Evaluation of Radiation Thermal Resistances in Industrial Motors

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***Abstract*—This paper deals with the role of the radiation thermal resistances in industrial motors and describes a test set useful for the resistance evaluation. The test set is based on a vacuum chamber and on a numerical acquisition system, and the resistances are obtained by monitoring motor temperatures during a heating test. An analytical model that describes how the radiation resistance depends on the motor temperature is also provided. Experimental results obtained on a totally enclosed fan-cooled 150-W induction motor are shown and discussed.**

***Index Terms*—Induction motors, thermal analysis and models, thermal radiation phenomena.**

I. Introduction

Nowadays, there is a growing interest in the electrical machine thermal analysis because a correct thermal design allows significant improvements to be obtained in the overall motor performance. As a consequence, accurate and reliable motor thermal models are nowadays an important tool for electrical motor design.

In this field, one of the more discussed problems is the role that radiation heat transfers have in electrical motors because literature lacks of experimental results concerning the measurement of motor radiation resistances. Radiation phenomena occur both inside and outside the motor, but are difficult to be analytically quantified because motor frames and windings are complex geometrical structures whose emissivities are often known with large uncertainties.

Moreover, radiation heat transfers almost always occur in parallel with natural and forced convection heat transfers; thus, it is also complex to separate the two contributions.

For these reasons, thermal models are frequently based on the assumption that the highest temperatures involved in the motor frame are not high enough for getting radiation significant. Although this is true when the motor is cooled with a fan (e.g., in totally enclosed fan-cooled (TEFC) motors), it could not be correct when the fan is not used or at very low motor speeds (e.g., in TEFC motors used in variable-speed drives).

The aim of this paper is to analyze and experimentally quantify the thermal exchanges by radiation that occurs in industrial motors in order to quantify the radiation contribution in the overall thermal exchange.

Radiation phenomena occur both inside and outside the motor. First, the heat exchange that involves the motor housing is taken into account, and a test set useful for the evaluation of the housing radiation resistance is proposed and described. Afterward, the paper is focused on the radiation phenomena inside the motor, and a procedure for the estimation of the radiation-related resistances is described.

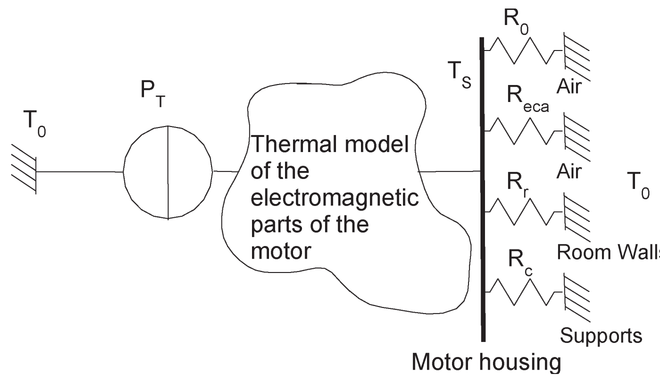

Fig. 1. Simplified motor thermal model.

II. Radiation Thermal Exchange Between Housing and Ambient

From a theoretical point of view, the analysis of the thermal behavior of a motor requires the knowledge of the thermal resistances related to the heat exchanges that occur inside and outside the motor [1], [2]. In particular, the total heat amount P_T that the motor transfers to the surrounding environment is the result of three physical processes, namely: 1) forced and natural convection; 2) conduction; and 3) radiation. Fig. 1 shows the simplified thermal model that can be used to take the effect of each process into account by means of four lumped, but nonconstant, resistances.

In the model of Fig. 1, the air, the motor support, and the room wall temperatures are equal to the air temperature T_0.

Resistances R_0 and $R_{\mathrm{ec-a}}$ are related to natural and forced convection phenomena, whereas resistances R_r and R_c are responsible for the heat transfer due to radiation and conduction.

Paper IPCSD-06-021, presented at the 2005 IEEE International Electric Machines and Drives Conference, San Antonio, TX, May 15–18, and approved for publication in the IEEE Transactions on Industry Applications by the Electric Machines Committee of the IEEE Industry Applications Society. Manuscript submitted for review November 2, 2005 and released for publication March 1, 2006.

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Digital Object Identifier 10.1109/TIA.2006.873655

Resistances R_0 and $R_{\mathrm{ec-a}}$ can be obtained by means of simple temperature measurements [10]. Inasmuch as R_c is depending on the mounting conditions, it is here not taken into account for simplicity reasons.

The radiation resistance R_r depends both on the geometrical and thermal characteristics of the motor and on the characteristics of the room where the motor is working. This resistance is often neglected because, when the motor is running at its nominal speed, the forced convection is the main responsible of the motor cooling, so that the radiation resistance R_r is much higher than the forced convection resistance $R_{\mathrm{ec-a}}$. However, in some situations, in particular when TEFC motors are used in variable speed drives, the radiation resistance can play a not negligible role at low speed, and an estimation of this resistance has to be done. Obviously, this consideration is also true in motors without ventilation such as machines designed for axis drives. Making reference to the model of Fig. 1, the measurement of the radiation resistance can be easily obtained from the measurements of the power P_T and of the motor and wall temperatures T_s and T_w, when the resistances R_0, $R_{\mathrm{ec-a}}$, and R_c are much greater than the radiation resistance R_r. This condition can be obtained by suspending the motor under test inside a vacuum chamber, so that both the convection and the conduction heat-transfer processes are negligible. If the motor is heated trough its stator winding with a power P_T, the radiating resistance R_r can be evaluated as

$$R_r = \frac{T_s - T_w}{P_T} \tag{1}$$

where T_w is the chamber wall temperature and T_s is the motor housing temperature measured after the thermal transient and considered uniform on the respective surfaces.

It is evident that the thermal resistance R_r is strictly dependent on the test conditions (the temperatures T_s and T_w and the chamber geometrical and thermal characteristics). Therefore, the measured resistance cannot be employed as a constant into the model of Fig. 1 when the motor works outside the chamber with different temperatures. In this case, the radiation resistance can be approximately estimated as described in the following.

The total radiation heat transferred from the motor to the surrounding ambient is the difference between the emitted and the absorbed heat [6]. When the motor is working in rooms where the surface walls have a much more extended area with respect to the housing surface, it is possible to approximate the room as a blackbody. The total radiant heat can, therefore, be written as

$$P_T = A\sigma\varepsilon\left(T_s^4 - T_w^4\right) \tag{2}$$

where

- σ Stefan–Boltzmann constant, 5.67×10^{-8} $(\mathrm{W/m^2/K^4})$;
- T_w absolute temperature of the wall (K);
- T_s temperature of the motor housing;
- ε apparent [7] emissivity coefficient of the motor surface;
- A motor surface area $(\mathrm{m^2})$;
- P_T active power absorbed by the motor during steady thermal conditions.

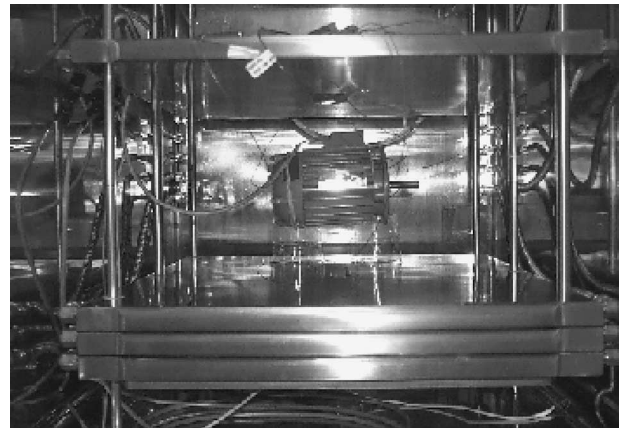

Fig. 2. Motor during the test inside the vacuum chamber.

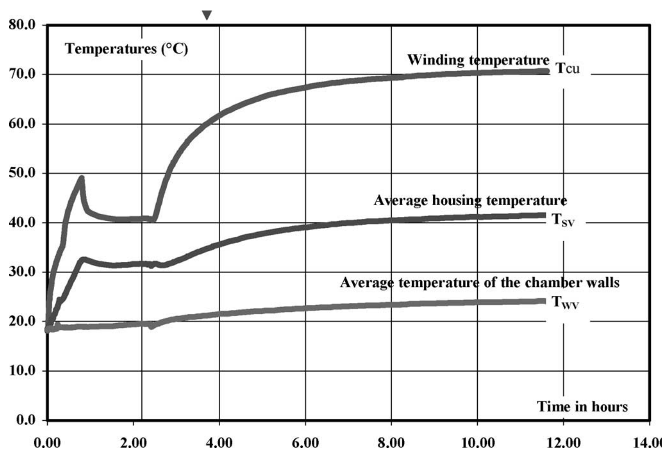

Fig. 3. Chamber-wall- and motor-related temperatures measured during the thermal test in vacuum conditions.

Equation (2) can be employed to evaluate the radiation thermal resistance when the walls and/or the motor temperatures are slightly different from the test ones. When the motor temperature and the wall temperatures are T_s' and T_w', the radiation resistance can be obtained from (1) and (2) as

$$R_r' = R_r \frac{T_s' - T_w'}{T_s - T_w} \frac{T_s^4 - T_w^4}{T_s'^4 - T_w'^4}. \tag{3}$$

III. Experimental Results

An induction motor was tested with the proposed test set, and the thermal resistances R_0 and R_r were measured. The motor under test is a 380/220-V TEFC induction motor employed to drive a cooling fan of a spindle dc motor; rated power and rotor speed are 150 W and 2800 r/min, respectively. The motor was hanged in a vacuum chamber, which is normally employed for lyophilization processes, over two thin plastic wires to make the conduction thermal exchange negligible. A programmable power supply and a power control system were employed to supply the motor with a dc constant power $P_T = 7 \pm 0.1$ W during the test.

Temperatures of motor and chamber walls were measured and acquired by means of seven thermocouples connected to an automatic data acquisition system. Fig. 2 shows the arranged

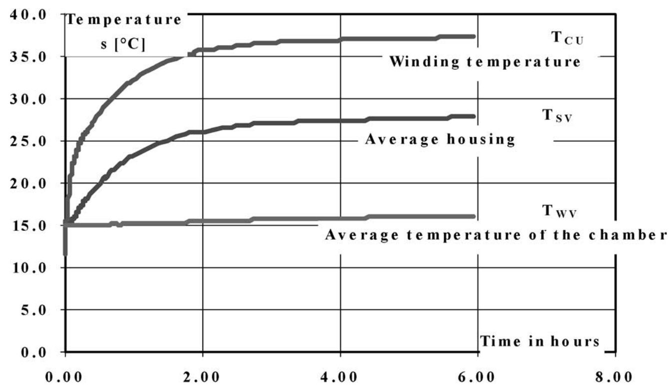

Fig. 4. Chamber-wall- and motor-related temperatures measured during the test performed in air.

test set. The measured temperatures are shown in Fig. 3 along with the winding temperature T_{cu} that was indirectly measured from the winding resistance.

The motor was firstly preheated in the air to speed up the test duration, and after about 2 h from the beginning of the test, the vacuum pump was turned on so that the pressure inside the chamber went down below 1 Pa. At the end of the thermal transient (about 8 h), the housing and wall temperatures were $T_{\text{sv}} = 41.5 \pm 0.5$ °C and $T_{\text{wv}} = 24.1 \pm 0.5$ °C, respectively.

The measured radiation resistance is, therefore,

$$R_r = \frac{T_{\text{sv}} - T_{\text{wv}}}{P_T} = 2.5 \pm 0.2 \text{ K/W}. \tag{4}$$

The natural convection resistance was also measured in the same chamber with the motor in the same position but in the presence of air. Fig. 4 shows the temperatures of the motor housing and air recorded when the motor heating power was $P_T = 7 \pm 0.1$ W. At the end of the thermal transient, after about 5 h, the housing and wall temperatures were $T_{\text{sa}} = 27.8 \pm 0.5$ °C and $T_{\text{wa}} = 16.2 \pm 0.5$ °C, respectively. In this condition, the equivalent thermal resistance is computed by

$$R_{\text{eq}} = \frac{T_{\text{sa}} - T_{\text{wa}}}{P_T} = 1.7 \pm 0.2 \text{ K/W} \tag{5}$$

where R_{eq} is the parallel between the natural convection resistance R_0 and the radiating resistance R'_r at the temperatures $(T_{\text{sa}}, T_{\text{wa}})$. The natural convection resistance R_0 of the motor can be therefore obtained if the radiation resistance at the temperatures $(T_{\text{sa}}, T_{\text{wa}})$ is known. The corrected radiation resistance R'_r can be obtained from R_r with (3) as shown in (6)

$$R'_r = R_r \frac{T_{\text{sa}} - T_{\text{wa}}}{T_{\text{sv}} - T_{\text{wv}}} \frac{T_{\text{sv}}^4 - T_{\text{wv}}^4}{T_{\text{sa}}^4 - T_{\text{wa}}^4} = 2.8 \pm 0.2 \text{ K/W} \tag{6}$$

and it is thus possible to obtain the natural convection resistance by (7)

$$R_0 = \frac{R_{\text{eq}} R'_r}{R'_r - R_{\text{eq}}} = 4.1 \pm 1.3 \text{ K/W}. \tag{7}$$

The obtained results show that, at the test temperatures ($T_{\text{sa}} = 27.8$ °C and $T_{\text{wa}} = 16.2$ °C), the radiation resistance is lower than the natural convection resistance.

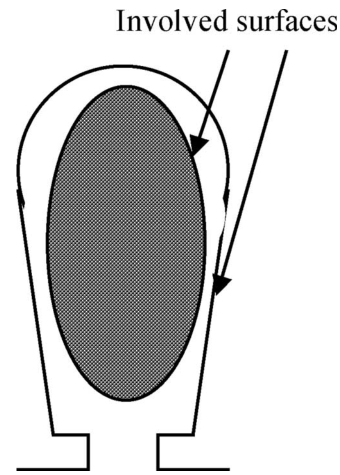

Fig. 5. Detail of the involved surfaces in radiation exchange between copper and stator slot.

Therefore, in these kinds of motors, the radiation resistance can be neglected when the forced ventilation is active, but it has to be taken into account when the motor is working at very low speed, such as in variable speed drives, or when the motor fan is missing.

It is important to underline that the test for the measurement of the natural convection resistance that is normally performed in air [3], [4] provides the equivalent resistance that is the parallel of the actual natural convection and of the radiation resistances. Consequently, the radiation effects are included in the measured natural convection resistance, but in this way, the different behaviors that the resistances have with respect to the temperature cannot be taken into account.

IV. Radiation Thermal Exchanges Inside the Motor

During deep vacuum conditions, as in the previously described test, it is possible to highlight and thus measure the radiation heat transfers that involve parts inside the motor. In particular, the most important ones are:

- between the active side of the windings inside the stator slots and the inner surface of the slots;
- between the end-winding space and the inner surface of the housing.

The radiation thermal resistance $R_{\text{cu-ir}}$ between the stator copper and the iron lamination (see Fig. 5) as well as the radiation resistance $R_{\text{ew-ec}}$ between the end inding and the external case (see Fig. 6) can be measured starting from the simplified thermal model reported in Fig. 7.

The model is derived by simplifying the full motor thermal model [5] according to the following criteria, which are true in deep vacuum conditions.

- All the natural and forced convection heat transfers are negligible. As a consequence, the related thermal resistances can be substituted by open circuits.
- All the conductive thermal resistances can be substituted with short circuits because their values are more than ten times lower than the other thermal resistances.

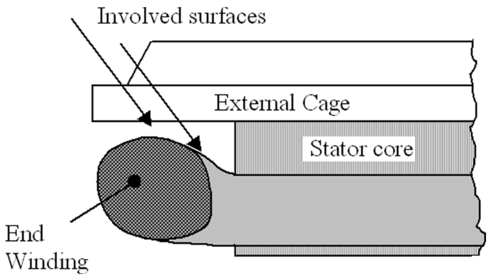

Fig. 6. Detail of the involved surfaces in radiation exchange between end winding and external cage.

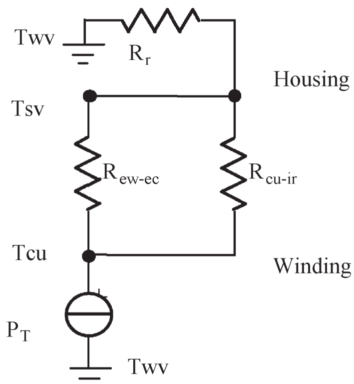

Fig. 7. Simplified thermal model of the motor in vacuum conditions.

- Radiation between the end windings and the motor end caps can be substituted by an open circuit because the involved surfaces have a very low view factor.
- Thermal resistances due to the interface gap between stator lamination and external frame are very low and can be neglected. This interface gap is due to the imperfections in touching stator lamination and external cage surfaces. Even if it is considered as an equivalent air layer [3], [4], the surfaces are in contact, and the conduction-related effects between the stator lamination and the external cage surface are much more effective than the radiation ones.
- Conduction between the winding and the stator is negligible because, in this motor, the impregnation process has not been applied to the stator.
- Radiation between the stator and rotor surfaces can be neglected because its related thermal resistance is higher than $R_{\mathrm{cu-ir}}$ and $R_{\mathrm{ew-ec}}$.

The resulting motor model in steady-state conditions is shown in Fig. 7, where the generator P_T represents the electrical power dissipated by the stator during the test and R_r is the radiation resistance between the external cage and the outer space measured as described in the previous section.

The temperature of the winding T_{cu} and the housing temperature T_{sv} as well as the motor power P_T can be measured during the test. In this way, it is easy to obtain the parallel between $R_{\mathrm{cu-ir}}$ and $R_{\mathrm{ew-ec}}$. Inasmuch as no other information is available to measure the two resistances separately, their values can be obtained assuming that they are inversely proportional to their respective exchange surfaces.

In this way, the radiation thermal resistance between stator copper and stator slots is $R_{\mathrm{cu-ir}} = 5.25$ K/W, whereas the radiation thermal resistance between end winding and external frame is $R_{\mathrm{ew-ec}} = 19$ K/W.

It is now possible to compute the heat-transfer coefficients h_i that, by definition [6], are

$$h_i = \frac{1}{R_i A_i} \tag{8}$$

where R_i is the generic thermal resistance and A_i is the involved surface. The radiation heat-transfer coefficients for the motor under test are, therefore,

$$\begin{aligned} h_{\mathrm{cu-ir}} &= 8.5\ \mathrm{W/m^2/^\circ C} \quad \text{stator copper}-\text{iron} \\ h_{\mathrm{ew-ec}} &= 6.9\ \mathrm{W/m^2/^\circ C} \quad \text{end winding}-\text{external cage} \\ h_r &= 5.7\ \mathrm{W/m^2/^\circ C} \quad \text{external}-\text{cage ambient.} \end{aligned}$$

It is important to underline that the radiation heat-transfer coefficient between housing and ambient has been obtained using the total external frame surface because these data are often available and simply measurable.

About the radiation heat-transfer coefficients, the following considerations can be done.

The value of $h_{\mathrm{cu-ir}}$ has been obtained for the motor under test, but it can be also employed as a good approximation for other similar motors. Actually, this coefficient is strongly dependent on two quantities. The first one is the stator slot fill factor, whereas the second one is the impregnation goodness factor. As a consequence, even if the stator slot fill coefficient depends on the motor size, the range of variation is limited (typically 0.4–05), and the stator copper–iron radiation heat-transfer coefficients can be quite constant. Also, the impregnation goodness factor has a very limited numeric spread; thus, the same previous considerations can still be done.

The value of $h_{\mathrm{ew-ec}}$ here measured can be also considered of general application because it depends on the geometry (not the size) of the motor end winding. For these reason, a value of about 6 $\mathrm{W/m^2/^\circ C}$ can be usefully adopted for other motors that have a frame structure similar the tested one.

Furthermore, the three coefficients, $h_{\mathrm{cu-ir}}$, $h_{\mathrm{ew-ec}}$, and h_r, are functions of the temperature, but suitable corrections can be applied by using the correction equation reported (6).

V. Final Considerations

On the basis of the obtained results, the following considerations can be drawn.

The procedure described in this paper for the housing radiation-resistance measurement is based on the resistance definition; thus, the resistance accuracy depends on the measurement uncertainties. The procedure does not require *a priori* information or geometrical approximations that are mandatory for other methods.

The obtained results show, for the motor under test, that radiation is comparable with the natural convection, in spite of the low involved temperatures. The numerical results cannot be automatically employed for other motors because the surface emissivity can be quite different. Nevertheless, commercial motors are rarely coated with low emissivity paints; thus, when the motor works without forced cooling, it is possible to reduce the radiation resistance and, therefore, the motor temperature, acting as follows.

- *Improve the housing emissivity*. The motor paint and its fin dimensions can be chosen to improve the motor apparent emissivity [7].
- *Reduce the surroundings temperature*. Hot devices, such as other motors working in the neighborhood, can transfer heat by convection, conduction, and radiation. The latter can be reduced, for example, by means of a separator.
- *Improve the surrounding absorptivity*. When the motor is located in a small working environment, e.g., in a small box, a high wall absorptivity reduces the reflected radiation heat that strikes the motor.

Significant radiation thermal exchanges are not only present on the external frame but also at several surfaces inside the motor. In particular, the main radiation paths are between the copper wires inside the slot and the stator lamination and between the end winding and the external frame.

The obtained heat-transfer coefficients are in good agreement with the values reported in the literature [1], [8], [9], and they can be adopted in thermal models including radiation effects. From a practical point of view, heat-transfer coefficients in the range of 6–8 $W/m^2/^\circ C$ can be employed as a reasonable approximation for motors with similar structures.

VI. Conclusion

The role the radiation resistance plays in motor thermal models has been discussed, and a measurement system, based on a vacuum chamber, has been developed for the thermal resistance measurement. The measured radiation resistance depends both on the motor and on the environment temperatures; thus, a simple, although approximated, radiation model has been also employed to correct the measured resistance when such temperatures are different from the test ones.

Experimental tests have been performed with a small induction motor, and both the radiation resistance and the natural convection resistance have been measured. The test results show that the radiation resistance and the natural convection resistance are of the same order of magnitude; therefore, the radiation resistance cannot be neglected in the motor thermal model when other heat dissipation phenomena, such as the forced convection, are not present.

In addition, the radiation effects inside the motor have been analyzed by using a simplified model suitable to represent the radiation thermal exchange, and the related radiation thermal resistances have been also determined.

Furthermore, some considerations useful to extend the numerical results to other motors and to reduce the radiation resistances have been provided.

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