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Review of the Analytical Flow Model to Predict the Hydraulic Behaviour in Electrical Machine

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***Abstract*—This paper considers the analytical flow analysis for the through-flow ventilated electrical machine to predict the airflow rate in the different sections of the machine. This method can be applied to other types of air forced cooling electrical machine. For these purposes, the airflow paths are modeled by flow resistance network. The developing of the flow resistance network and calculating the flow resistances are described in details.**

Keywords—Analytical model, electrical machine, flow network analysis, hydraulic resistances, minor loss factor

I. INTRODUCTION

Nowadays, electrical machines are manufactured by higher power density and compact structure. Accordingly, selecting the proper cooling method has a significant impact on the design process that the machine enhances its desired power density, torque, and reliable performance.

The heat is transferred in an electrical machine by three mechanisms: conduction, convection, and radiation [1]. The majority of the heat is transferred by the convection phenomenon [2]. Accordingly, the designers try to find the proper cooling method to increase the convection phenomenon. During the thermal design of an electrical machine, the most challenging part to consider the amount of the heat dissipated from the machine is calculating the convection heat transfer coefficient from machine surface [3]. In the air forced cooling method, this coefficient mainly depends on airflow speed.

The airflow speed in the different sections of a through-ventilated machine can be calculated by two different methods: analytical flow network analysis and numerical computational fluid dynamic (CFD) [4]. The hydraulic circuit method is the 1D analytical method which models the various flow paths of the machine [5]. This method is the fast calculation method with acceptable accuracy [4]. However, the CFD method is the most precise method in flow speed calculation, but it has a high setup and computational time [4].

This study considers the hydraulic flow network analysis to calculate the airflow speed in different parts of the machine. For this purpose, the different hydraulic resistances for the flow analysis are described. Besides, it proposed the different empirical correlations to calculate the minor loss factor for the various conditions of the flow paths.

II. THE CONCEPT OF FLOW NETWORK ANALYSIS

The hydraulic behavior of the cooling system is described by Bernoulli's principle [3], [6]. Accordingly, in the ideal condition (in the absence of energy losses) this principle is described by below correlation [6], [7]:

$$P_1 + \frac{\rho {v_1}^2}{2} + \gamma Z_1 = P_2 + \frac{\rho {v_2}^2}{2} + \gamma Z_2 \,, \qquad (1)$$

where ρ is the density of the fluid (air) [kg/m^3], γ specific weight of fluid [N/m^3], P_1 and P_2 are the pressure at the inlet and outlet respectively [Pa], v_1 and v_2 are the inlet and outlet speeds [m/s], respectively, and Z_1 and Z_2 are the inlet and outlet height [m], respectively.

To the get a correct overview of the hydraulic behavior of the system, another factor is added to the outlet part of the Bernoulli's equation to account the energy losses eventuating frictional and separation effect [3], [6]. The frictional effect is related to the fluid friction at the duct wall and the separation effect due to changes in cross-section area of the flow path as well as in the direction of fluid, junction and interaction with other fluid paths [3], [6].

$$P_1 + \frac{\rho {v_1}^2}{2} + \gamma Z_1 = P_2 + \frac{\rho {v_2}^2}{2} + \gamma Z_2 + \sum \Delta P_{losses}, \qquad (2)$$

To reduce the complexity of the machine correlation, two hypotheses are applied; first, air density is presumed constant and equal to the average value [3], [6]. Moreover, the height of the inlet and outlet grills are equal [3], [6]. Accordingly, the Bernoulli's correlation is converted to [3], [6]:

$$P_1 + \frac{\rho {v_1}^2}{2} = P_2 + \frac{\rho {v_2}^2}{2} + \sum \Delta P_{losses}, \qquad (3)$$

In the general form, the energy losses are calculated by the empirical loss coefficient based on the kinetic energy as [3], [6], [8] :

$$\Delta P_{losses} = k\frac{\rho v^2}{2} = k\frac{\rho Q^2}{2A^2} = R_h Q^2, \qquad (4)$$

where k is minor loss factor (dimensionless hydraulic resistance), Q is the volume of the flow [m^3/s], A is the area of the flow section [m^2], and R_h is the hydraulic resistance [kg/m^7].

There are two types of hydraulic resistance: the hydraulic resistance due to changing the flow condition and the second one is due to fluid friction [8]. The hydraulic resistance due to the changing flow condition is divided into three main categories: contraction resistance, expansion resistance, and bends resistance [6].

III. MINOR LOSS FACTOR

According to (4), the hydraulic resistance is defined as [7], [8]:

$$R_h = \frac{k\rho}{2A^2}\,. \qquad (5)$$

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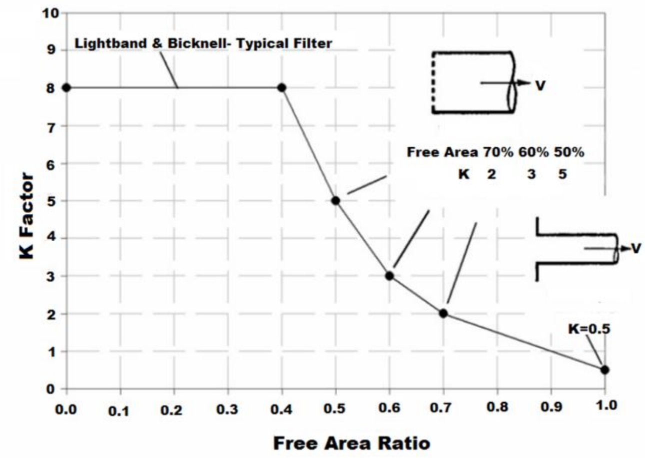
Accordingly, the most critical parameter in the calculation of hydraulic resistance is the minor loss factor [8], [9]. The minor loss factor is defined according to the flow path condition. Typically, the flow resistances in the flow network model of a through-ventilated machine are divided into six various categories and calculated by the experimental and empirical correlations. The flow resistances are as follows:

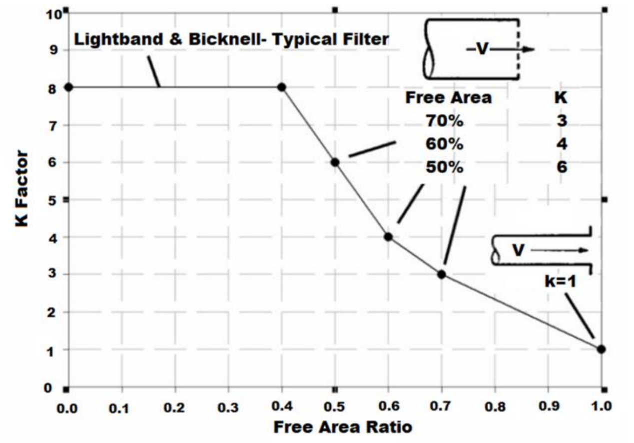
1 – inlet grill, 2 – outlet grill, 3 – expansion,
4 – contraction, 5 – bend, 6 – straight length [6], [8].

A. Inlet and Outlet Grill

These resistances are defined to model the effect of the inlet and outlet cover on the pressure drop of a model. Fig. 1 provides the value of k for different modes. In these pictures, arrows show which area should be used in the flow resistance calculation [8], [9].



a)



b)

Fig. 1. Minor loss factor for a) inlet grill and b) outlet grill [8].

B. Sudden Expansion and Contraction

The sudden expansion and contraction are divided into two main groups: the stationery and the rotational minor loss factors [4].

The minor loss factor for the sudden expansion (k_{se}) and contraction (k_{sc}) in the stationary condition are calculated respectively as follow [10]:

$$k_{se} = (1 - \frac{A_i}{A_o})^2, \tag{6}$$

$$k_{sc} = 0.5(1 - \frac{A_o}{A_i})^{0.75}, \tag{7}$$

where A_i and A_o [m^2] are inlet and outlet cross-section areas respectively.

Whereas minor loss factor for the contraction in the entrance of air gap k_{ag} is calculated as [4], [10]:

$$k_{ag} = \begin{cases} 0.1(\frac{V_r}{U})^2 - 0.06(\frac{V_r}{U}) & \frac{V_r}{U} > 1 \\ 0 & \frac{V_r}{U} \leq 1 \end{cases}, \tag{8}$$

where V_r is the rotor rotational speed [m/s] and U is the axial flow speed [m/s].

The minor loss factor for the contraction in the entrance of rotor axial ducts k_r is calculated as [4], [10]:

$$k_r = \begin{cases} 0.234(\frac{V_r}{U})^2 - 0.043(\frac{V_r}{U}) & \frac{V_r}{U} > 0.5 \\ 0 & \frac{V_r}{U} \leq 0.5 \end{cases}, \tag{9}$$

Besides, another way for determining the minor loss factor for contraction in the entrance of the rotor axial cooling duct is present by Taylor as follow [6], [8]:

$$k_r = k_{sc}\frac{U^2 + V_r^2}{U^2}, \tag{10}$$

C. Bend

To calculate the minor loss factor, mainly, the worst case of right angle bend is presumed; in this manner, the minor loss factor equals one [8], [9]. Further, the area for the calculation of the hydraulic resistance equals the average area at each end of a bend [8], [9]. Fig. 2 shows the value of the minor loss factor for other angles of bends.

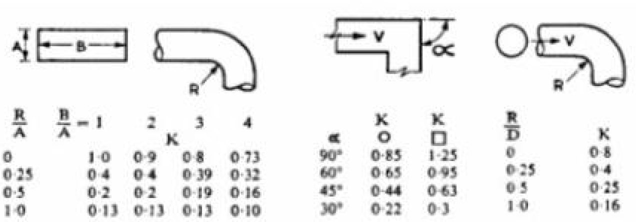


Fig. 2. Minor loss factor for various bends [8], [9].

D. Straight Length

This section focuses on the hydraulic resistance and the minor loss factor calculation for the passing flow through the circular, rectangular or annular paths due to the flow friction with a surface. There are several empirical correlations for the minor loss calculation based on different studies that they are presented hereafter.

Approximate minor loss factor for short ducts such as radial cooling duct in stator and rotor are as [9]:

$$k_f = \begin{cases} 0.02\frac{L}{D} & \text{for circularsection} \\ 0.01\frac{A+B}{AB}L & \text{for rectangular section} \\ 0.01\frac{Perimeter}{Area}L & \text{for other section} \end{cases}, \tag{11}$$

where L is the length of duct [m], D is the diameter of the duct [m], A and B are the length and width of the rectangular section [m].

The minor loss factor for the friction between the flow and the surface of the axial cooling duct between the stator lamination and the housing is calculated as [10]:

$$k_f = f_s \frac{L}{D}, \tag{12}$$

where f_s is the stationary friction factor and depends on the flow mode laminar or turbulent. However, the turbulent one is mostly applied during the calculation. This factor presents it by Reynold number (Re) as follow [10]:

$$f_s = \begin{cases} \frac{64}{\text{Re}} & \text{Re} < 2300 \\ \frac{0.316}{\text{Re}^{0.25}} & 4000 < \text{Re} < 10000 \end{cases}. \tag{13}$$

The minor loss factor for the rotating section of the machine is defined as [10]:

$$k_f = f_r \frac{L}{D}, \tag{14}$$

where f_r is the rotating friction.

The amount of the rotation friction factor for the air gap is calculated as [10]:

$$f_r = f_s\left(1 + \left(\frac{7\text{Re}_r}{16\ \text{Re}}\right)^2\right)^{0.38}, \tag{15}$$

where Re_r is the rotational Reynold number

The rotation friction factor for the rotor ducts is determined as follow[10]:

$$f_r = \begin{cases} f_s\left(0.5\text{Re}_r{}^{0.16}\text{Re}^{-0.03}\right) & 900 < \text{Re} < 9880 \\ f_s\left(0.842\text{Re}_r{}^{0.023}\text{Re}^{0.002}\right) & \text{Re} > 9880 \end{cases}. \tag{16}$$

IV. Flow Network Analysis

The analytical flow network consists of a combination of the series and parallel circuits, which capture the airflow paths of the machine [3]. According to Table I, the flow network circuit is analogous to the electrical circuit [3]. Consequently, the nodal pressure is akin to voltage, the airflow rate is analogous to the current, and the hydraulic resistances are analogous to electrical resistances [3]. However, the only difference between the electric circuit and the hydraulic circuit is the relation between the voltage and current and pressure and airflow rate [3], [8]. According to the Ohm's law, the voltage and current have a linear relation, while according to (4) due to the turbulent nature of the flow the relationship between pressure and rate is not linear [3], [8].

TABLE I. Analogous Hydraulic and Electrical Quantities

Hydraulic resistances	Electric circuit
Pressure (*P*)	Voltage (*V*)
Airflow (*Q*)	Current (*I*)
Hydraulic resistance (R_h)	Electric resistance (*R*)

Fig. 3 provide the flow distribution inside through ventilated machine. The ventilation system of the electrical machines consists of two main parallel paths, the axial cooling duct between the stator and housing and one is the machine air gap. Besides, there are four radial cooling ducts located in the stator part. Table II provides the condition of the airflow during passing inside the machine.

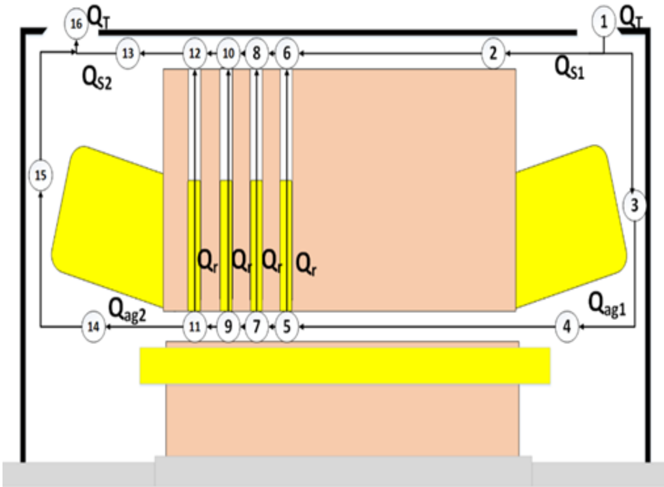


Fig. 3. The airflow distribution inside the through ventilated machine.

Fig. 4 illustrates the hydraulic flow network of the through-ventilated machine presented in Fig. 3. Accordingly, the most important parameters in the hydraulic network circuit are the hydraulic resistances, which are calculated according to the condition of the airflow presented in Table II.

TABLE II. Different Flow Condition in the Machine

Node number	Kind of resistance
1	Inlet grid and sudden expansion
1 to 2	Bending 90°and sudden contraction
1 to 3	Sudden contraction
3 to 4	Bending 90°and sudden expansion
4 to 5	Sudden contraction and straight length
5 to 6	Bending 90°, sudden contraction, and straight length
6 to 8	Bending 90°, sudden expansion, and straight length
5 to 7	Straight length
7 to 8	Bending 90°, sudden contraction, and straight length
8 to 10	Bending 90°, sudden expansion, and straight length
7 to 9	Straight length
9 to 10	Bending 90°, sudden contraction, and straight length
10 to 12	Bending 90°, sudden expansion, and straight length
9 to 11	Straight length
11 to 12	Bending 90°, sudden contraction, straight length, and sudden expansion
12 to 13	Bending 90°, sudden expansion, and straight length
11 to 14	Straight length and sudden expansion
14 to 15	Bending and sudden contraction
13 to 16	Contraction and bending
15 to 16	Expansion
16	Outlet grid and sudden expansion

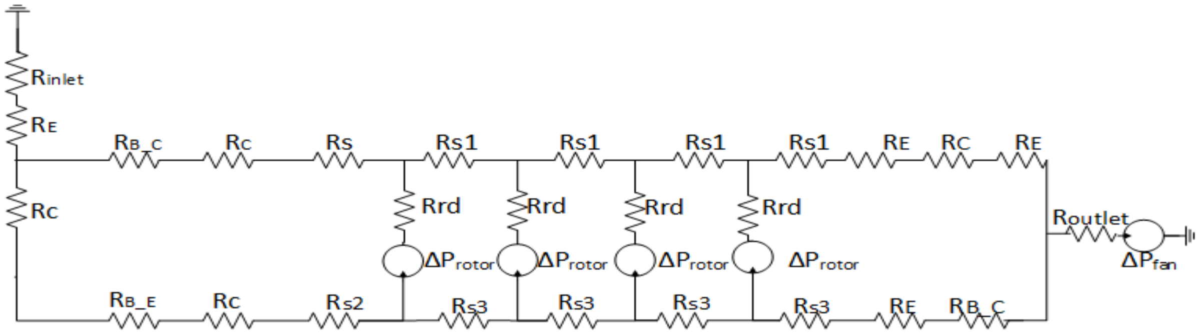


Fig. 4. Hydraulic circuit.

According to Fig. 4, there are two-pressure generators in the hydraulic circuit; the pressure rise due to a fan (ΔP_{fan}) and the pressure rise due to the rotor rotational speed (ΔP_{rotor}). The value of ΔP_{fan} is evaluated according to the fan characteristic, which is the function of pressure versus volume of airflow rate. The fan characteristic can be calculated or measured. The fan characteristic can be calculated by using analytical calculation or numerical CFD method [6], [8].

On the other hand, the value of the rotor pressure generation is applied to the model at the entrance of the radial cooling ducts to implement the effect of the rotor rotation speed. This value is calculated as [6]:

$$\Delta P_{rotor} = \frac{1}{2} k_{rotor} \rho V_r^2, \tag{17}$$

where k_{rotor} is evaluated by the CFD method.

Some of the hydraulic resistances are calculated by using the Reynold number (Re). Forasmuch as this parameter is directly proportional to the airflow rate, the hydraulic flow network is solved by using the iterative method (Fig. 5) [3], [7]. Accordingly, in the first iteration step the flow network solve by the presumed value of the speed and in the following, the iteration steps will be continued until reaching to the arbitrarily defined accuracy [3], [7]. As the flow network circuit is analogous to the electric circuit, the flow network circuit can be solved by Kirchhoff low. However, the relation between the pressure and flow rate is not linear and the equations of the flow network models appear in the second order form [3], [7]. For this case, the equations are iteratively solved by using Newton-Raphson method [3], [7].

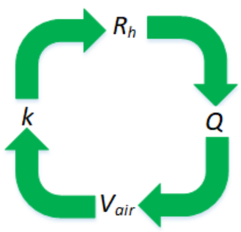


Fig. 5. The iteration loop to find the correct value of the hydraulic resistance.

V. CONCLUSION

This paper focused on determining the airflow speed in different parts of the through-ventilated electrical machine by using analytical flow network analysis. For this purpose, different hydraulic resistances have been described. The minor loss factor which is the most important parameter in the calculation of the hydraulic resistance has been described in details. Furthermore, the different empirical correlations have been proposed to determine the minor loss factor in different flow condition.

In following, the flow network circuit has been developed for a through-ventilated machine and the calculation method of the flow model based on the iteration method has been described.

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