Thermal Analysis of Induction and Synchronous Reluctance Motors

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Abstract - **In this paper the thermal behavior of two induction motors (2.2 and 4 kW, 4 pole) and two synchronous reluctance motors (transverse laminated) are investigated and compared. Both motor types use the same stator, but have different rotors. Using a lumped parameter simulation program, a thermal analysis has been also carried out and the obtained results have been compared to the experimental ones. A direct comparison of the thermal behavior of the two motor types has been thus made, for constant load and constant average copper temperature conditions. Since the synchronous reluctance motor has negligible rotor losses compared to the induction motor, it is capable of a larger rated torque, from 10% to more than 20%, depending on the relative size of end connections and motor length.**

I. INTRODUCTION

Induction motors are the worldwide most common drive for industrial and civil applications. This is largely due to their simple construction and robustness and the fact that they can operate directly form the sinusoidal supply, without the need of power electronics converter and related control system. Obviously the last advantage is not valid when the application requires speed regulation. In such case there could be many advantages in adopting alternative motor typologies. When choosing a motor type suitable for variable speed drives, characteristic such as high torque/volume ratio, high efficiency, simple controllability and feasibility of sensorless control are often desired. In the last 10 years the Synchronous Reluctance Motors "SynRM" have gained interest [3], [4], [5], due to several factors:

- reduced cost with respect to PM machines;
- quite simple production and assembly process, even if the rotor lamination geometry shows flux barriers (Fig. 1);
- flux weakening capability for spindle and traction applications.

Since in the SynRM there are no rotor losses, this motor has a cooler rotor compared to the induction motor one. This allows higher efficiency and reduced problems related to bearing temperature.

The SynRM suited for mass production is the transverse laminated one. It is composed by a three phase stator (a common induction motor stator can be employed), while the rotor is realized by a multiple-barrier structure, traditionally laminated.

As a schematic example, Fig. 1 shows a SynRM rotor lamination of a four-pole motor. The thin ribs connecting the flux guides are designed to withstand the centrifugal forces produced at high speed.

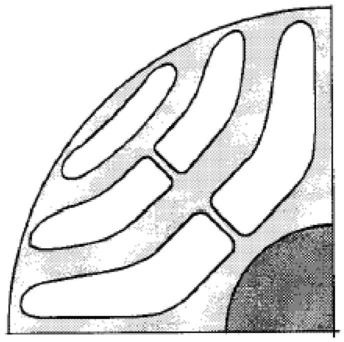

Fig.1: Schematic of rotor lamination of a Transverse Laminated Synchronous Reluctance Motor (SynRM).

II. THERMAL ANALYSIS AND COMPARISON

In order to compare the thermal behavior of a SynRM to that of an induction motor, both thermal analysis by a simulation package and experimental tests have been carried out. The comparison has been performed using induction and SynRM motors produced by the same company, having the same stators. Thus, the difference in the motor performance is due to the rotor lamination only. The motors adopted in the analysis are TEFC induction motors, with 2.2 kW and 4 kW rated power (380V, 50 Hz, 4 poles, F insulation class). The SynRMs have been equipped with encoders for the closed loop control. As an example, Fig. 2 shows a picture of the 4 kW motor.

The step-by-step analysis has been developed in the following way:

- Induction motor tests.
- Induction motor thermal simulation and thermal model set up.
- SynRM motor thermal simulation.
- Thermal comparison between SynRM simulation and experimental results.
- Comparison between SynRMs and induction motors performance.

Fig.2: TEFC 4 kW (380V, 50 Hz, 4 poles) induction motor.

III. Induction Motor Test

Several tests have been performed on the two induction motors. In particular, the following tests have been chosen for the thermal characterization:

Load test with AC Inverter supply

This test, performed at rated load, allows to define the steady state thermal conditions. The temperatures of the frame and stator iron have been measured by thermal probes.

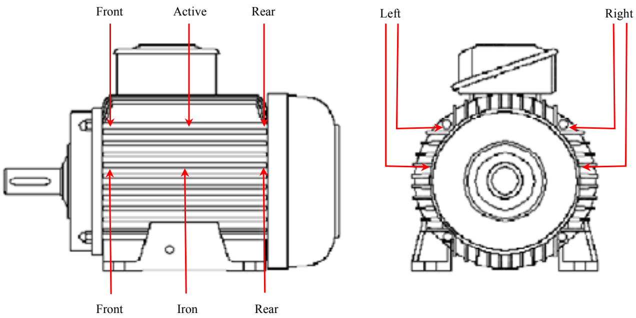

Fig. 3: Temperature measurement points.

The windings average temperature has been measured through dc supply. It is important to underline that all the motors have been monitored with thermocouples on the end-windings, while the iron temperature have been measured through a hole drilled on the motor frame. The frame temperatures have been measured, at several points, on the motor frame surface and an average temperature value has been used for the subsequent analysis. During the load test all the measurable electrical and mechanical quantities have been monitored. The measured values have been used for the loss segregation using the procedure proposed by the IEEE 112 method B. Even if this method is a standard procedure for sinusoidal supply, it is possible to apply it to an inverter supply if some simplified hypotheses are introduced. Since the quantities are related to inverter supply all the measured and computed powers have to be total active powers, while the related voltages have to be the first harmonic of the applied inverter voltages. The additional losses have been neglected for two reasons:

- The additional losses are small with respect to the other contributions and their effect on the thermal behavior can be neglected, for simplicity.
- The IEEE procedure is for sinusoidal supply. As well known, the additional losses are related to the effects of the space harmonics content on the rotor cage. With inverter supply new additional losses due to supply are involved (in particular, voltage and currents time harmonics components). Anyway, these losses are automatically included in the loss balance using the measured rms currents values. As a consequence there is not a simple and reliable procedure to separate these two contributions.

During the load test, a map of the cooling air speed on the motor frame surface has been determined by means of an anemometer probe. This data have been used to calibrate the thermal simulation. A complete discussion on the problems linked to the air speed measurements in TEFC motors can be found in [2] and [6]

No load test with AC inverter supply

This test allows evaluation of core loss and mechanical loss. Both losses are requested in the IEEE 112 Method B loss separation and they have to be known in the thermal model set up.

Thermal test with DC supply

This test is performed with the motor supplied by a DC voltage and is the base for the thermal model set up. The data collected by this test are used to determine:

- the equivalent thermal conductivity of the impregnation varnish (considering an impregnation goodness equal to 1);
- the interface gap between stator core and motor frame;
- the natural convection heat transfer coefficient.

These three quantities are of fundamental relevance for a correct set up of the thermal model. The thermal set procedure is described in references [2] and [6]. Anyway, a short summary is hereafter reported.

During the DC test the shaft is still and the fan cooling is not active. As a consequence, in order to avoid a motor damage, the current has to be regulated between 40%-60% of the rated one.

The test starts by measuring the motor resistance at the ambient temperature, thus constituting the reference value.
When the motor reaches the steady-state temperature, the external housing temperatures are measured in different points (Fig. 3) to get the average housing temperature. In addition, an internal temperature is measured too, up to the stator iron. Last, the new value of the stator resistance is

measured and the motor winding temperature is computed by the trivial relationship (1):

$$T_2 = (235 + T_1)\frac{R_2}{R_1} - 235 \qquad (1)$$

where:

T_1 ambient temperature

R_1 stator resistance at ambient temperature

R_2 stator resistance at temperature T_2

IV. SET UP OF THE INDUCTION MOTOR THERMAL MODEL AND SYMULATIONS

The induction motor model set up and the thermal simulations have been performed using the commercial software package Motor-CAD [7], that is a code devoted to electrical motor thermal analysis [1]. The implemented model is based on an analytical lumped circuit. The comparison between the simulated and the measured overtemperatures are reported in Table I and Table II, for both the DC test and the AC load test respectively. Fig. 4 shows the test bench for the AC tests.

The DC tests are matched, of course, since they have been used to set up the model. Regarding the AC tests, a fairly good matching is shown for winding and housing temperatures. On the contrary, a discrepancy is pointed out regarding the iron temperature.

As a possible explanation the holes drilled in the motors, to insert the temperature probe, could have been not sufficiently deep inside the yoke. As a consequence, the measured temperature would be intermediate between iron and stator frame, since a thermocouple probe with silicon grease was used. Of course, other concurrent explanations can be found. Anyway, the impact of this discrepancy on the following comparison is limited, since it is mainly based on the copper temperature.

Fig.4: Test bench for the AC load test.

During the AC load test, the dissipative effect of the test bench has to be taken into account. In fact, the metal structure of this bench (Fig. 3) cannot be neglected. As discussed in section III, the DC test was performed on the motor alone, to get the thermal characteristic of the motor only. To take into account the presence of the test bench in the thermal model, since the software code allows the inclusion of a rectangular flange with dimensions imposed by the user, a flange equivalent to the test bench was introduced.

TABLE I

Induction motor 2.2 kW Overtemperatures [°C]				
	DC Test		AC Test	
	Exper.	Simul.	Exper.	Simul.
Housing	35.5	37.0	38.8	47.0
Stator iron	37.6	40.4	49.0	74.9
Winding average	46.1	46.2	102.8	102.1

TABLE II

Induction motor 4 kW Overtemperatures [°C]				
	DC Test		AC Test	
	Exper.	Simul.	Exper.	Simul.
Housing	48.3	52.9	61.5	60.9
Stator iron	53.2	57.5	72.6	92.9
Winding average	61.6	61.3	106.8	107.0

An additional DC test, with the motor mounted on the bench has been performed, similarly to the DC test without bench (Section III). Thus, using the thermal model previously set up, the flange dimension is modified till the predicted temperatures cope the measured ones. The use of a thermal equivalent flange in the model leads to an excellent agreement between the measured and predicted motor temperatures, as shown in Table I and Table II. It can be pointed out that the described procedure (two DC tests with and without bench) has the advantage of overcoming the difficult evaluation of the thermal characteristics of the real flange.

V. SYNRM MOTOR THERMAL MODEL

The thermal behavior of the SynRM has been carried out using the software code adopted for the induction motor analysis. However, this software does not provide an "ad hoc" thermal model for SynRMs. As a consequence, the thermal model used for the induction motor has been adapted to the SynRM. Taking into account that the main difference between the two motors is the rotor structure, the following approximations was adopted:

- the rotor losses were set to zero;
- the thermal conductivity of the rotor cage was set equal to the thermal conductivity of the air;
- the difference between the thermal resistances of the two rotors was neglected;

- since bearings and fans are equals and the two motors are supplied by the same inverter, mechanical and iron losses have been assumed equal for the two motors.

The obtained SynRM thermal model has been used to analyse the two SynRMs under test, as described in the following.

VI. Thermal Comparison between Simulation and Experimental Results on SynRMs

As a first step, the two SynRMs have been tested at load and at the same torque and shaft speed of the two the induction motors.

At steady state, the SynRM temperatures have been measured and compared with the temperatures obtained from the SynRM thermal model previously discussed.

The comparison is reported in Table III and Table IV. The two tables show a fairly good agreement between the measured and the predicted values, with reference to winding and housing temperatures. As usual, a discrepancy is found for the stator iron temperature but the considerations concerning the hole drilled in the stator frame and the temperature probe insertion are still valid.

TABLE III

SynRM 2.2 kW Overtemperatures [°C]		
	AC Test	
	Exper.	Simul.
Housing	39.8	37.4
Stator iron	44.1	60.0
Winding average	85.0	85.0

TABLE IV

SynRM 4 kW Overtemperatures [°C]		
	AC Test	
	Exper.	Simul.
Housing	42.9	47.8
Stator iron	47.6	64.4
Winding average	79.0	80.9

VII. Induction vs. Synchronous Reluctance Motors

On the basis of the previous results, it is possible to compare induction and synchronous reluctance motors from the thermal point of view by using the winding average temperatures shown in Tables I - IV. As expected, it is well evident that the SynRMs are cooler than induction motors, at the same load conditions. In particular, a reduction of about 14 °C has been found for the 2.2 kW motors and of 28 °C for the 4 kW motors. A rotor without joule losses is a considerable advantage for the SynRM, which leads to a consistent reduction of the winding temperature at the same load torque and speed. As a consequence, rather than using the SynRMs at a lower temperature, an increase of the rated torque in order to get the same temperature of the induction motor is a viable and profitable approach. In other words, at constant stator winding temperature, the SynRMs show higher rated torque; this load condition can be briefly pointed as "overload" As far as mechanical and stator iron losses can be considered independent with respect to the motor torque, the stator copper losses (i.e. the stator current) can be increased until the winding temperatures of the SynRMs match the temperature of the induction motors. This procedure has been applied both by simulation using the thermal model and by direct load tests. With reference to the winding temperature Table V and Table VI show the comparison between simulated and measured results.

TABLE V

SynRM 2.2 kW – "Overload" Overtemperatures [°C]		
	Exper.	Simul.
Winding average	103.4	103

TABLE VI

SynRM 4 kW – "Overload" Overtemperatures [°C]		
	Exper.	Simul.
Winding average	108.6	107.6

Both tables show a good agreement between predicted and simulated results, confirming the reliability of the proposed SynRM thermal model. The temperatures of Tables V and VI have to be compared to the ones reported in Tables I and Table II.

The ratio between the power dissipations of the two motors (Pdi for the induction motors and Pdr for the SynRMs) at constant torque and shaft speed Pdi / Pdr, and the ratio between the two torques (Ti for the induction motors and Tr for the SynRMs) at constant average winding temperature Tr/Ti can be evaluated. These ratios are reported in Tables VII and VIII.

TABLE VII

Constant torque and shaft speed Ratio of dissipated powers		
	2.2 kW	4 kW
Pdi/Pdr	0.83	0.73

TABLE VIII

Constant average winding overtemperature Ratio of output torques		
	2.2 kW	4 kW
Tr/Ti	1.09	1.20

At constant load, the power dissipation of the induction motors is 20% - 37% higher than that of the SynRMs.

On the other hand, when the same power dissipation is imposed, the torque of the synchronous reluctance motor is 10%- 20% larger than that of the induction motor.

It can be surprising the quite different amount of torque increasing, between 2.2kW and 4kW motors. It is explained by the quite different impact of end connections. The main motor dimensions are reported in Table IX.

Where:

- D.ext is the stator lamination outer diameter;
- D.int is the stator lamination bore diameter;
- l is the stack length.

TABLE IX

Main dimensions of the motor frames [mm]			
	D.ext	D.int	l
2.2 kW	165	98	70
4 kW	165	98	120

The 2.2 kW motors are very short, compared to the stack length. Since the extra torque of the SynRM is due to a transfer of the induction motor rotor losses, the shorter the motor is, the lower this transfer is, since the large loss amount due to end connections does not contribute to torque production.

Moreover, consider that even the 4 kW motors can still be considered "short" motors. As a consequence, a larger torque increase could be expected, for a longer motor.

In principle, for a motor of infinite length all the induction motor rotor losses could be transferred to the stator and a maximum torque increase would be reached. In practice, however, only a portion of these losses is useful to increase the torque capability.

Using the simulation program this point has been analysed in detail. The obtained results have shown the peculiarities of the thermal dissipation of the stator end-windings, in comparison to the active section of the windings inside the stator slots. In particular, the end windings have a high thermal resistance between the two end bells and the external frame. By the simulation program, the maximum temperature values of end connections have been calculated, for both the considered motor frames and both the motor types. In the worst case, the maximum temperature is higher than the average one by twelve degrees, which looks reasonable. On the other hand, by comparing the highest temperatures of synchronous reluctance and induction motors, the former was typically showing three degrees more than the latter. This confirms the validity of the previous comparison, based on the average temperature values.

A way to reduce the impact of end connections should be the adoption of potted end windings [8], as shown in Fig. 5. The thermal simulation code previously used has been also applied to this case and the obtained results are shown in Table X.

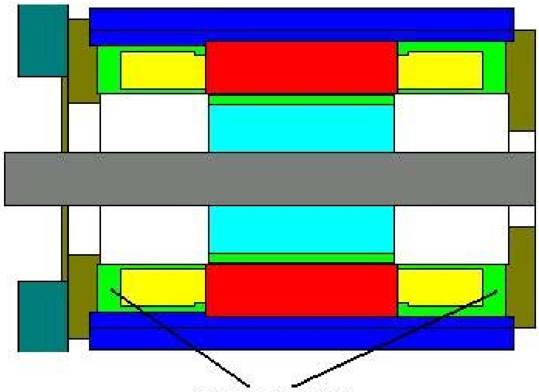

Fig.5: Example of potted end windings.

A material with a thermal conductivity of about 1 W/°C/m has been supposed. Both the induction motor and the synchronous reluctance motor have been simulated, since the potted ends are profitable in both cases.

As a result, the ratios given by the Table X were found. They represent the rated current of the synchronous reluctance motor referred to the I.M. one, at the same average winding temperature. As expected, the shorter motor improves his performance more than the other one. Anyway, the impact of potted ends looks quite limited, with reference to our comparison. On the other hand, the difference between maximum and average temperatures is limited, in this case, to few degrees: this constitutes an advantage, in general.

TABLE X

Rated current ration (SynRM current over induction motor current) Constant average winding temperature		
	2.2 kW	4 kW
non potted end windings	1.10	1.22
potted end windings	1.13	1.23

VII. CONCLUSIONS

In the paper a direct comparison between induction motors and synchronous reluctance motors has been presented. A simplified thermal model of the synchronous reluctance motor has been proposed. The comparison between the predicted and the measured results has shown a good agreement, with a main reference to the stator winding temperature.

The obtained results have highlighted the quite higher torque density of the modern synchronous reluctance motor with respect to the standard induction motor. Due to his negligible rotor losses, the synchronous reluctance motor show a rated torque which is from 10% to 20% larger, depending on the ratio between stack length and stator diameter. Last, the impact of potted windings on this comparison has been quantified.

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