearly seen from the following analysis. The effectiveness of machines with a power of 0.5 ÷ 5 kW and a speed of 1500 rpm over the years is clearly visible are given in Table 1.

Table 1. Analysis of the dependence of the efficiency of electrical machines on the cooling system

Years	1910	1935	1950	1965	1975	2000
Mass reduction, %	120	60	42	38	33	27

Although the efficiency obtained was due to improvements in the characteristics of materials, filling coefficient, design and methods, the increase in the efficiency of cooling was of primary importance.

The efficiency of heat transfer of machines can be increased by various methods, but the economic idea should be the main one in this matter. It should be borne in mind that the machine designed using optimal calculations, based on the minimum prices, will be the most efficient machine [2].

Such an electric machine will have an optimal useful work coefficient (U.W.C) and, accordingly, will meet the optimal loss level. The requirement for the efficiency of the cooling system makes it difficult to eliminate losses while ensuring the permissible value of the permissible temperature of the main parts. The fact that the cooling intensity exceeds the permissible value cannot be justified economically, since as a result it leads to an increase in ventilation losses and noise generated by the fan; on the other hand, the cost of the cooling system also increases.

Regardless of the requirements set for the designer: maximizing the efficiency of heat transfer or setting the optimal level for it - the fulfillment of the technical and economic requirements for the designed machine of ventilation (or hydraulic) and thermal calculations is very high.

All the above requirements and instructions are fully accepted and effective design, ventilation and optimal U.W.C are created for the designed two-rotor machine.

III. Problem solution

Temperature characteristics of the general structure and its elements.

It is known that the thermal characteristics of electric machines have a special character. Here, the main thing is not only the general structure of the machine or its parts, but also the temperature difference between individual elements of the structure, as well as the cooling medium and the windings. This feature is due to the long-term operating conditions of insulating materials.

When the machine is connected to the load, the temperature increase primarily affects the condition of the insulation and steel of the windings. Under the influence of heat and the mechanical forces associated with it, the properties of insulating materials deteriorate, and over time their quality is lost. As a result of the decrease in quality, the insulating properties are lost and, as a result, thermal or electrical breakdown of the insulation occurs. Thus, the service life of the insulation (the period of trouble-free operation at the rated load) is one of the most important parameters, but it does not depend on the operating temperature, but on the fact that the temperature increase of the active parts of the machine exceeds the temperature of the surrounding air [4].

The negative effect of the absolute temperature increase on the endurance of insulating materials has been relatively well studied. Numerous studies and operational experience show that for each class of insulation materials, a certain temperature level has been determined. A temperature increase of just a few degrees leads to a significant reduction in operating time. The duration of the temperature increase also plays a significant role here.

For some classes of insulation materials, there is a rate law of aging. According to this law, with a temperature increase of Δθ degrees during operation, the operating time of the insulation is reduced by half (2):

$$D_\theta = D_v \cdot 2^{\frac{v-\theta}{\Delta\theta}} \qquad (3)$$

where D_θ – operating time at temperature rise; D_v – operating time determined experimentally at temperature θ (for example, 7 years at v=105⁰ S for class A insulation materials); Δθ – constant temperature rise. This can also be seen from the characteristics are shown in Table 2.

For class A insulation materials, Δθ=8K is usually assumed. For thermosetting insulation (class B), Δθ=10K.

Table 2. Dependence of insulation service life on temperature

Year, D_v	0,875	1,75	3,5	7	14	28	56
Tempreraturе,θ ^{0}S	127	120	113	105	100	90	80

The logarithmic nature of the dependence (3), which requires compliance with strict operating rules for electric machines. Of course, for the thermal conductivity of an electric machine to be good, it must be performed during design. Determining the local temperature value in the machine is an important step. The local temperature is sometimes also called the peak temperature.

It can be said that the peak temperature determines the practical duration of the machine's operation. Therefore, it can be noted that the lower the ratio of the peak temperature to the average temperature, the higher the service life of the machine, and the more useful it is to use the active volume of the machine.

In the design of the presented design, attention should also be paid to the known stator design, and when applying a new ventilation system, the temperature issue in the stator winding should also be considered. Here, the effect of the difference in temperature between the insulation and the cooling medium should be accurately assessed. The temperature difference between the winding copper and the body steel causes the winding to slip in the housing, which results in copper expansion. The winding slippage has a greater effect on the deterioration of the insulation than the temperature increase of the winding copper [5-7].

The temperature process in the electric machine, the design of which is presented, is significantly complicated by the change in the season and also the speed of rotation. If the engine is located in the atmospheric air zone and operates in the speed regulation mode, then at low temperatures of the surrounding environment the local temperature values will also change. Therefore, the temperature should be controlled in all cases. At low speeds, the torque value should not be lower than the ventilation system. Therefore, when considering the operation of the electric machine, the maximum torque value corresponding to the specified speeds should be seriously considered so that the temperature limit in individual insulation elements is normal.

Based on the above considerations, it can be concluded that the operation of the electric machine should be carried out at a constant temperature [3]. Temperature changes damage the integrity of the insulation and, in general, affect the service life of the electric machine. Accordingly, it is always necessary to prevent temperature changes with changes in load and climatic conditions. Of course, a strong connection should be established between the ventilation system and the above changes. The rational operating temperature of the electric machine under given design and power conditions can be achieved by a rational cooling system of the machine. This should be the main goal for the engineer designing the electric machine. In organizing the cooling system of the machine, such heat exchange with the cooling medium should be carried out so that the temperature and temperature increases of the active parts of the machine do not exceed the intended norm relative to the temperature of the cooling medium.

Issues considered in ventilation calculations [8].

The main purpose of the ventilation calculations of the designed electric machine is to determine the selection of the ventilation scheme as a whole, as well as the operation of the air intake elements, thereby ensuring the necessary volume of the cooling medium per unit time, or in other words, to create the necessary air consumption.

The volumetric air consumption (or consumption for short) is the volume of the medium passing through the cross section of the channel per unit time. This is the volume that, as applied to the entire electric machine, passes either through all parallel paths of the ventilation path or through the cross section of the leading (leading) gaps per unit time [14].

The consumption Q is expressed in meters cubed per second and is simply related to the average speed of air movement in the channel ω (3):

$$Q = \omega S \tag{3}$$

where in (3) S- is the cross-sectional area of the channel.

Thus, it is possible to compare the air consumption with the current in the electric circuit, while the speed, that is, the consumption per unit cross-section of the channel, can be considered as the density of the electric current. Since the cooling air takes into account the losses of the electric machine and connects it with the cold environment, the required amount of air is determined by the volume of the removed losses, that is, the design of the electric machine is the result of electromagnetic and thermal calculations. Thus, the nominal consumption Q within the framework of ventilation calculations is a given value.

The air circulating in the ventilation duct channels of the machine overcomes resistance in the direction of its movement. In other words, it is necessary to expend mechanical energy to ensure the circulation of air. This work is performed by air-turning elements, creating a pressure difference at the inlet and outlet cross-sections of the ventilation duct [11-13].

Each ventilation area has resistance, and therefore the total air pressure at the end of the area is always lower (relative to the initial area); the decrease is equal to the pressure loss that has completely disappeared; we denote the pressure loss by Δp. Regardless of the form of air movement (laminar or turbulent), the pressure loss is calculated by the following expression (4):

$$\Delta p = zQ^2 \tag{4}$$

This expression should be understood as follows:

When the pressure loss is proportional to the second power of the flow, the proportionality coefficient Z will be a constant value in the expression (4). If the indicated ratio is not actually observed, the coefficient z will be such that the expression (4) will be true.

The coefficient z is determined for each aerodynamic resistance not only by the dimensions of the duct and the properties of the air, but also by the local resistance ξ. This statement shows that it is necessary to take only the local resistance in a suitable form (for example, from experience).

As a result, the relative coefficient z (called aerodynamic resistance) is calculated by the following expression (5):

$$Z = \xi \frac{\rho}{2S^2} \tag{5}$$

The selection of the air blowing elements of the electric machine, i.e., the determination of the required nominal pressure Pn of the fans, taking into account the given nominal consumption Q_n, can be calculated using the following expression (6):

$$P_n = zQ_n^2 \tag{6}$$

where z is the total aerodynamic resistance of the electric machine.

It can be seen from this statement that the pressure loss in the machine is equal to the pressure created by the air-pumping elements, so equation (6) confirms the fact of equality.

Thus, in the ventilation calculations of the electric machine, its aerodynamic resistance z and equation (6) should be solved. After that, the calculation of consumption distribution in separate branches of the scheme can be made [10].

Based on the known value of the aerodynamic resistance z, the pressure drop in the machine$\Delta P_n = zQ_n^2$ can be determined, but later it should be compared with the nominal pressure of the fan due to the given consumption Q_n.

Here the complexity of the issue arises, as the pressure of the fan is a complex function of the consumption P=φ(Q), and this is called the aerodynamic characteristic of the fan.

Characteristics obtained experimentally or by calculations from a model cannot always be subjected to simple analytical writing. For this reason, writing the equation of equality in analytical form creates many difficulties.

In the practice of designing electrical machines, the graphical solution of equation (7) is widely used. This method is very simple and clear.

$$\varphi(Q) = zQ^2 \tag{7}$$

In the coordinates Q and p, two consumption functions are written: P=φ(Q) and $\Delta p = zQ^2$. Their intersection point is the point of equality: the point is the point of mutual correspondence of the pressure loss and the fan pressure (figure 1).

As a result of ventilation calculations, the working flow rate Qi is never equal to the nominal flow rate Q_n. This happens for two reasons. On the one hand, because when selecting the air blowing elements, the intersection of their characteristics with the pressure curve occurred at the required point (Q_n, ΔP_n). On the other hand, it is taken into account that the fan characteristics and the pressure loss curve are determined with some error, which leads to an unpleasant air shortage, although the electric machine is calculated for the value of Qn. In this regard, the air blowing elements should be selected so that the working flow rate Q_i is 10% higher than the nominal. Such a margin will compensate for 20% of the error made in determining the pressure loss [12].

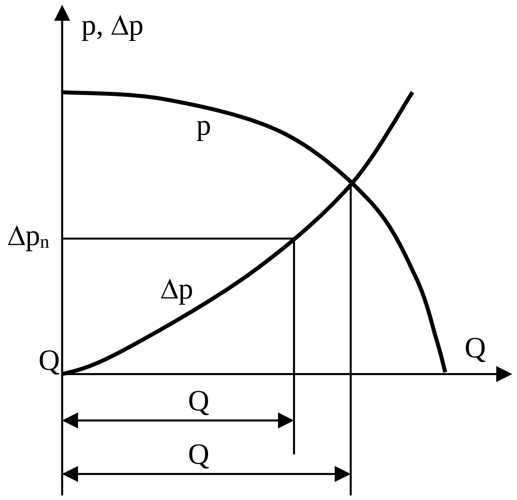

Figure 1. *Schematic determination of the working flow rate*

Information on the operation of ventilation.

Since the designed machine has a wide range of changes in the value and direction of the rotation frequency, the processes, parameters, torque changes, and the heating processes caused by the losses during operation are also quite complex. Speed regulation requires the correct design of the cooling system. The approximate stability of the cooling process in the design of an electric machine, the fact that the working rotor has a wide rotation frequency zone, and also the creation of variable losses, further complicate the cooling process [15-17].

The placement of two rotors ensures that the additional rotor performs the ventilation operation in the system with high efficiency, regardless of the operation of the working rotor. Although the rotation frequency of the working rotor varies within wide limits, the additional rotor continues to operate in asynchronous mode. At minimum rotation frequencies of the working rotor, the speed of the additional rotor may decrease by several percent of the slip, which will not significantly affect the operation of the cooling system.

The designed two-rotor asynchronous motor can be manufactured for various operating modes and in the program of changing the direction of rotation of the working rotor. For machines designed with the same and changing directions of rotation, a high-quality and high-capacity ventilation system with high air delivery capacity should be designed. If the operating mode of the designed machine is two-directional, both internal and external fans should blow air in only one direction. This direction should be from the auxiliary rotor to the working rotor. The point is that the power of the heat source in the high-resistance short-circuit loop of the copper winding of the working rotor placed in the opposite direction of the auxiliary rotor is high, and from there there is a large amount of heat flow relative to the ventilation system. For this purpose, the designed centrifugal fans (both internal and external) blow the cooling ambient air into the cooling channels in one direction in both directions of rotation. If the designed engine is created for the same direction of rotation, the ventilation system must be provided with fan devices with a high useful operating mode. In the considered design, the internal and external fans are driven by a certain rotating (auxiliary rotor) element, which indicates that both fans have a maximum operating coefficient. For this, the design of centrifugal fans is possible by selecting a design with a high air blowing capacity. The air blowing elements of such fans can be made forward or backward inclined [11].

IV. Conclusions

1. In conclusion, the thermal management of electric machines plays a crucial role in ensuring their long-term reliability, efficiency, and optimal performance. The conversion of mechanical energy to electrical energy inevitably leads to heat losses, which must be effectively managed to prevent overheating and deterioration of key components like insulation. The design of the cooling system is integral to this process, as it directly influences the machine's power output, operational lifespan, and safety. Efficient heat transfer, achieved through methods such as conduction, convection, and radiation, alongside well-calculated ventilation and hydraulic systems, helps maintain the permissible temperature limits for critical machine parts.

2. As the power and complexity of electric machines increase, so too does the need for advanced cooling solutions. Insufficient cooling can accelerate the aging of insulating materials and lead to electrical and mechanical failures. The optimization of cooling systems not only improves the thermal efficiency of the machine but also reduces the associated costs and energy losses. Furthermore, understanding the relationship between temperature increases, insulation life, and cooling system efficiency is essential for designing machines that meet both technical and economic objectives.

3. Ultimately, the integration of reliable cooling systems is vital for maximizing the lifespan and performance of electric machines, making it a key focus in modern machine design. By ensuring that thermal management is prioritized throughout the design process, engineers can enhance the durability, safety, and operational effectiveness of electric machines across a wide range of applications.

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