Thermal Behavior of Induction Motors under Different Speeds

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Abstract

Recently different electronic speed controllers have been widely used. As is known, the thermal condition of IM is significantly dependent on its speed of operation. The common thermal circuit of IM, which consists of a system of heat courses, interconnected by thermal conductivities, can also be used for studying IM under different speed operation. This circuit can be furthermore simplified to a system of three main heat courses (stator, rotor windings and stator magnetic circuit) interconnected by three generalized thermal resistances. The value of these thermal resistances and their dependency on speed was investigated by new methods of loading proposed in this study. Using these methods of loading, the dependency on speed may be obtained with high accuracy so that the difference between the testing results and calculation does not exceed 2-3 degrees.Two totally enclosed fan-cooled induction motors were tested by these methods.

1 Introduction

The thermal condition of IM is one of the main factors that define the thermal behavior of IM and their ability. One of the most effective methods of estimating the IM heating processes is the method of the equivalent thermal circuits of the IM in which it is simulated as a system of heat sources that are interconnected and connected to the environment by means of thermal conductivities [1,2,3]. To predict the temperature distribution within the motor using the thermal circuits, it is necessary to know the location and magnitude of the heat losses and all the thermal conductivities. The latter can only be calculated if the thermal properties of the materials used and the behavior of the cooling system is known. However, considerable uncertainties exist regarding the thermal conductivity of the materials from which the motor is constructed and regarding the used coefficients of the cooling surface. Another way of determining the thermal conductivities is by the synthesis of the IM thermal model using the experimentally obtained results of measuring the temperatures of different parts and the power loss [4]. In [5] a simple empirical thermal model which estimates the stator and rotor winding temperatures in an inverter-driver IM under both transient and steady state conditions is proposed. This model is based on thermal-torque derating for inverter-driven induction machines and features a single frequency dependent thermal resistance and time constant for each winding. The disadvantage of this method is that only one thermal course (the total losses) and only one thermal resistance are used for the thermal model which predicts the temperature rise of the stator winding or the rotor winding. This simple model gives a temperature error of about 10^0 which is relatively low accuracy.

In [6] the authors have proposed new methods of loading IM for testing the heat condition. By these methods of loading main generalized thermal resistances of simplified thermal model were deteminated. This thermal model consists of only three heat courses (stator, rotor winding and stator core) and also three generalized thermal resistances. In this study the simplified thermal model have been investigated for different speeds and the dependence of their thermal resistances by speed was obtained. In this study two methods of IM loading were used:

1) The reverse rotating regime, where a three-phase low voltage is supplied to the IM rotated by a dc motor, so that the direction of the revolving magnetic field is opposite to the direction of the IM rotor rotation. The total losses depend on the value of the supply voltage and their can be made close to the cooper losses by full load operation, since the losses in stator core may be neglected.

2) The direct current regime, where the IM is rotated by a dc motor and its three stator windings are connected in series and are supplied by direct current so that the main magnetic field is absent. The advantage of this test is that the measurement of losses and the average value of the stator winding temperature rise can be carried in a very simple way and with high accuracy.

Using the dc motor as an external motor has an advantage in its easy way of controlling different speeds and more precise results in power and temperature measurements

2 Simplified Thermal Model

The thermal behavior of electrical machines for transient and steady-state conditions can be studied by using equivalent thermal circuits [3], Fig.1, which consist of several elements: heat sources representing the losses in different parts of IM, thermal conductivities and thermal capacitances. These elements of IM are interconnected and connected to the environment by means of thermal conductivities.

The common equivalent thermal circuit of IM by transient behavior may be represented by a system of equations (which are like the nodal equations of electrical circuits) [3].

$$\begin{aligned} C_1\frac{d\theta_1}{dt} &= \Delta P_1 - a_{12}(\theta_1-\theta_2)-\ldots-a_{1n}(\theta_1-\theta_n) \\ C_2\frac{d\theta_2}{dt} &= \Delta P_2 - a_{21}(\theta_2-\theta_1)-\ldots-a_{2n}(\theta_2-\theta_n) \qquad (1) \\ C_n\frac{d\theta_n}{dt} &= \Delta P_n - a_{n1}(\theta_n-\theta_1)-\ldots a_{n,(n-1)}(\theta_n-\theta_{n-1}) \end{aligned}$$

where ΔP_i are the losses in the i-th element, θ_i is the

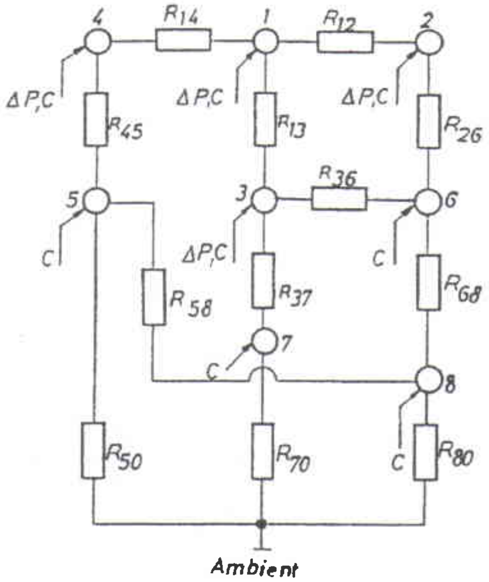

Fig.1 Thermal equivalent circuit of IM

temperature rise in the i-th node (appropriate part), a_{ij} are the thermal conductivities between modes i and j and C_I is the thermal capacitance of i node.

For the steady-state regime in (1) all the derivatives are zero: $d\theta_i/dt = 0$. Therefore, for the steady-state regime, Eq.(1) is simplified to a system of equations with the left side being zero. Its solution will be:

$$\theta_1 = R_{11}\Delta P_1 + R_{12}\Delta P_2 + ..R_{1n}\Delta P_n$$
$$\theta_2 = R_{21}\Delta P_1 + R_{22}\Delta P_2 + ... + R_{2n}\Delta P_n \quad (2)$$
$$\theta_n = R_{n1}\Delta P_1 + R_{n2}\Delta P_2 + ... + R_{nn}\Delta P_n$$

where $R_{ii} = \Delta_{ij}/\Delta$ is the input thermal resistances seen between the i-th node and the based node, i.e. ambient; R_{ij} are the transfer thermal resistances between the i-th and the j-th modes, Δ-is the determinant of the matrix $A = [a_{ij}]$ and Δ_{ij} are the elements of the inverse matrix A^{-1}, i.e. the co-factors of the A matrix.

Taking into consideration only the three main heat sources ΔP_1, ΔP_2, and ΔP_3 (stator and rotor windings and stator core), Fig.2, the system of equations (2) will be reduced to only three equations for the temperature rises θ_1, θ_2 and θ_3.

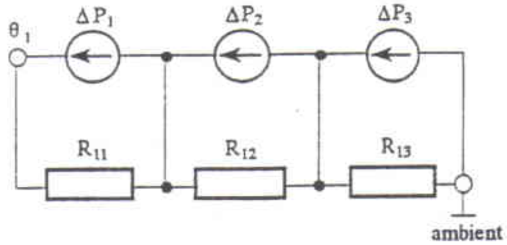

Fig.2 Simplified circuit of IM

Thus, for the stator winding, whose thermal conditions are of the utmost importance, the temperature rise becomes:

$$\theta_I = R_{11}\Delta P_1 + R_{12}\Delta P_2 + R_{13}\Delta P_3 \quad (3)$$

The calculations of the three generalized thermal resistances in (3) and the experiment show that $R_{12} \approx R_{13}$ and therefore in (3) it is necessary to determine only two resistances R_{11} and R_{12}.

These resistances can be obtained from two equations for two different tests of IM:

$$\theta_{11} = R_{11}P_{11} + (\Delta P_{21} + \Delta P_{31})R_{12}$$
$$\theta_{12} = R_{11}\Delta P_{12} + R_{12}(\Delta P_{22} + \Delta P_{32}) \quad (4)$$

where ΔP_{1n}, ΔP_{2n} and ΔP_{3n} (n =1,2) are the losses in stator and rotor windings and in a stator core respectively by the n-th test of a different method of loading of IM (reverse field and direct current regimes) and θ_{1n} is the temperature rise of a stator winding by the n-th test.

Therefore, carrying out only two tests of loading an IM at different speeds, the dependence of the generalized thermal resistances by speed maybe obtained.

Now, we have to define the different losses in (4).

1. In the reverse field regime the stator and rotor losses are calculated as

$$\Delta P_{11} = 3I_1^2 r_1$$
$$\Delta P_{21} = \Delta P'_{21} + \Delta P''_{21} \quad (5)$$

where (see Tables 1 and 3): r_1 is the measured value of the stator winding resistance by steady-state thermal conditions; I_1 is the current supply to the checked motor; $\Delta P'_{21}$ is the power absorbed by the rotor of the IM, which is transferred from the stator through the magnetic field and $\Delta P''_{21}$ is the power absorbed by the rotor of the IM, which is actually transferred to the IM from the dc motor (which drives the IM) through the shaft. Therefore,

$$\Delta P'_{22} = P_1 - \Delta P_{11}$$
$$\Delta P''_{21} = V_d(I_d - I_{do}) - r_a(I_d^2 - I_{do}^2) \qquad (6)$$

where P_1 is the three-phase power supply to the checked motor; V_d and I_d are the voltage and armature current of the dc motor which drives the checked IM, I_{do} is its idling current and r_a is the armature winding resistance of the dc motor.

2. In the direct current regime the losses are calculated as

$$\Delta P_{12} = 3I_=^2 r_1$$
$$\Delta P_{22} = V_d(I_d - I_{do}) - r_a(I_d^2 - I_{do}^2) \qquad (7)$$

where $I_=$ is the direct current supplied to the stator winding of IM and ΔP_{22} is again the power transferred to the rotor of the IM from the dc motor.

Using these data we may solve Eqs.(4) to determine the thermal resistances of the checked motor. For two different motors these resistances are given in Table 4.

The losses in a rotor winding create the immovable harmonics of the stator magnetic field.

The transient thermal condition of IM may be investigated by (1) in taking into account the change of effectiveness of cooling by speed. Approximate calculations of the transient thermal process for totally enclosed fan-cooled IM may be obtained as

$$\theta_1 = \theta_{1st}(1 - e^{-t/\tau}) \qquad (8)$$

where θ_{1st} is the steady-state temperature rise of a stator winding by (3) for known losses and the generalized thermal resistances for calculated speed.

The thermal time constant can be obtained accordingly to [3] for totally enclosed fan-cooled IM and for n_r = 1.500 rev/min

$$\tau = \frac{420G}{K_m L_f \pi D_f \alpha}\ ,\text{sec} \qquad (8a)$$

where G is the mass of IM im Kg

L_f and D_f are the length and diameter of a stator frame in m, K_m=2-2,5 is the coefficient which takes into account the frame surfaces' increase due to the frame edges,

$\alpha = 14 + 56\,\dfrac{n}{n_r}$ - is the dependence of the heat transfer coefficient unit frame surface by speed in W/m^2 K°

4 Experimental verification

Two different motors (K90S-1,1 kW and K100L-3kW (made by the Yona Ushpiz Factory, Israel) were checked. The technical data of these motors is given in Table 1. The test results by revolving field and direct current regimes for different speed are given in Tables 2 and 3. The dependence of the generalized thermal resistances by speeds for these two motors is given in Table 4 and their thermal time constants for different speeds are given in Table 5.

4 Conclusions

1. A simplified thermal circuit used for investigating the behavior of IM under different speed conditions is introduced.
2. Two new methods of loading IM for determining the thermal parameters of the simplified thermal circuit for different speeds have been proposed.
3. The dependence of generalized thermal resistances on speed was obtained by a test and calculated analytically.
4. Using these resistances and knowing the losses in a motor, the temperature rise of a stator winding for different speeds or the permissible value of a stator current for these speeds may be calculated.

Table 1. Data of checked motors

Type	P, kW	I, A	r_1, Ω	cosφ	η, %	ΔP_1, W	ΔP_2, W	ΔP_3, W
K90S	1.1	2.5	7.95	0.8	79.5	145	52	53
K100L	3.0	6.2	7.70	0.82	84.0	303	130	130

Table 2. Test results of a K100 L motor

n, rpm	Direct current regime			Reverse field regime		
	ΔP_1, W	ΔP_2, W	θ_1, °K	ΔP_1, W	ΔP_2, W	θ_1, °K
1500	231	211	57	150	194	41.9
900	230	142	63	150	156	45
500	239	97,6	69,6	154	135,5	54.2
300	241	74,3	77,3	162	126	66,8
150	206	42,2	82	164	124,5	84,5

Table 3. Test results of a K90S motor

n, rpm	Direct current regime			Reverse field regime		
	ΔP_1, W	ΔP_2, W	θ_1, °K	ΔP_1, W	ΔP_2, W	θ_1, °K
1500	158	72,3	44	148	124	50
900	162	54	51	153,6	110,5	59,0
500	166	43	61,5	155,5	108	73,3
300	119	26	55,5	165	109,5	87
150	122	20	69	102	70,3	72

Table 4. Dependency of generalized thermal resistance on speed

n, rpm	1500	900	500	300	150
		K90S			
$^{*}R_{11}$	0,2074	0,2569	0,3093	0,4097	0,494
$^{**}R_{11}$	0,2449	0,285	0,33	0,38	0,50
$^{*}R_{12}$	0,1553	0,1816	0,235	0,24	0,296
$^{**}R_{12}$	0,1132	0,151	0,189	0,221	0,345
		K100L			
$^{*}R_{11}$	0,1916	0,2298	0,239	0,262	0,354
$^{**}R_{11}$	0,16	0,196	0,216	0,265	0,34
$^{*}R_{12}$	0,0613	0,0695	0,129	0,492	0,2128
$^{**}R_{12}$	0,0865	0,108	0,133	0,176	0,244

* obtained by test ** calculated by (2)

Table 5. Dependency of the thermal time constant on speed

n, rpm	1500	900	500	300	150
		K90S			
$^{**}\tau_{min}$	11,2	16,5	22,6	31,5	45,2
$^{*}\tau_{min}$	12		30		50
		K100L			
$^{**}\tau_{min}$	16,4	22	32	43	65
$^{*}\tau_{min}$	17,0		30		60

* obtained by test ** calculated by (8a)

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