Calculation Methods for Heating and Ventilation System of Electrical Machines

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Additional information is available at the end of the chapter

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1. Introduction

To design as accurately electrical machines it is necessary as the cold machine to be efficient and to determine values and distribution of temperature in the machine (along the rotor). For this, must do a complete and accurate analysis of temperature field in steady state (or in transient regime) which requires the knowledge and location of the temperature loss amounts, the knowledge of the velocity distribution of the cooling fluid in the cooling channels different of the machine, the determination of thermal flux values and the distribution of these values in some component parts of the electric machine.

Considering the analogy between a ventilation network of cooling and a nonlinear resistive circuit, the flows of the cooling agent of an electric machine can be determined.

The aim of thermal computation of electric machines is necessary to establish heating, temperature overrunning or overheating in some parts of the machine from the environment temperature at a given operating condition of the machine.

The service life of the insulations used in electric machines is limited heating which greatly decreases in the same time with temperature increasing. Heating determined is stabilized, because the electrical machine which will be discussed has a long-lasting operating regime. Inside the electric machine a heat quantity is produced which has to be exhausted to outside for limiting the excessive heating, heating due to the losses which occur in the active materials.

2. Heat transfer

The heat transfer is the science of spontaneous and irreversible processes of heat propagation in space and is the exchange of thermal energy between two objects, two

regions of the same part and respectively two fluids, as a result of a difference of temperature between two fluids.

In technical, the heat transfer must be:

- more intense (e.g. steam boilers, the optimal exchange in heat exchangers);
- Stopped (e.g. steam by thermal insulation).

The heat is the transfer of energy between phisical-chemical systems or between different parts of the same systems, if there is a transformation where is not performed any mechanical work.

The heat transfer deals with the processes where the thermical energy at higher parameters is changed in thermal energy to lower parameters, usually, the parameter which appreciates the heat quality is the temperature, defined as a global measure of processes' intensity which determines the internal energy of an object (thermal agitation of molecules in liquid and gases, atoms vibration and free electrons motion in metals, etc.).

The heat exchange follows thermodynamics principles: **the first principle of thermodynamics** expresses the energy conservation rule and it establishes the quantitative relationship between heat and mechanical work, and allows integral transformation of heat in mechanical work and the reverse; **the second principle of thermodynamics** states the necessary conditions for transforming heat in mechanical work and establishes natural meaning of heat propagation, always from the source with higher temperature to the source with lower temperature.

The main objectives of the heat transfer are: first, the determination or ensuring the amount of heat exchanged per time unit in fixed temperature conditions, and second, checking the compatibility of materials used with the regime of temperature faced by, in determining the temperature field. We can say that an exchange of heat device is an optimal solution from thermic, hydraulic, mechanic, economic and reliability points of view, mainly, the heat transfer being the determining factor. We should add to these, finding the enhancing methods and procedures or, in certain cases, heat transfer breaking. [5]

Conduction, radiation and convection are distinct forms of heat transfer. As defined above, only **conduction** and r**adiation** are heat exchange processes due solely to the difference in temperature, **convection** is a more complex process, necessarily involving the mass transfer. Because, the convection makes energy transfer from regions with higher temperature in regions with lower temperature, it was generally accepted „heat transfer by convection" as being the third mode of heat exchange.

Basic sizes in heat transfer

The temperature field. The status scalar parameter, the temperature, in any point of space M(x, y, z) depends on position and time, namely it is a function of the following form.

$$t = f\left(x, y, z, \tau\right) \tag{1}$$

The temperature field is such, the total of the temperature t values throughout all space, at some time τ, the expression (1) representing the equation of this field.

The temperature field may be constant (stationary or permanent) and transient (non-stationary or variable) as time τ is explicitly or nonexplicitly in equation (1) and namely:

- the temperature constant field has the equation:

$$t = f_1(x,y,z), \quad \frac{\partial t}{\partial \tau} = 0 \tag{2}$$

- the temperature transient field is expressed by equation (1)

Regarding the number of coordinates, the temperature field can be one, two or tridirectional. So, in equations (1) and (2), the temperature field is tridirectional in transient regime, respectively, constant. If the temperature is depending on two coordinates and time, the field is bidirectional transient, with the equation:

$$t = f_2(x,y,\tau), \quad \frac{\partial t}{\partial z} = 0 \tag{3}$$

and if it is expressed as a function of a coordinate and time, the field is onedirectional transient, with equation:

$$t = f_3(x,\tau), \quad \frac{\partial t}{\partial y} = \frac{\partial t}{\partial z} = 0. \tag{4}$$

The equation of temperature in the onedirectional constant field is the most simple:

$$t = f_4(x), \quad \frac{\partial t}{\partial y} = \frac{\partial t}{\partial z} = \frac{\partial t}{\partial \tau} = 0. \tag{5}$$

All points of space considered which have the same temperature t at a moment in time τ form **isothermal surface**. Because, a point in an object can not concomitant has two different temperature values, the result is that isothermal surfaces are continuous surfaces which do not intersect one another. [5]

The temperature gradient is a measurement which expresses elementary increase of temperature to a point of a temperature field, at a given time τ.

The temperature gradient is a normal vector to isothermal surface and it is numerically equal with the limit of the report between the temperature variation Δt between two isothermal surfaces and the distance Δn of these two, measured on normal to surface, when Δn tends to zero, namely:

$$grad\, t = \lim_{\Delta n \to 0} \frac{\Delta t}{\Delta n} = \frac{\partial t}{\partial n} \quad [\degree C/m] \tag{6}$$

The heat amount ΔQ passing through an object or from an object to another, by an isothermal surface S, in time unit $\Delta\tau$, is called **heat flow (thermal flow)** Q:

$$\dot{Q} = \frac{\Delta Q}{\Delta\tau} \quad [\text{W}], \tag{7}$$

The unitary heat flow q_s is the heat flow which crosses the surface unit in the time unit:

$$\dot{q}_S = \frac{\dot{Q}}{S} = \frac{\Delta Q}{S\Delta\tau} \quad [\text{W/m}^2] \tag{8}$$

where S is the area of heat exchange surface, in m².

Electrical analogy of heat transfer

Two systems are analogous when they have different natures, but respect similar equations with similar boundary conditions. This implies that equations describing the action of a system can be transformed into the equations of the other system by simply exchanging the variable symbols. So, Ohm's law for Electrotechnics expressing the link between DC I, voltage (potential difference) ΔU and the electrical resistance R_e, has an analog form in heat transfer, by the relationship between unitary thermal flow q, temperature difference (thermal potential) Δt and a size called **thermal resistance** R_t, namely:

$$I = \frac{\Delta U}{R_e} \; ; \; \dot{q}_S = \frac{\Delta t}{R_t} \tag{9}$$

In equation (9), when q is measured in W/m² and Δt is measured in °C, the thermal resistance R_t is expressed in (m²·°C)/W.

Based on this analogy, a series of concepts of DC circuits can be applied to the heat transfer problems (for example, electrical circuit has an equivalent thermal circuit and reverse) and in dynamic regime (for example, electrical modeling of some transient thermal processes). The electrical analogy of heat transfer can be used as a calculation tool and as viewing heat transfer equations by linking them to the electrical engineering domain.

Corresponding to the three fundamental types of heat transfer, we can establish the expressions for calculating the thermal resistance to conduction, convection and respectively, radiation, which can take place in the complex processes of heat exchange, equivalent electrical diagrams serially or mixed connected.

Inverse thermal resistance is called **thermal conduction.** [5]

3. The calculation methods for heating system of electrical machines

The heat flow Q (the amount of thermical energy which pass through a given surface S in time unit) expressed in J/s is numerically equal with losses of power P, expressed in W, which determine heat in any part of the machine. So, instead of heat flow, in relations used,

will use losses P, directly. The object characteristics and the difference between object temperature to the environment that transfers heat determines heat transfer on the mass and on the surface of that object. For thermal calculation, the analogy is made between electrical resistance from the power of a circuit and thermal resistance R from heat flow Q.

Based on this analogy, the temperature drop in mass or surface of an object corresponding to heat flow Q, (or losses P) is determined by multiplying between thermical resistance of the object opposed to heat flow in its mass, respective its surface, R, and losses P, relation (10):

$$\theta = PR\left[°C\right], \tag{10}$$

Where: $\theta = v_1 - v_2$ – is the temperature drop, over temperature or object heating, in °C.
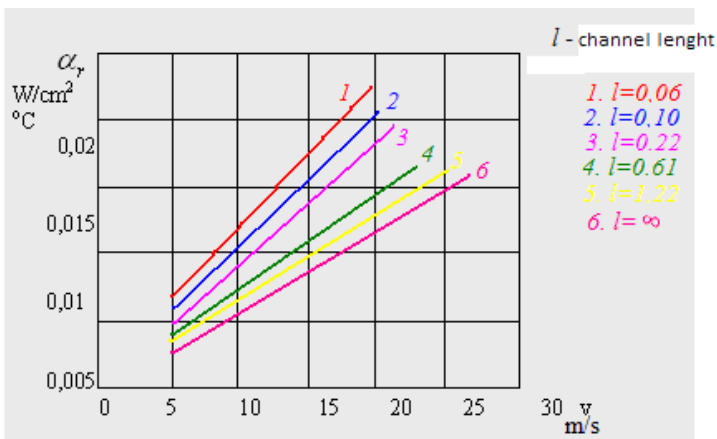
On the relation (10) we may work with equivalent *thermal diagrams* with means which, for certain values of thermal resistance and losses, the heat θ is resulting.

The way to solve the thermal schemes, depending on the thermal resistances connection (series, parallel or mixed) is identical to the electrical schemes. [2, 3]

Next we will present the thermal resistances expressions depending on the types of heat transmission and the structure encountered in building electrical machines.

Heat transmission by radiation and convection in the case of heat transmission in axial channels and radial channels of electrical machines

In heat transmission by radiation and convection in the case of heat transmission in axial channels and radial channels of electrical machines, the transmission coefficients of heat depend on the air velocity which blows on the surface. For certain lengths of the channel, transmission coefficients of heat will be taken from the diagrams shown in „figure 1" for axial channels and „figure 2" for radial channels.

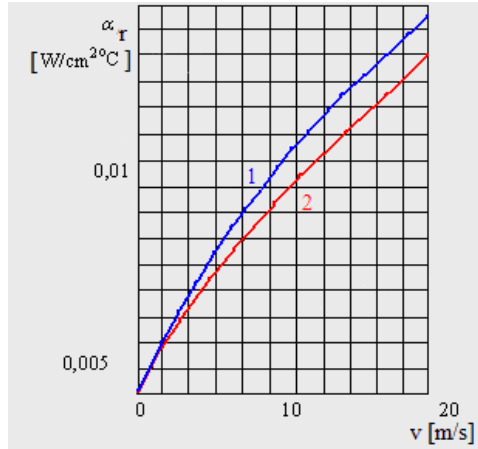**Figure 1.** Transmission coefficient of heat in axial channels

Figure 2. Transmission coefficient of heat in radial channels

4. Common thermal schemes used by electrical machines

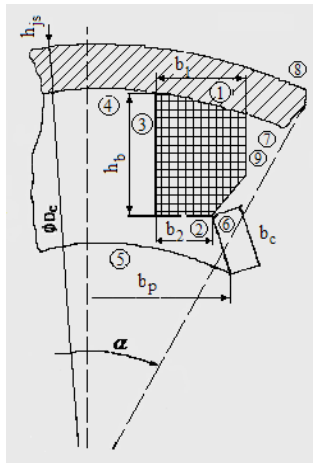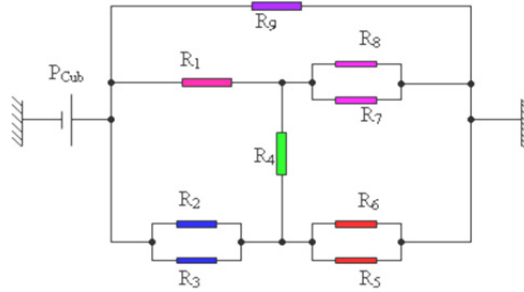**Operating winding of electrical machines**

Figure 3. Transversal section through a winding pole of a DC machine.

In "figure 3", it is presented the transversal section through a winding pole of an electrical DC machine, for that the temperature is considered constant around the coil mass, calculating the average temperature value, the temperature drop is practically null, as well as in the coil mass and in the machine housing, for the part of housing which contributes to cooling of a magnetizing coil and corresponds an angle $\alpha = \dfrac{\pi}{2p}$, this is the angle between symmetry axes from a main pole and the auxiliary neighboring poles.

The real thermal diagramme of heat transmission to a coil from a pole of DC machine is indicated in „figure 4", where there are indicated losses by Joule effect of one coil $P_{cub,}$ thermal resistance from coil to housing R_1 corresponding the domain ① of „figure 3", thermal resistance from coil to pole by pole piece R_2 corresponding the domain ② of „figure 3", thermal resistance from coil to pole by the pole body R_3 corresponding the domain ③ to figure 3, thermal resistance from pole to housing R_4 considering the pole-housing jonction ≈ 0.1 mm corresponding the domain ④, thermal resistance from pole to air by air-gap R_5 corresponding the domain ⑤, thermal resistance from pole to the space air between poles R_6 corresponding the domain ⑥, thermal resistance from housing to air inside machine R_7 corresponding the domain ⑦, thermal resistance from housing to environmental medium R_8 corresponding the domain ⑧, thermal resistance from coil to air R_9 corresponding the domain ⑨. All resistances are measured in ⁰C/W.

Figure 4. Main diagram of heat transmission to a coil from a pole of DC machines

For learning the total equivalent resistance we need to reproduce intermediate thermal diagrams, „figure 5.a, b".

Thermal resistances for determining the heating of magnetizing coil from „figure 5.a" correspond to relations:

$$R_A = \frac{R_2 R_3}{R_2 + R_3}; \ R_B = R_1; \ R_C = R_4 \, ;$$
$$R_D = \frac{R_5 R_6}{R_5 + R_6}; \ R_E = \frac{R_7 R_8}{R_7 + R_8}$$

(11)

And for „figure 5.b" after transforming the triangle R_D, R_C and R_E from „figure 5.a" into star R_x, R_y and R_z the relations for thermal resistances are:

$$R_x = \frac{R_C R_D}{R_C + R_D + R_E}; \ R_y = \frac{R_C R_E}{R_C + R_D + R_E}; \ R_z = \frac{R_D R_E}{R_C + R_D + R_E};$$
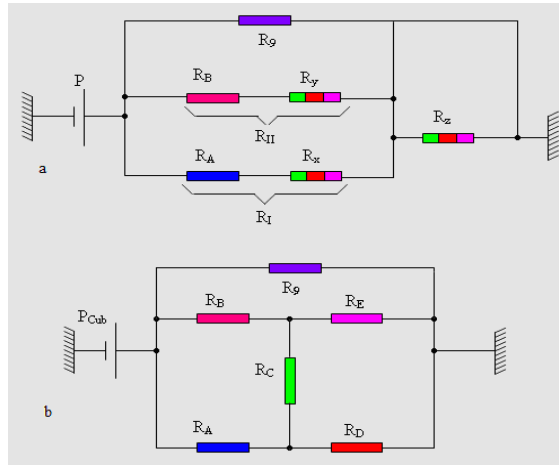$$R_I = R_A + R_x; \ R_{II} = R_B + R_y$$

(12)

According to (12) and the equivalent diagram from „figure 5.b" we can determine the total equivalent resistance:

$$R_T = \frac{\left(\dfrac{R_I R_{II}}{R_I + R_{II}} + R_z\right) R_9}{\dfrac{R_I R_{II}}{R_I + R_{II}} + R_z + R_9} \tag{13}$$

After having known the total equivalent resistance R_T, we can determine the heating of magnetizing coil towards the cooling air in the machine:

$$\theta_{cub} = R_T P_{cub} \tag{14}$$

Figure 5. Intermediate thermal diagrams for determining the heating of magnetizing coil: a – real diagram; b – equivalent diagram.

The calculation of thermal resistances from the real diagram (figure 4)

The thermal resistance from coil to machine housing

Thermal resistance from coil to machine housing R_1 is calculated according to total thickness β_{t1} (thickness coil insulation β_b, insulation thickness to the housing β_c, thickness of protecting lac from impregnation $\beta_l \approx 0,025$ cm), of equivalent thermal conductivity λ_1 (thermal conductivity when coil is separately isolated λ_b, thermal conductibility for insulation from housing λ_c, thermal conductivity for protecting lac λ_l) and from the corresponding surface S_1 by which the heat is transmitted, considering only the side parts. [2, 3]

$$\beta_{t1} = \beta_b + \beta_c + \beta_l \quad [cm];$$

$$\lambda_1 = \frac{\beta_{t1}}{\dfrac{\beta_b}{\lambda_b} + \dfrac{\beta_c}{\lambda_c} + \dfrac{\beta_l}{\lambda_l}} \tag{15}$$

$$S_1 = 2b_1(l_m + b_m + 2b_1), \quad \left[cm^2\right]$$

Where:

b_1 - the thickness of the coil to the upper part, in cm;

b_m – the polar core width, in cm;

l_m – the polar core length, in cm.

These are obtained by:

$$R_1 = \frac{\beta_{t1}}{\lambda_1 S_1} \quad \left[°C/W \right].$$

(16)

The thermal resistance from the coil to the polar piece.

The thermal resistance from the coil to the polar piece, R_2, is calculated as the thermal resistance from coil to machine housing for same insulation, but get calculating only the isolated frame bottom and the transmission surface of heat S_2.

$$R_2 = \frac{\beta_{t2}}{\lambda_2 S_2} \quad \left[°C/W \right]$$
$$\beta_{t2} = \beta_{t1} \quad and \quad \lambda_2 = \lambda_1$$
$$S_2 = 2b_2\left(l_m + b_m + 2b_2\right), \left[cm^2 \right]$$

(17)

where b_2 is the thickness the coil to the below part, in cm.

The thermal resistance from the coil to the pole object

The thermal resistance from the coil to pole object R_3, is calculated according to the thickness of the insulated coil β_b only when the coil is isolated separately, β_m, the thickness of the insulation toward the body of the pole, the impregnation layer $\beta_l \approx 0{,}025$ cm, the thermal conductivity of the insulated coil λ_b, thermal conductivity of insulation from the pole body λ_m, the thermal conduction of the protecting lac λ_l and of the corresponding surface S_3.

$$\beta_{t3} = \beta_b + \beta_m + \beta_l \quad \left[cm \right]$$
$$\lambda_3 = \frac{\beta_{t3}}{\dfrac{\beta_b}{\lambda_b} + \dfrac{\beta_m}{\lambda_m} + \dfrac{\beta_l}{\lambda_l}}$$
$$S_3 = 2b_3\left(l_m + b_m + 2b_3\right), \left[cm^2 \right]$$

(18)

$$R_3 = \frac{\beta_{t3}}{\lambda_3 S_3} \quad \left[°C/W \right]$$

(19)

The thermal resistance from the pole core to the housing

The thermal resistance from the pole core to the housing R_4 is calculated according to the thickness of the parasite airgap to the pole-housing jonction at about 0,1 mm, for thermal conductivity in electrical machines whose stator is not impregnated after winding $\lambda_4 =$

0,00025 W/cm°C, or for electrical machines with the impregnated stator $\lambda_4 = \lambda_l$, and, also according to the corresponding calculated surface with b_m the polar core width and l_m the polar core length.

$$R_4 = \frac{0,01}{\lambda_4 S_4} \quad [\text{°C/W}] \tag{20}$$

The thermal resistance to the heat transmission from the core pole to airgap

$\alpha_0 = 1,42 \times 10^{-3}$ W/cm² °C	Iron and steel surfaces, grouted (housing surfaces)
$\alpha_0 = 1,67 \times 10^{-3}$ W/cm² °C	Iron and steel surfaces, nongrouted
$\alpha_0 = 1,33 \times 10^{-3}$ W/cm² °C	Cooper or brass surfaces, and coil impregnated or varnished surfaces

Table 1. The coefficient values of heat transmission α_0, on the non-blast surfaces

Considering the corresponding surface S_5 calculated according to the length and width of the polar piece l_p respectively b_p, the thermal resistance to the heat transmission from the core pole to airgap is determinate by relation:

$$R_5 = \frac{1}{\alpha_{t5} S_5} \quad [\text{°C/W}] \tag{21}$$

The coefficient of heat transmission on the object surface α_{t5} is determined admitting that $\theta'_{aer} = 20°C$ is half of the total heating of the air in the machine, k = 0,8 chosen from „table 2", the coefficient of heat transmission chosen from „table 1" is $\alpha_0 = 1,67 \times 10^{-3}$ W/cm² °C and air velocity in the airgap $v_\delta = \frac{1}{2} v_r$.

$$\alpha_{t5} = \alpha_0 \left(1 + k\sqrt{v_\delta}\right)\left(1 - 0,5a\right) \left[\text{W} / \text{cm}^2 °\text{C}\right]$$

$$a = \frac{\theta'_{aer}}{\theta_a}$$

$a = \dfrac{20^o}{70^o} = 0{,}28$ class of insulation B, $a = \dfrac{20^o}{90^o} = 0{,}22$ class of insulation F

$$S_5 = b_p l_p \ [\text{cm}^2].$$

The name of the surface and the type of blast	k
The blast surface in the most perfect way	1,3
The surface of the front linkage of induced winding	1,0

The name of the surface and the type of blast	k
The surface of the active part of the induced	0,8
The surface of the magnetizing coils	0,8
The collector surface	0,6
The outer surface of the housing	0,5

Table 2. The coefficient values of blast intensities k

The thermal resistance to heat transmission from polar piece to the space between poles

In the heat transmission to space between poles, by polar pieces, the thermal resistance is determined regarding the coefficient of heat transmission α_{t6} and the surface located on the polar width of the object $b_c\ l_m$ polar core length:

$$R_6 = \frac{1}{\alpha_{t6}S_6} \quad \left[{}^\circ\text{C/W} \right]$$

$$S_6 = 2b_c l_m \left[\text{cm}^2 \right]$$

$$\alpha_{t6} = 1{,}6.7\ \text{x}10^{-3}\left(1 + 0{,}8\sqrt{v_6}\right)\left(1 - 0{,}5a\right) \left[\text{W}/\text{cm}^2{}^\circ\text{C} \right],\ \text{cu}v_6 = v_\text{p}$$

(22)

The thermal resistance to heat transmission from the housing to interior

When heat transmission is done from housing to interior, the thermal resistance R_7 is determined the same as in heat transmission to the space between poles, by polar pieces with $\alpha_{t7} \approx \alpha_{t6}$, $v_7 = v_6$, and the corresponding surface S_7 is calculated regarding the interior diameter of the housing D_c, the number of pole pairs p and the housing length l_c.

$$R_7 = \frac{1}{\alpha_{t7}S_7} \quad \left[{}^\circ\text{C/W} \right]$$

$$S_7 \approx \frac{\pi D_c}{4p}l_c - \left(b_m + 2b_1\right)\left(l_m + 2b_1\right) \quad \left[cm^2 \right]$$

(23)

The thermal resistance to heat transmission from housing to exterior (quiet air)

The heat transfer from the housing to outer where the air is quiet, thermal resistance is calculated taking into account the heat transmission coefficient $\alpha_0 = 1{,}42\text{x}10^{-3}$ W/cm^{20}C determined in „table 1", by the appropriate surface S_8, at which involved, the height of stator yoke h_{js}, the inner diameter of the housing D_c, the number of pole pairs p and the housing length l_c.

$$R_8 = \frac{1}{\alpha_0 S_8} \quad \left[{}^\circ C/W \right]$$

$$S_8 = \frac{\pi\left(D_c + 2h_{js}\right)}{4p}l_c$$

(24)

The thermal resistance to heat transmission from coil directly to cooling air in the machine

When the heat transmission is done from coil directly to cooling air in the machine, the thermal resistance depends on the thickness and the thermal conductivity of coil insulation when the coil is isolated separately β_b and λ_b, by the coefficient of heat transmission α_{t9}, and by the corresponding surface S_9.

$$R_9 = \frac{\beta_b}{\lambda_9 S_9} + \frac{1}{\alpha_{t9} S_9} \quad \left[\,^o C / W \right]$$

$$\alpha_{t9} = \alpha_0 \left(1 + 0.8\sqrt{v_9}\right)\left(1 - 0.5a\right) \left[W / cm^2 \,^o C \right],$$

$$\alpha_0 = 1.33 \bullet 10^{-3}. \, W / cm^2 \,^o C, \text{ from table 1; } v_9 = v_6;$$

$$S_9 \approx 2\left(b_m + l_m + 4b_1\right)1.1h_b \quad \left[cm^2 \right]$$

(25)

5. The losses by Joule effect, a single coil

The losses by Joule effect P_{cub} are the total losses in the magnetizing reeling P_{cuc} reported to the number of poles of the electrical machine $2p$.

$$P_{cub} = \frac{P_{cuc}}{2p} \quad \left[W \right]$$

(26)

6. The total heat of magnetizing reeling

Heating the magnetizing coil to the air in the machine, is determined by the relation (14) together with heating the air to the contact with the coil ($\theta_{aer} \approx 20°C$ – from rotor to stator) determining heating of the magnetizing reeling towards the external environment.

$$\theta_{cue} = \theta_{cub} + \theta'_{aer} < \theta_{admis}$$

(27)

7. The diagrams of ventilation and calculation of aerodynamic resistances
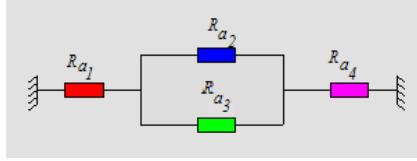
In the construction of rotating electrical machines, the cooling air is most frequently used. Depending on the construction type and the type of protection of the electrical machine the best ventilation system is chosen.[1]

Calculating ventilation of rotating electrical machine is done as follows:

- establishing the ventilation diagram and calculating aerodynamic resistances;
- calculating the pressure determined by means of air entrainment;
- calculating air flow at different sections.

Preparing the ventilation diagram for a rotating electrical machine requires prior execution of the diagram to the scale of general assembly (longitudinal section and cross section) and

establishing the routes where cooling air circulates. For calculation aerodynamic resistances we need to know longitudinal and transversal dimensions of all pipes that form the routes for air circulation.

Figure 6. The diagram of mixed connection of aerodynamic resistances

When we solve an aerodynamic diagram, we aim to find the equivalent resistance R_{ae}.. Between aerodynamic diagrams used for air circuits and electrical diagrams may be an analogy, the aerodynamic resistances act as passive elements.

Determining the equivalent resistance depends on how aerodynamic resistances are connected:

-    to series arrangement R_{ae} is the sum of the aerodynamic resistances and it is determined by relation:

$$R_{ae} = \sum_{i=1}^{n} R_{ai} \tag{28}$$

-    to shunt connection R_{ae} is determined by relation:

$$\frac{1}{\sqrt{R_{ae}}} = \sum_{i=1}^{n} \frac{1}{\sqrt{R_{ai}}} \tag{29}$$

-    to mixed connection, „figure 6", R_{ae} is calculated according to relations of calculation for the series arrangement and shunt connection and we obtain:
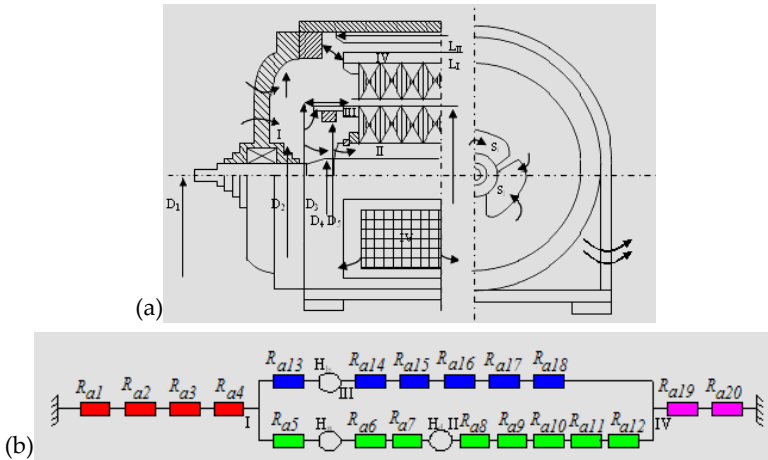
$$R_{ae} = R_{a1} + \frac{R_{a2}R_{a3}}{\left(\sqrt{R_{a2}} + \sqrt{R_{a3}}\right)} + R_{a4} \tag{30}$$

Bilateral axial-radial ventilation for an electrical machine in protected construction

In „figure 7.a" are represented the longitudinal section and the frontal view for an induction motor with the rotor in short-circuit, in protected construction, and with arrows we indicate routes that circulate the cooling air.

Typically, in asynchronous machine the role of inductor is accomplished by the stator, while the rotor is the induced machine. The machine excitation is done in AC. The collector body is of „collector rings" type.

The asynchronous machine can not develop a couple unless the speed „n" of the rotor is different by the speed „n_1" of the stator rotating field. [2, 3]

(a)

(b)

Figure 7. Ventilation diagram of asynchronous electrical machine with bilateral radial ventilation: a) physical diagram; b) main diagram.

Because depression created in the rotor bars ends and the rotor ribs (the electrical machine has not its own ventilator), the air is absorbed through the windows of the two fore-shields, washes the active elements and it is thrown out through the windows of its middle, by the bottom of the housing.

Air flow is symmetrical to the middle of the machine length, and is, therefore, sufficient to calculate ventilation only on one side, which is half of the machine.

The sources of pressure are denoted by „H", the aerodynamic resistance by „R_a" and are divided in sections. [3, 11, 12]

8. Section I

We established I section, which contains aerodynamic resistances R_{a1}, $R_{a\,2}$, $R_{a\,3}$, and $R_{a\,4}$, which are connected in series and is calculated the total aerodynamic resistance for section I, according the relation:

$$R_{atrI} = \sum_{i=1}^{4} R_{ai} \qquad (31)$$

For determining total aerodynamic resistance of the I section we calculate, in turns, each aerodynamic resistance which is part of the I section regarding the coefficients of aerodynamic resistances and the sections of the channels by which the air circulates.

The air enters through the shield windows under sharp edges (blinds) by narrowing from the external environment to the input section. From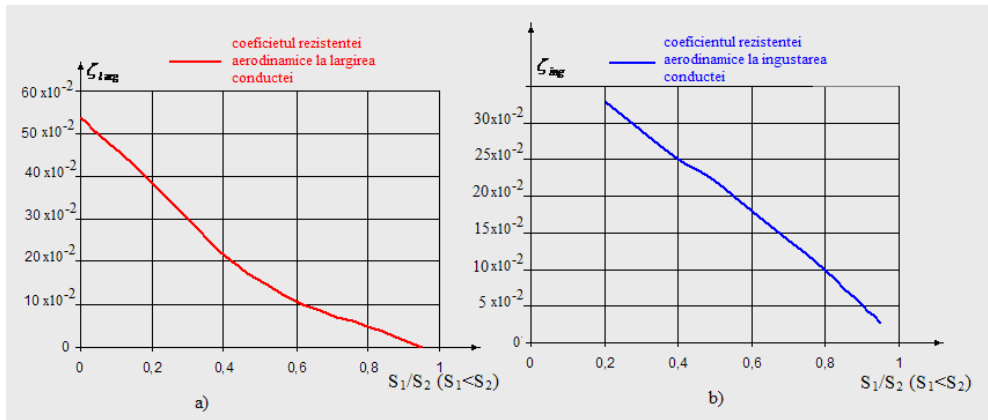 „table 3", for sharp edges $\zeta_{as} = 62 \cdot 10^{-2}$, and for narrowing $\dfrac{S_1}{S_{ext}} \approx 0$, as in „figure 8" $\zeta_{ing} \approx 32 \cdot 10^{-2}$.

Conditions of entry	ζ
Entry with sharp edges	62×10^{-2}
Entry with edges at angle of 90°	30×10^{-2}
Entry with rounded edges	$(12,5...0) \times 10^{-2}$

Table 3. The values of the resistance coefficient to the air admission pipes

The angle of deviation	ζ
135°	32×10^{-2}
90°	70×10^{-2}

Table 4. The values of the resistance coefficient to deviation in different angles

Figure 8. The aerodynamic coefficient resistance to widening and narrowing core

Aerodynamic resistance R_{a1} is calculated according to the net input surface in the shield windows S_1, to the coefficient of aerodynamic resistance to narrowing ζ_{ing} and to the coefficient for sharp edges ζ_{as}.

$$R_{a1} = \frac{\zeta_{as} + \zeta_{ing}}{S_1^2} = \frac{(62 + 32) \cdot 10^{-2}}{S_1^2} \tag{32}$$

Where: - $S_1 = k_i S_i \left[m^2 \right]$

- S_i is the total surface of the shield windows, in m²;
- k_i is the coefficient of reduction in section because the coatings required by the machine protection: $k_i = 0,6 \div 0,7$

There is a relaxation of the air coming out of the shield and to the input in the machine and a deviation to 135º by deflector (figure 7.a)

$$S_2 = \frac{\pi}{4}\left(D_1^2 - D_2^2\right) \; \left[m^2\right] \tag{33}$$

For $\dfrac{S_1}{S_2} = ... \Rightarrow \zeta_{larg} = ...$, and for the deviation to 135º from „table 4″ $\Rightarrow \zeta_r = 32 \cdot 10^{-2}$

The aerodynamic resistance R_{a2} is calculates according to the net output surface of windows shield S_1, to the coefficient of aerodynamic resistance to enlargement ζ_{larg} and to the coefficient to the air relaxation of shield output ζ_{as}.

$$R_{a2} = \frac{\zeta_{larg} + \zeta_r}{S_1^2} \tag{34}$$

Next, there is a relaxation to the output of deflector under sharp edges.

$$S_3 = \frac{\pi}{4}\left(D_3^2 - D_4^2\right) \; \left[m^2\right] \tag{35}$$

For $\dfrac{S_2}{S_3} = ... \Rightarrow \zeta_{larg} = ...$, and for sharp edges $\zeta_{as} = 62 \cdot 10^{-2}$

We calculate the aerodynamic resistance R_{a3} regarding the net input surface in the machine S_2, the coefficient of aerodynamic resistance to widening ζ_{larg} and the coefficient for sharp edges ζ_{as}.

$$R_{a3} = \frac{\zeta_{larg} + \zeta_{as}}{S_2^2} \tag{36}$$

At the rotor winding input occurs a narrowing and there are sharp edges for the short-circuited rotor.

$$S_4 = \frac{\pi}{4}\left(D_5^2 - D_4^2\right) \; \left[m^2\right] \tag{37}$$

For $\dfrac{S_4}{S_3} = ... \Rightarrow \zeta_{ing} = ...$, and for sharp edges $\zeta_{as} = 62 \cdot 10^{-2}$.

We calculate the aerodynamic resistance R_{a4} regarding the net input surface under rotor winding S_4, the coefficient of aerodynamic resistance to narrowing ζ_{ing} and the coefficient for sharp edges ζ_{as}.

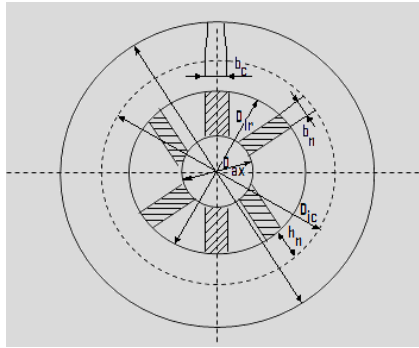$$R_{a4} = \frac{\zeta_{ing} + \zeta_{as}}{S_4^2} \tag{38}$$

After we calculated the aerodynamic resistances R_{a1}, R_{a2}, R_{a3}, R_{a4}, regarding the narrowing or widening ventilation channels by relation (31) we calculate the *total aerodynamic resistance of the section I.*

9. Section II

The II section contains aerodynamic resistances R_{a5}, R_{a6}, R_{a7}, R_{a8}, R_{a9}, R_{a10}, R_{a11}, R_{a12}, connected in series and we calculate the total aerodynamic resistance to the section II with the relation:

$$R_{atrII} = \sum_{i=5}^{12} R_{ai} \tag{39}$$

To calculate the aerodynamic total resistance by section II, we calculate, as for section I, each aerodynamic resistance, in turns, considering the widening and the narrowing of the ventilation channels.

Figure 9. Cross section in the rotor with ribbed shaft

When the air begins to cross the section II, it enters under the rotor core which occurs in narrowing, and the input is done under sharp edges (figure 9).

$$S_5 = \frac{\pi}{4}\left(D_{ir}^2 - D_{ax}^2\right) - n_n b_n h_n \quad \left[m^2\right] \tag{40}$$

Where:
- D_{ir}, is the interior diameter of the armature core disc, in m;
- D_{ax} is the diameter of the shaft, in m;
- b_n is the ridge width, in m;
- $h_n = \dfrac{D_{tr} - D_{ax}}{2}$ is the ridge height, in m;
- n_n is the ridges number.

For $\dfrac{S_5}{S_4} = ... \Rightarrow \zeta_{ing} = ...$ and for sharp edges $\zeta_{as} = 62 \cdot 10^{-2}$.

We calculate the aerodynamic resistance R_{a5}, regarding the net surface to the output under the rotor core S_5, the coefficient of aerodynamic resistance to the narrowing ζ_{ing} and the coefficient for sharp edges ζ_{as}.

$$R_{a5} = \frac{\zeta_{ing} + \zeta_{as}}{S_5^2} \tag{41}$$

For the input of radial ventilation channels of the rotor under sharp edges occurs a deviation to 90°, $\zeta_c = 70 \cdot 10^{-2}$, from „table 3" $\left(\zeta_{as} = 62 \cdot 10^{-2} \right)$ and a narrowing.

$$S_6 = 0{,}9\pi D_{ir} b_v \frac{n_v}{2} \quad \left[m^2 \right] \tag{42}$$

Where:
- b_v is the width of the radial channel for ventilation, in m;
- n_v is the number of radial channels for ventilation;
- 0,9 is the coefficient which takes into consideration the presence of spacers.

For $\dfrac{S_6}{S_5} = ... \Rightarrow \zeta_{ing} = ...$

The aerodynamic resistance R_{a6} is calculated, using the relation (42) which takes into consideration the net surface to the input of radial channels of the ventilator S_6, the coefficient of aerodynamic resistance to narrowing ζ_{ing} and the coefficient for sharp edges ζ_{as}.

After the air entered in the channels of ventilation the relaxation occurs (figure 9)

$$S_7 = 0{,}9\pi D_{ic} b_v \frac{n_v}{2} \quad \left[m^2 \right] \tag{43}$$

Where:

- D_{ic} is the diameter of the rotor slots base, in m.

For $\dfrac{S_6}{S_7} = ... \Rightarrow \zeta_{l\arg} = ...$

The aerodynamic resistance R_{a7} is calculated, taking into consideration the relaxation in the channels of ventilation:

$$R_{a7} = \frac{\zeta_{l\arg}}{S_6^2} \tag{44}$$

A new narrowing occurs to the entry in the region of rotor coils under sharp edges, for the short-circuited rotor or the rounded edges of rotors and widening to the outside rotor.

$$S_8^{'} = S_7 - z_2 b_{c2} b_v \frac{n_v}{2} \quad \left[m^2 \right] \tag{45}$$

$$S_8^{''} = 0,9\pi D_r b_v \frac{n_v}{2} - Z_2 b_{c2} b_v \frac{n_v}{2} \quad \left[m^2 \right] \tag{46}$$

Where:

- D_r is the exterior diameter of the rotor, in m;
- z_2 is the number of rotor slots;
- b_{c2} is the width of the rotor slot, in m.

For $\dfrac{S_8^{'}}{S_7} = ... \Rightarrow \zeta_{ing} = ...$ and for sharp edges $\zeta_{as} = 62 \cdot 10^{-2}$.

For $\dfrac{S_8^{'}}{S_8^{''}} = ... \Rightarrow \zeta_{l\arg} = ...$

We obtained the aerodynamic resistance R_{a8}, calculated to the input of the coils region by narrowing the ventilation channel and the output of rotor by widening the ventilation channels for short-circuited rotor where the edges are sharp:

$$R_{a8} = \frac{\zeta_{ing} + \zeta_{as} + \zeta_{l\arg}}{S_8^{'2}} \tag{47}$$

And R_{a8}, for phase-wound rotor where the resistance of coils rounded edges are neglected is:

$$R_{a8} = \frac{\zeta_{ing} + \zeta_{l\arg}}{S_8^{'2}} \tag{48}$$

At the transition from the rotor coils zone to the stator coils zone and the input under rounded edges a widening (or a narrowing) occurs $\left(\zeta_r = 12,5 \cdot 10^{-2} \right)$.

$$S_9^{'} = 0,9\pi D b_v \frac{n_v}{2} - z_1 b_{c1} b_v \frac{n_v}{2} \quad \left[m^2 \right] \tag{49}$$

Where:

- D is interior diameter of the stator, in m;
- z_1 is the number of slots of the stator;
- b_{c1} is the width of stator slots, in m.

For the rapport $\dfrac{S_8^{''}}{S_9^{'}}$ or $\dfrac{S_9^{'}}{S_8^{''}}$ (the lower section is used to the numerator) we determine ζ_{larg} or ζ_{ing}. For determining the resistance we put at the denominator the smallest section.

The resistance R_{a9} is obtained, taking into account the net surface in the stator coils zone S_9, the aerodynamic resistance coefficient to narrowing/widening ζ_{ing} /ζ_{larg} and the coefficient for the input under sharp edges ζ_r.

$$R_{a9} = \frac{\zeta_{l\arg(ing)} + \zeta_r}{S_{8(9)}^{"2}} \tag{50}$$

In the stator coils zone and to the output between coils, the net surface increases and a relaxation occur.

$$S_{10} = 0,9\pi\left(D + 2h_{cl}\right)b_v \frac{n_v}{2} \quad \left[m^2\right] \tag{51}$$

$$S_9^{'} = S_{10} - z_1 b_{c1} b_v \frac{n_v}{2} \quad \left[m^2\right] \tag{52}$$

Where:

-    h_{c1} is the height of the stator slot, in m.

For $\dfrac{S_9^{'}}{S_9^{"}} = ... \Rightarrow \zeta_{l\arg}^{'} = ...$; For $\dfrac{S_9^{"}}{S_{10}} = ... \Rightarrow \zeta_{l\arg}^{"} = ...$

The resistance R_{a10}, is calculated taking into account the net surface in the stator coils zone S_9 and the net surface to the output between coils S_{10}, the aerodynamic resistance coefficient to widening ζ_{larg} in both zones.

$$R_{a10} = \frac{\zeta_{l\arg}^{'}}{S_9^{'2}} + \frac{\zeta_{l\arg}^{"}}{S_9^{"2}} \tag{53}$$

To the exterior armature core disks in the radial channels of the stator a widening is produced, again, the surface S_{11} is bigger than the surface S_{10}.

$$S_{11} = 0,9\pi D_e b_v \frac{n_v}{2} \quad \left[m^2\right] \tag{54}$$

Where:

-    D_e is the exterior diameter of the stator core disk, in m.

For $\dfrac{S_{10}}{S_{11}} = ... \Rightarrow \zeta_{l\arg}^{'} = ...$

The result is R $_{a11}$:

$$R_{a11} = \frac{\zeta_{l\arg}}{S_{10}^2} \tag{55}$$

To the output of radial channels of the stator, the air suffers a relaxation again.

$$S_{12} = \pi D_e \frac{L_1}{2} \quad \left[m^2 \right]$$
(56)

Where:

- L_1 is the geometric length of the machine plus the thickness pressure rings, in m.

For $\dfrac{S_{11}}{S_{12}} = ... \Rightarrow \zeta_{l\arg} = ...$

Because there is a widening of ventilation channels to the output of the stator radial channels R_{a12} is calculated regarding the aerodynamic resistance coefficient to widening and S_{11}:

$$R_{a12} = \frac{\zeta_{l\arg}}{S_{11}^2}$$
(57)

10. Section III

The aerodynamic resistances R_{a13}, R_{a14}, R_{a15}, R_{a16}, R_{a17}, R_{a18} constitute the section III, they are serially connected. Taking into account the equation (28) the total aerodynamic resistance is calculated by the section III with equation:

$$R_{atrIII} = \sum_{i=13}^{18} R_{ai}$$
(58)

After the air got out of the stator radial channels, it will cross the rotor ends coils by deviation to 135° for which $\zeta_c = 32 \cdot 10^{-2}$ (figure 7 and figure 10).

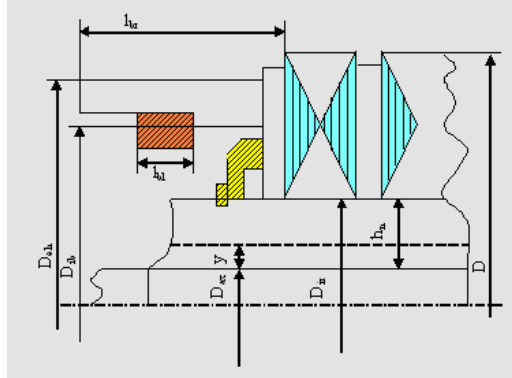$$S_{13} = \pi D_3 l_{br} \quad \left[m^2 \right]$$
(59)

Where:

- l_{br} is the axial length of the rotor coil end, in m.

Because there is no widening or narrowing, the resistance R_{a13} is calculated regarding the crossing surface to the rotor coil ends and the coefficient for rounded edges:

$$R_{a13} = \frac{\zeta_c}{S_{13}^2}$$
(60)

After that a narrowing to input follows between rotor bars ends and sharp edges. ζ_{as}= 62 x 10^{-2} for short-circuited rotors from bars with sharp edges. For the rotor with bars with rounded edges ζ_{as}=0.

Figure 10. Partial longitudinal section through a rotor cage induction motor with ribbed shafts and bars ends having a ventilator effect (the rotor from figure 7)

$$S_{14} = \pi D_3 \left(l_{br} - l_{bi} \right) - z_2 b_{r2} \left(l_{br} - l_{bi} \right) \quad \left[m^2 \right] \tag{61}$$

Where:

- l_{bi} is the shorting ring width, in m (figure 10)

For $\dfrac{S_{14}}{S_{13}} = ... \Rightarrow \zeta_{ing} = ...$

Resulting the resistance R_{a13} calculated using the net surface to the input between the rotor bars ends and the coefficients of aerodynamic resistances to narrowing under sharp edges:

$$R_{a14} = \frac{\zeta_{as} + \zeta_{ing}}{S_{14}^2} \quad or \quad R_{a14} = \frac{\zeta_{ing}}{S_{14}^2} \tag{62}$$

The isolated support of the bandages does not allow air to enter through the coils and as a result in the right front end, to winding motors only a narrowing occurs.

To the ends output (the bars) of the rotor coils there is a relaxation of the air, a relaxation caused by widening the channel (figure 7)

$$S_{15} = \pi D l_d \quad \left[m^2 \right] \tag{63}$$

For $\dfrac{S_{14}}{S_{15}} = ... \Rightarrow \zeta_{l \arg} = ...$

Is obtained:

$$R_{a15} = \frac{\zeta_{ing}}{S_{14}^2} \tag{64}$$

There is a passing through the spaces between the stator coils ends which can be of two types.

-    prefabricated coils
-    winding to the round conductor.

The prefabricated coils (from profiled conductor or bars) are represented in „figure 11".

We determine the surface S_{16} under the front part to which we consider the narrowing of the lower layer.
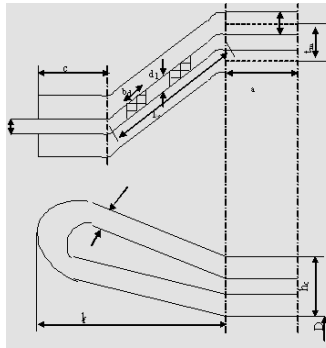
$$S_{16} = \pi D l_f \quad \left[m^2 \right]$$ (65)

We admit then, that the distances d_1 and k between coil ends, to lower part, are equal to those at the upper part (d_1 and k are constant on front ends height).

Narrowing at the lower layer (figure 11)

$$S'_{16} = \left[l_{bs} d_1 + \left(l_{mi} - b_c \right) a + kc - b_d d_1 n_d \right] z \quad \left[m^2 \right]$$ (66)

Where:
-    n_d is the number of distances between coil adjacent ends;
-    l_{mi} is the dental corresponding to the mean diameter of the coil lower side, in m.

Figure 11. End of prefabricated stator coil

For $\dfrac{S'_{16}}{S_{16}} = ... \Rightarrow \zeta_{ing} = ... $, and for rounded edges $\zeta_r = 12{,}5 \times 10^{-2}$

The resistance R'_{a16} is:

$$R'_{a16} = \frac{\zeta_r + \zeta_{ing}}{S'^2_{16}}$$ (67)

For the output relaxation from lower layer S''_{16} is:

$$S_{16}^{''} \approx \pi\left(D + h_{c1}\right)l_f \quad \left[m^2\right] \tag{68}$$

Where:

h_{c1} is height of stator slot, in m.

For $\dfrac{S_{16}^{'}}{S_{16}^{''}} = ... \Rightarrow \zeta_{l\arg} = ...$

We obtained:

$$R_{a16}^{''} = \frac{\zeta_{l\arg}}{S_{16}^{'2}} \tag{69}$$

Narrowing in the upper layer and the input under the slightly rounded edges.

$$S_{16}^{'''} \approx S_{16}^{'}; \quad \text{for} \quad \frac{S_{16}^{'}}{S_{16}^{''}} = ... \Rightarrow \zeta_{ing} = ...$$

For the slightly rounded edges from „table 3" $\zeta_r = 12{,}5 \times 10^{-2}$

The resistance $R^{'''}{}_{a16}$ is:

$$R_{a16}^{'''} = \frac{\zeta_r + \zeta_{ing}}{S_{16}^{'2}} \tag{70}$$

The total resistance to airflow between the ends of stator winding is the sum of calculated resistances for narrowing in the lower layer, the relaxation to the output from lower layer and the narrowing in the upper layer and the input under the slightly rounded edges:

$$R_{a16} = R_{a16}^{'} + R_{a16}^{''} + R_{a16}^{'''} \tag{71}$$

In the case of winding from round conductor (from wire), the air can not penetrate through the coil ends, because spaces between coils are obstructed of isolated strips between phases, so the air avoid them. The distance X between the end of stator coil and deflector, must be large enough not to exclude the air (figure 7.a)

The narrowing in the section X.

$$S_{16} \cong \pi\left(D + h_{c1}\right)X \left[m^2\right] \tag{72}$$

For $\dfrac{S_{16}}{S_{15}} = ... \Rightarrow \zeta_{ing} = ...$ and the resistance R_{a16} is:

$$R_{a16} = \frac{\zeta_{l\arg}}{S_{16}^{2}} \tag{73}$$

After passing by front ends of stator winding there is a relaxation of air after widening the ventilation channel.

$$S_{17} \approx \pi\left(D + 2h_{c1}\right)\left(l_f + X\right) \; \left[m^2\right] \tag{74}$$

For $\dfrac{S_{16}}{S_{17}} = ... \Rightarrow \zeta_{ing} = ...$ and aerodynamic resistance R_{a17} is:

$$R_{a17} = \frac{\zeta_{l\arg}}{S_{16}^2} \tag{75}$$

The air flows in a narrow channel between housing ribs to a deviation of 135° (ζ_c= 62 x 10^{-2}).

$$S_{18} = \pi D_c p - b_{nc} p n_{nc} \; \left[m^2\right] \tag{76}$$

Where:
- b_{nc} is the housing rib width, in m;
- n_{nc} is the number of the housing ribs;
- D_c, p (from figure 7.a) in m.

For $\dfrac{S_{18}}{S_{17}} = ... \Rightarrow \zeta_{ing} = ...$ and so:

$$R_{a18} = \frac{\zeta_c + \zeta_{as} + \zeta_{ing}}{S_{18}^2} \tag{77}$$

11. Section IV

The total resistance of section IV is calculated as in the other sections with the equation (26) for the series connection:

$$R_{atrIV} = \sum_{i=19}^{20} R_{ai} \tag{78}$$

A deviation at 90° occurs (ζ_c= 70 x 10^{-2}) to the output sided windows (figure 7.a) without the narrowing or widening of ventilation channels:

$$S_{19} = \frac{L_n B_n}{2} \; \left[m^2\right] \tag{79}$$

And the result is:

$$R_{a19} = \frac{\zeta_c}{S_{19}^2} \tag{80}$$

The output of the air from the housing is done to the deviation at 90°(ζ_c= 70 x 10⁻²) for the relaxation of the outside air (figure 7.a).

$$S_{20} = \frac{1}{2} L_p h_p k_i \quad \left[m^2 \right]$$

(81)

For this k_i we must take into account the calculation of R_{a1}.

For $\dfrac{S_{20}}{S_{ex}} \approx 0 \Rightarrow \zeta_{larg} = 60 \cdot 10^{-2}$ and so:

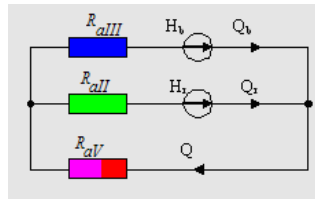$$R_{a20} = \frac{\zeta_c + \zeta_{larg}}{S_{20}^2}$$

(82)

In the scheme from „figure 7.b", H_b is the pressure produced by the ends of moving rotor bars, H_n is the pressure produced by rotor ribs, and H_d is the pressure produced by rotor spacers.

12. The calculation air flow

The calculation of air flow is done after we solved the ventilation scheme regarding the air flows of different sections and after we calculated the aerodynamic resistances values and pressures values created by sources.

Bilateral radial-axial ventilation for an electrical machine in protected construction

We calculate the flows for the asynchronous electrical machine with bilateral radial ventilation from „figure 7.a", the cooling air is driven only by the effect of ventilator of ends of rotor bars and of ribs and spacers on rotor.

Figure 12. Variation for the representation of scheme from figure 7.b

The flows Q_b, Q_r and Q by sections III, II, and V, respectively I and IV from „figure 7.b", are determined by equations:
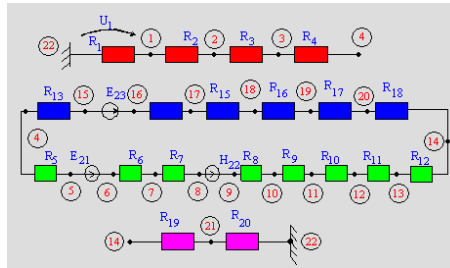
$$Q_b = \sqrt{y} \quad \left[m^3 / s \right]$$

(83)

$$Q_r = \frac{1}{\sqrt{R_{aII}}} \sqrt{R_{aIII} Q_b^2 - H_b + H_r} \quad \left[m^3 / s \right]$$

(84)

$$Q = Q_b + Q_r \tag{85}$$

When the flow which enters and exit from the machine is less than the flow calculated for half of the machine it is necessary to adopt a solution by decreasing the equivalent resistances on the sections by sections increasing, or giving up the constructive solution adopted and finding other solutions.

The example of calculation for asynchronous electrical machine with bilateral radial ventilation:

- We calculate the aerodynamic resistance on every section, starting from the nominal data.

Figure 13. The principal ventilation scheme of asynchronous electrical machine with bilateral radial ventilation

- Equivalent resistance by section I is: $R_{atrI} = \sum\limits_{i=1}^{4} R_{ai}$

- Equivalent resistance by section II is: $R_{atrII} = \sum\limits_{i=5}^{12} R_{ai}$

- Equivalent resistance by section III is: $R_{atrIII} = \sum\limits_{i=13}^{18} R_{ai}$

- Equivalent resistance by section IV is: $R_{atrIV} = \sum\limits_{i=19}^{20} R_{ai}$

By means of the computer program PANCIA (Program Analysis of Analog Circuits) we obtain the system solution. [7, 8, 9, 10]

• The unknowns of the system								
	V1	V2	V3	V4	V5	V6	V7	V8
V9	V10	V11	V12	V13	V14	V15	V16	V17
V18	V19	V20	V21	I21	I22	I23		
• The system of equations								
+ (+G1+G2)*V1 + (-G2)*V2 = 0								
+ (-G2)*V1 + (+G2+G3)*V2 + (-G3)*V3 = 0								

+ (-G3)*V2 + (+G3+G4)*V3 + (-G4)*V4 = 0
 + (-G4)*V3 + (+G4+G5+G13)*V4 + (-G5)*V5 + (-G13)*V15 = 0
 + (-G5)*V4 + (+G5)*V5 + (+1)*I21 = 0
+ (+G6)*V6 + (-G6)*V7 + (-1)*I21 = 0
+ (-G6)*V6 + (+G6+G7)*V7 + (-G7)*V8 = 0
+ (-G7)*V7 + (+G7)*V8 + (+1)*I22 = 0
 + (+G8)*V9 + (-G8)*V10 + (-1)*I22 = 0
+ (-G8)*V9 + (+G8+G9)*V10 + (-G9)*V11 = 0
+ (-G9)*V10 + (+G9+G10)*V11 + (-G10)*V12 = 0
+ (-G10)*V11 + (+G10+G11)*V12 + (-G11)*V13 = 0
 + (-G11)*V12 + (+G11+G12)*V13 + (-G12)*V14 = 0
 + (-G12)*V13 + (+G12+G18+G19)*V14 + (-G18)*V20 + (-G19)*V21 = 0
 + (-G13)*V4 + (+G13)*V15 + (+1)*I23 = 0
 + (+G14)*V16 + (-G14)*V17 + (-1)*I23 = 0
+ (-G14)*V16 + (+G14+G15)*V17 + (-G15)*V18 = 0
 + (-G15)*V17 + (+G15+G16)*V18 + (-G16)*V19 = 0
+ (-G16)*V18 + (+G16+G17)*V19 + (-G17)*V20 = 0
+ (-G18)*V14 + (-G17)*V19 + (+G17+G18)*V20 = 0
+ (-G19)*V14 + (+G19+G20)*V21 = 0
+ (+1)*V5 + (-1)*V6 = -E21
+ (+1)*V8 + (-1)*V9 = -E22
+ (+1)*V15 + (-1)*V16 = -E23

• Potential at nodes	• Currents and voltages sides	
V1=-31.752799	U1=31.752799	I1=0.365521
V2=-43.259396	U2=11.506597	I2=0.365521
V3=-57.299053	U3=14.039657	I3=0.365521
V4=-58.125131	U4=0.826077	I4=0.365521
V5=-335.922113	U5=277.796983	I5=0.108940
V6=864.077887	U6=533.914906	I6=0.108940
V7=330.162981	U7=36.309700	I7=0.108940
V8=293.853281	U8=36.309700	I8=0.108940
V9=2393.853281	U9=164.468886	I9=0.108940
V10=2357.543581	U10=721.801534	I10=0.108940
V11=2193.074695	U11=1.873768	I11=0.108940
V12=1471.273161	U12=43.867956	I12=0.108940
V13=1469.399393	U13=0.726124	I13=0.256581
V14=1425.531437	U14=1.424024	I14=0.256581
V15=-58.851254	U15=0.251449	I15=0.256581
V16=1441.148746	U16=11.463264	I16=0.256581
V17=1439.724722	U17=0.130856	I17=0.256581
V18=1439.473272	U18=2.347715	I18=0.256581
V19=1428.010008	U19=511.729234	I19=0.365521
V20=1427.879152	U20=913.802203	I20=0.365521
V21=913.802203	U21=-1200.000000	I21=0.108940
V22=0	U22=-2100.000000	I22=0.108940
	U23=-1500.000000	I23=0.256581

• Balance of powers	• Nodal analysis results
- The power generated: 744.373309	V1 = -31.752799
- The power consumption: 744.373309	V2 = -43.259396
	V3 = -57.299053
	V4 = -58.125131
	V5 = -335.922113
	V6 = 864.077887
	V7 = 330.162981
	V8 = 293.853281
	V9 = 2393.853281
	V10 = 2357.543581
	V11 = 2193.074695
	V12 = 1471.273161
	V13 = 1469.399393
	V14 = 1425.531437
	V15 = -58.851254
	V16 = 1441.148746
	V17 = 1439.724722
	V18 = 1439.473272
	V19 = 1428.010008
	V20 = 1427.879152
	V21 = 913.802203
	I21 = 0.108940
	I22 = 0.108940
	I23 = 0.256581

PANCIA is based on the modified nodal method (MNM) which is, due to its flexibility, the most used and the most efficient method of simulating the electrical circuits on computer. [7, 8] The system of the equations that describes the equivalent circuit as ventilation scheme is a nonlinear algebraic system because the constants of pressure have the expressions:

$$\Delta H_K = R_{aK} Q_K^2 \quad \left(U_K = R_K I_K^2 \right)$$

For every nonlinear resistance, we considered the linear section of the characteristic U-I, so the circuit obtained is a linear resistive circuit.

In the example given, we found that the method used is good for calculating the ventilation systems of different types of electrical machines.

13. The thermal calculation. The heat transfer

Our thermal model is based on the analyses of the characteristic circuit providing almost instant calculation speeds. This allows the user to perform any calculation on time. Alternative numerical methods, for example, the analysis of finite elements [FEA] and

calculable dynamic fluids [CFD], normally require some days/weeks to put together a three-dimensional model. The numeric mode may then take some hours (days for a complex problem of transit) to calculate a solution. [13]

The characteristic diagram (the characteristic circuit) is like an electrical scheme:

- The thermal resistance instead the electrical resistance
- Sources of power instead of current sources
- Thermal capacity instead electrical capacity
- Nodal temperatures instead voltages
- Power flow through the resistance instead the current.

All thermal resistances and thermal capacity from the model Motor-CAD are automatically calculated from geometric dimensions and materials properties. The user must be familiar with complex phenomena of heat transfer such as the dimensional analysis of conversion. Motor-CAD automatically selects and solves most appropriate formulation for a given surface and selected cooling time. Motor-CAD configures efficient, precise and robust mathematical algorithms for forced and natural convection, for cooling liquid, for radiation and conduction. A vast library of lamination correlations and demonstrated turbulent convections is used to give precise models for all internal and external surfaces. The air gap model includes laminar, vortex and turbulent convection.

The calculation in stationary regime

Motor-CAD simplifies the analyses of output dates of the stationary regime by using schematic diagrams, simple and easy to read. [13]

In "figure 14" we observe the solved main scheme. This scheme is used very much by post processing calculation in stationary regime. The resistances and the power sources indicated in scheme are color coded as machine components shown in editors of cross sections. The vertically oriented resistances represent radial heat transfer and horizontally oriented resistances represent axial heat transfer. The resistances which contain the letter "C" are resistances of convection and resistances which contain the letter "R" are resistances of radiation. Two colors resistances represent interface resistances between two components.

The diagram also shows labels for each of its components (resistances and nodes). With a single click of a button the user can change the scheme to indicate the nodal temperature and the thermal resistance or power values, so will avoid elaborate images. The main scheme is very useful for visualizing the place where there may be restrictions on the heat transfer and what can be done to improve cooling.

The calculation in transient regime

The Motor-CAD software allows the thermal transition of the motor to be calculated and the outputs to be viewed in graphical format. The opposite graph shows how the test data is important to emphasize on the precision of calculation. Also, Motor-CAD includes facility analyses of the operation cycle. A major advantage of this is that it allows the motor to be directed to its full potential without overheating.
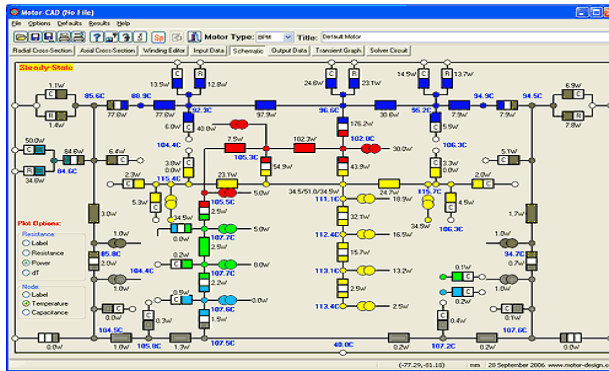
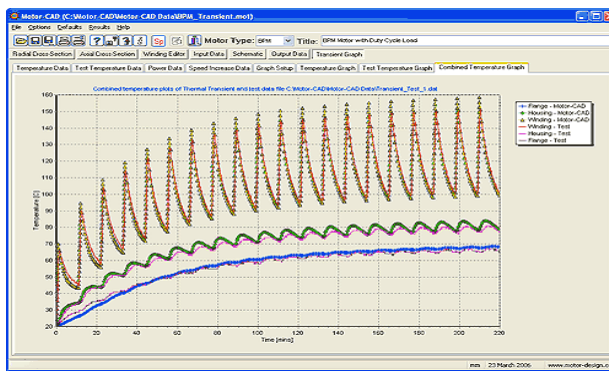**Figure 14.** The main scheme (modeling by the characteristic circuit)

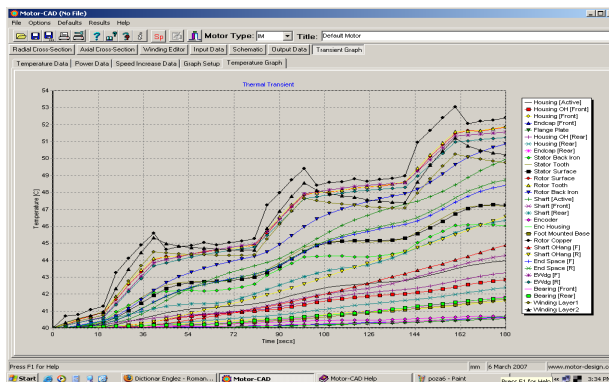**Figure 15.** The variation in transient regime

Figure 16. The variation in transient regime on temperature in diverse points in time of the machine

The transient regime can be modeled, so in any case the thermal capacities are automatically added to circuit. It is essential to consider the transient thermal analysis when using operational complex loads if the motor will be used to its full potential. The graph below

shows a typical transient regime. In this case we have a repetitive duty cycle (three overloads followed by half loads).

The Motor-CAD software incorporates mathematical efficient and suitable algorithms for the cooling methods. All these, and facility of prescribe miscalculation, if is necessary, provides customization calculations so as to suit the unique construction methods.

14. Conclusions

Determining or providing the amount of exchanged heat per unit in time in given conditions of temperature is a problem to be taken into account for calculating heating and ventilation for the electrical machines. Were presented the basic sizes of the heat transfer studied in the literature and the distinct forms of heat transfer, the conduction, the radiation and the convection, the basic equations and rules of conduction, radiation and convection. Between the thermal sizes and the electrical sizes we showed a correspondence using the method of thermal resistances and concentrated losses.

By analogy between a network of cooling ventilation and a nonlinear resistive circuits were determined the values of the cooling fluid flows of an electrical machine.

Also by analogy, the temperature drop in the mass or on the surface of an object, corresponding the caloric flow (or loses), was determined by the product between the thermal resistance of the object opposed to the caloric flow in the mass or on surface and loses.

Solving the thermal schemes, were done analogous with solving the electrical schemes, as in electrical circuits of conexions between thermal resistances are series, parallel or mixed.

As we said the exhaust heat from the electric machine is as important as and phenomena related to the proper functioning of the machine. Choosing the most appropriate ventilation is done even by the assignation of electromagnetic stresses.

Were showed the equivalent resistances,and the aerodynamic schemes used were solved according to the conexions between aerodynamic resistances (series, parallel or mixed).

The discussed example for axial-radial bilateral ventilation in an electrical machine under protected construction for which the air circulation is symmetrical towards the mid of machine and it is sufficient to calculate ventilation only for one part, which is half of the machine.

After calculating the aerodynamic resistances, were calculated the pressures and air flows using the computer program PACEN (Program of Analysis of Nonlinear Electrical Circuits), and were obtained the system solutions.

Motor-CAD is an example for the analytical analysis of the characteristic circuit, is a program dedicated to electrical motors and generators and has all the indications on limiting design effort.

Motor-CAD has some advantages over CFD:

- The problem of defining time (minutes to hours/days/weeks)
- The calculating rate (instantly to hours/days)
- The postprocesing time (instantly to hours)
- Easy to use.

Motor-CAD allows optimization of the cooling system and identifies vulnerable points of design and/or problems of fabrication; it checks if a provided motor is suitable for a particular application.

The final conclusion for using Motor-CAD is that the program is a quick method designing for motors and electrical generators of thermal point of view, taking into account the fact that the thermal analogous circuit of the electrical machines is as important as designing the electromagnetical, mechanical.

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