Transient regimes thermal analysis of an induction machine

Valentin NĂVRĂPESCU[1], Mihaela CHEFNEUX[1], Mihaela SCORȚESCU[1],
Aurel-Ionuț CHIRILĂ[1], Ioan-Dragoş DEACONU[1]
[1]Centrul 3
[1]ICPE SA
[1]Splaiul Unirii 313, Sector 3
ROMANIA
valentin.navrapescu@upb.ro,   http://www.actionari.plc.pub.ro

Abstract: - The paper presents a three-phase squirrel-cage induction machine thermal analysis for various operating regimes. In order to identify the hot spots within the machine different standard duty services are considered. This type of analysis generates the premises for the evaluation of the load capability of the machine (without exceeding the insulation class) when used as a generator in a micro Combined Cooling Heat and Power – with Stirling Engine system.

Key-Words: - Thermal transfer, Squirrel-cage induction machine, Transient regimes, Simulation, Duty cycles

1 Introduction

The evaluation of the specific temperature field for an electric machine during operation is one of the most important design stages [1]. This prediction allows for the machine designers to evaluate for a given load if the insulation class of the machine is in correspondence with the imposed one in the designing project to check for thermal back-up or to identify the over-temperature regions [2]. In the case of enclosed machine types the cooling is an essential issue because the heat is evacuated only through the machine's housing [3][4].

The squirrel-cage induction machines are mainly increasingly used due to their robustness, i.e. well protected against common risks (sparks, dust, water) [5]. In comparison with wounded induction machines, the squirrel cage types the maintenance costs are lower. The rotor-wound type is mainly used for wind turbine generators because they can operate with variable frequency when connected to the grid [6].

Based on the temperature variation different electric driving machines can be chosen [7]. Another important factor is the duty cycle because the parts temperature is not constant ranging between a minimum and a maximum value.

2 Electric machine model

The machine model has been implemented using the electric machine dedicated heat transfer analysis environment, Motor-CAD. The analysis is performed using thermal circuits. The circuit elements such as thermal resistances and capacitances are obtained based on the geometrical data and material properties. The analytical relations are the ones known for given cases [8][9][10] (horizontal or vertical flat plate for natural or forced convection, horizontal cylinder) and based on experiments.

The basic elements for a thermal approach based on the Motor-CAD environment are presented in many papers [11]–[17].

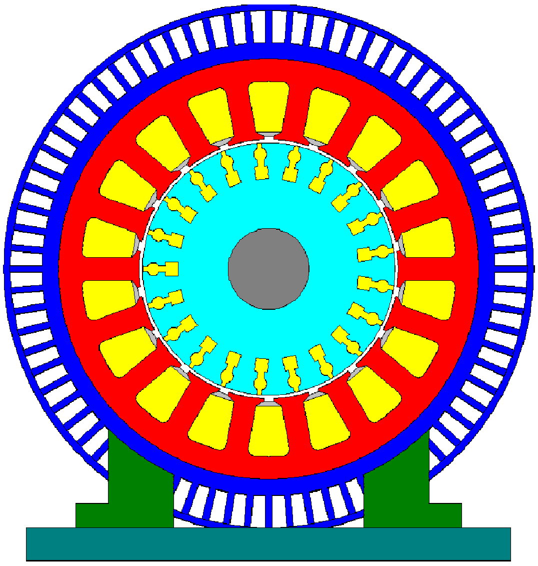


Fig. 1: Radial cross-section of the induction machine model.

From the cooling point of view, the considered type of the three phase induction machine is Totally Enclosed Fan-Cooled (TEFC). The rotor winding is squirrel cage type. The fan is mounted at one end of the mechanical shaft, and in order for the cooling air to be driven along the cooling channels formed by the housing fins a fan-cowling is needed to cover the fan.

The enclosed induction machines have finned housing. Thus, the considered housing geometry has radial disposed fins all over the circumference, as it is shown in Fig. 1.

The fins thickness is 3 mm, the height 10 mm, the pitch 2 mm, and the total number of fins is 76. The machine is supposed to be mounted in horizontal position and placed on a platform, fixed by feet.

In section, the geometry sizes of the implemented model are the following:

- Stator outer diameter = 140 mm;
- Stator bore = 80 mm;
- Rotor outer diameter = 79 mm;
- Rotor inner diameter = 54 mm;
- Air-gap = 1 mm;
- Shaft diameter = 25 mm;
- Shaft height = 90 mm.

The stator lamination has 18 slots with a height of 18 mm. The rotor lamination has 21 slots, and the squirrel-cage is double. The total axial length of the machine is 220 mm.

An axial cross-section of the machine is shown in Fig. 2. The stator winding is impregnated and has one layer. The conductor cross-section is round and its gauge is 0.4547 mm (without insulation) and 0.5055mm (with insulation). The filling factor is 0.4. This factor is defined as the ratio between the surface covered by the round insulated conductors and the available slot surface with the liner present.

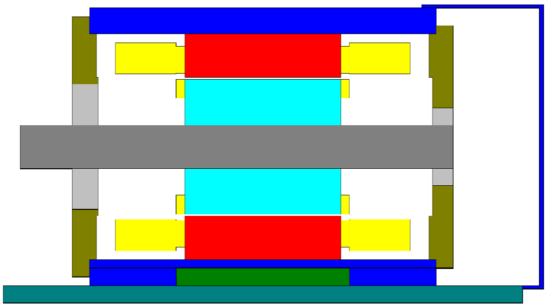


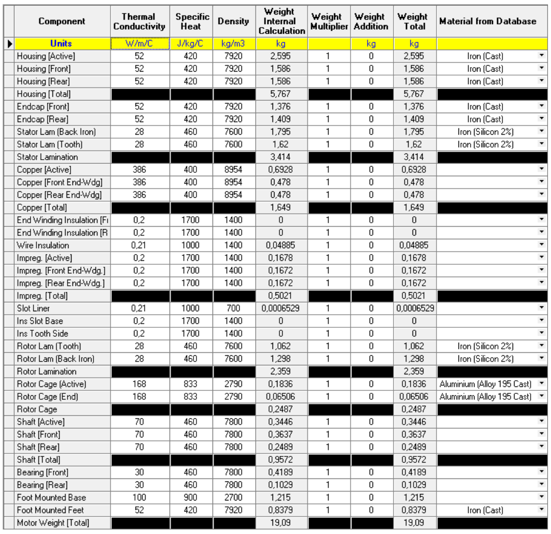
Fig. 2: Axial cross-section of the induction machine model.

3 Parts materials

The materials supposed for the machine parts are the following:

- cast iron for the housing;
- iron alloy with 2% silicon for the stator lamination;
- iron alloy with 2% silicon for the stator lamination;
- aluminum for the rotor squirrel-cage;
- steel for the shaft;
- cast iron for the housing feet.

Some of the thermal properties of the materials can be found on the Motor-CAD material database [18]. In Fig. 3 is shown the machine parts material assignation interface (housing, feet, windings, laminations, shaft) and their thermal properties (thermal conductivity, specific heat, mass density).



Component	Thermal Conductivity	Specific Heat	Density	Weight Internal Calculation	Weight Multiplier	Weight Addition	Weight Total	Material from Database
Units	W/m/C	J/kg/C	kg/m3	kg		kg	kg	
Housing [Active]	52	420	7920	2,595	1	0	2,595	Iron (Cast)
Housing [Front]	52	420	7920	1,586	1	0	1,586	Iron (Cast)
Housing [Rear]	52	420	7920	1,586	1	0	1,586	Iron (Cast)
Housing [Total]				5,767			5,767	
Endcap [Front]	52	420	7920	1,376	1	0	1,376	Iron (Cast)
Endcap [Rear]	52	420	7920	1,409	1	0	1,409	Iron (Cast)
Stator Lam (Back Iron)	28	460	7600	1,795	1	0	1,795	Iron (Silicon 2%)
Stator Lam (Tooth)	28	460	7600	1,62	1	0	1,62	Iron (Silicon 2%)
Stator Lamination				3,414			3,414	
Copper [Active]	386	400	8954	0,6928	1	0	0,6928	
Copper [Front End-Wdg]	386	400	8954	0,478	1	0	0,478	
Copper [Rear End-Wdg]	386	400	8954	0,478	1	0	0,478	
Copper [Total]				1,649			1,649	
End Winding Insulation [Fr	0,2	1700	1400	0	1	0	0	
End Winding Insulation [R	0,2	1700	1400	0	1	0	0	
Wire Insulation	0,21	1000	1400	0,04885	1	0	0,04885	
Impreg. [Active]	0,2	1700	1400	0,1678	1	0	0,1678	
Impreg. [Front End-Wdg.]	0,2	1700	1400	0,1672	1	0	0,1672	
Impreg. [Rear End-Wdg.]	0,2	1700	1400	0,1672	1	0	0,1672	
Impreg. [Total]				0,5021			0,5021	
Slot Liner	0,21	1000	700	0,0006529	1	0	0,0006529	
Ins Slot Base	0,2	1700	1400	0	1	0	0	
Ins Tooth Side	0,2	1700	1400	0	1	0	0	
Rotor Lam (Tooth)	28	460	7600	1,062	1	0	1,062	Iron (Silicon 2%)
Rotor Lam (Back Iron)	28	460	7600	1,298	1	0	1,298	Iron (Silicon 2%)
Rotor Lamination				2,359			2,359	
Rotor Cage (Active)	168	833	2790	0,1836	1	0	0,1836	Aluminium (Alloy 195 Cast)
Rotor Cage (End)	168	833	2790	0,06506	1	0	0,06506	Aluminium (Alloy 195 Cast)
Rotor Cage				0,2487			0,2487	
Shaft [Active]	70	460	7800	0,3446	1	0	0,3446	
Shaft [Front]	70	460	7800	0,3637	1	0	0,3637	
Shaft [Rear]	70	460	7800	0,2489	1	0	0,2489	
Shaft [Total]				0,9572			0,9572	
Bearing [Front]	30	460	7800	0,4189	1	0	0,4189	
Bearing [Rear]	30	460	7800	0,1029	1	0	0,1029	
Foot Mounted Base	100	900	2700	1,215	1	0	1,215	
Foot Mounted Feet	52	420	7920	0,8379	1	0	0,8379	Iron (Cast)
Motor Weight [Total]				19,09			19,09	

Fig. 3: The machine parts material assignation interface.

4 Induction machine duty cycles simulations

In general, the duty cycle represents the numeric values of the electric and mechanic quantities that are encountered during the operation time of a machine. In particular, the rated operating regime corresponds to the rated values of the quantities [19].

The time period of a duty cycle can be established for an electric machine by the integration of the following equation:

$$dt = 2 \cdot \pi \cdot J \cdot \left[M(n) - M_r(n)\right]^{-1} dn$$
$$t = 2 \cdot \pi \cdot J \cdot \int_{n_0}^{n} \frac{dn}{M(n) - M_r(n)} \quad (1)$$

where J represents the inertial moment of rotating masses, M represents the electromagnetic torque developed by the machine, M_r represents the load torque, t_0 represents the initial time moment, and n_0 represents the initial speed.

Thus, the no-load start-up time of the machine ($M_r = 0$) when it is directly connected to the grid is:

$$t_p = 2 \cdot \pi \cdot J \cdot \int_0^n \frac{dn}{M(n)} \tag{2}$$

Usually, the electric machines operate with cyclic duties for which duty is defined as the percent ratio of the driving period and the cycle period. There are standard duties: 15%; 25%; 40%; 60%; 100%.

In the field of electric machine manufacturing, these are designed for a specific duty cycle that is standardized. In the analysis the following duty cycles are examined:

- - S1 – continuous duty;
- - S2 – short-time duty;
- - S3 – intermittent periodic duty;
- - S4 – intermittent periodic duty with starting;
- - S5 – intermittent periodic duty with electric braking.

4.1 S1 – Continuous duty

This duty supposes that the machine works at a constant load for enough time to reach temperature equilibrium (theoretically the time is indefinite – see Fig. 4).

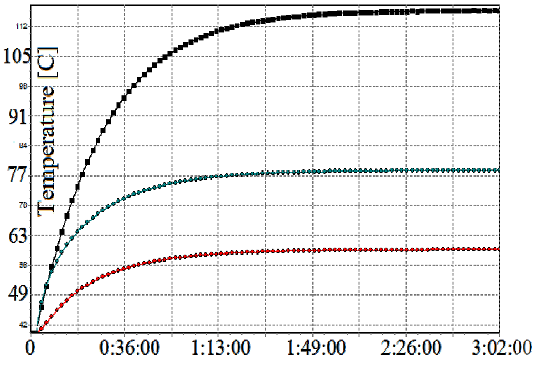


Fig. 4: S1 duty cycle results (bottom: active housing temperature, middle: stator winding temperature, top: rotor squirrel-cage temperature).

For the simulation of this duty the machine is supposed to operate at constant load for 3 hours. The maximum reached temperature is about 125˚C corresponding to the rotor squirrel-cage. The stator end windings have reached at 82.1˚C at the driving end and 82˚C at the fan end, so the values are similar. The active housing region (i.e. the region covering the stator lamination) has had around 59.7˚C. For this analysis the considered heat sources, that are the machine losses, were in totally 274W.

Based on the obtained temperatures, it can be stated that the machine can be F insulation class because the maximum temperature is below the threshold value of 155˚C. The ambient temperature was 40˚C. An inferior insulation class would be B (max. temperature, 130˚C) but if a safety region of 10% is considered then the maximum temperature is 137˚C (i.e. 125˚C × 1.1). Moreover, the machine is loaded at rated value.

4.2 S2 – Short-time duty

The machine works at a constant load, but not long enough to reach temperature equilibrium, and the rest periods are long enough for the machine to reach the cold state (see Fig. 5).

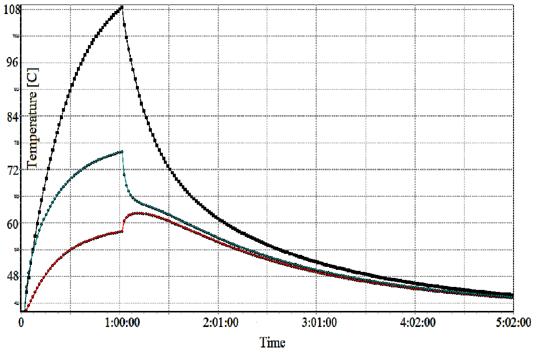


Fig. 5: S2 duty cycle results (bottom: active housing temperature, middle: stator winding temperature, top: rotor squirrel-cage temperature).

In this case the machine is operating for one hour, and after some iteration the obtained pause time needed for the machine to reach the cold state (i.e. the ambient temperature, 40˚C) is about 4 hours.

The maximum temperature obtained during the operation time is 115.8˚C for the rotor squirrel cage. The stator end windings have about 79.6˚C at the driving end and 79.4˚C at the fan end. The active housing region has reached at about 59.7˚C.

4.3 S3 – Intermittent periodic duty

For this duty the machine operates in a sequential mode. One cycle (sequence) contains a constant load period followed by a pause period under the condition that the amount of heat at start-up or stop to be less than 10% of the total amount of heat corresponding to the entire cycle (see Fig. 6). Temperature equilibrium is never reached and the starting current has little effect on temperature rise.

In this case the machine operates at constant load for one hour and afterwards pauses for 2 hours. The duty is in this case 33%. The end windings have reached at 79.6˚C towards the drive end and 79.3˚C at the fan end. The maximum temperature (for the rotor squirrel cage) is 115˚C. It can be observed that the temperature for the active housing increases suddenly when the machine stops and then decreases as it is expected. This increase is due to the fact that when the machine stops the fan is also stopped and so the heat inside the machine is transferred to the environment with a different rate. The forced convection becomes natural convection, i.e. the thermal resistance steps from a lower value to a higher one (vice-versa, the equivalent thermal conductance is dropping).

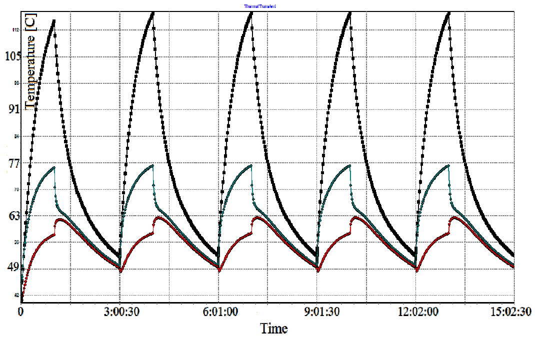


Fig. 6: S3 duty cycle results (bottom: active housing temperature, middle: stator winding temperature, top: rotor squirrel-cage temperature).

4.4 S4 – Intermittent periodic duty with starting

This duty is similar to S3 but the one cycle contains and a start-up period. During the start-up period the amount of heat is greater than 10% of the total amount of the cycle (see Fig. 7). Temperature equilibrium is not reached, but starting current affects temperature rise.

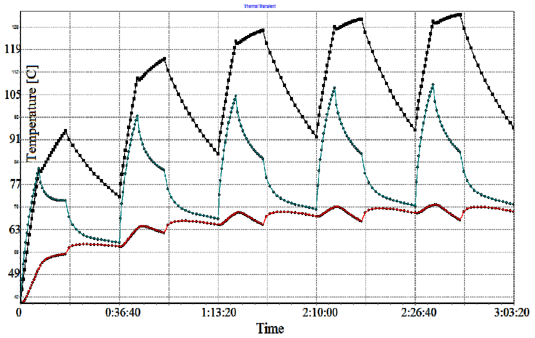


Fig. 7: S4 duty cycle results (bottom: active housing temperature, middle: stator winding temperature, top: rotor squirrel-cage temperature).

In this case the start-up period is 6 minutes and 40 seconds (due to an inertial load) and then for 10 minutes the machine operates at constant load and in the end a pause period of 20 minutes. During the start-up period, the Joule losses are considered higher than the rated value. For a proper evaluation of the insulation class for the studied machine and duty more cycles have been considered and in the end the conclusion was that after 5 cycles the temperature values are repeating. The maximum values obtained are the following: for the stator end-windings 114.3˚C towards the drive side and 113.9˚C for the fan side. The maximum temperature obtained for the rotor squirrel-cage is about 131˚C. From the graphs obtained it can be observed that the rotor cage temperature continues to increase after the machine start-up period while the stator winding temperature decreases. This can be explained by the fact that the rotor assembly has an increased thermal inertia in comparison with stator assembly. As previously explained the heat flows from the interior towards the exterior only through the housing.

4.5 S5 – Intermittent periodic duty with electric braking

This duty is similar to S4 but an additional period is present, the electric break. During the break the dissipated heat is greater than 10% of the entire cycle heat amount (see Fig. 8).

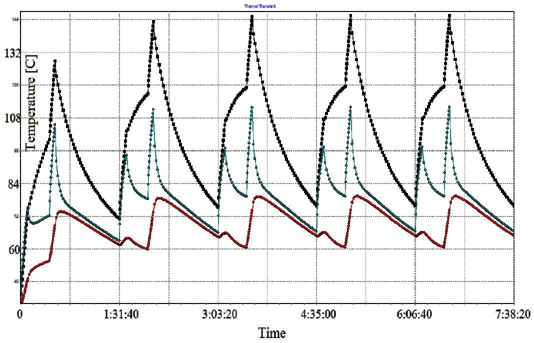


Fig. 8: S5 duty cycle results (bottom: active housing temperature, middle: stator winding temperature, top: rotor squirrel-cage temperature).

In this case the start-up period is 6 minutes and 40 seconds followed by a continuous constant load of 20 minutes and then the electric break for 5 minutes followed by a pause period of 1 hour. The stator end windings have reached the temperature of 139.3˚C for the both ends (driving and fan). The temperature for the rotor cage is 146˚C. In this case it can be also observed that for the analyzed duty cycle the F insulation class is suited.

5 Conclusion

The studies performed with Motor-CAD allow for the evaluation of the field temperature in case of a totally enclosed fan cooled three-phase squirrel-cage induction machine, both for its distribution and hot spots. The temperatures have been obtained for various standard duty cycles. Thus, for all the studied cases, the hot spot is at the rotor cage. The temperature difference between the active housing and the stator end windings are greater than 10˚C, so monitoring the housing temperature is not a good option. Another advantage of this type of analysis is that since the designing stage, it generates the premises for the evaluation of the load capability of the machine without exceeding the threshold value of the used materials (insulation class), especially when used a as a generator into a micro Combined Cooling Heat and Power – with Stirling Engine (mCCHP-SE) system.

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