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HEATING OF AN INDUCTION MOTOR AT REVERSING DUTY

U. Traussnigg, H. Köfler
Institute for Electrical Machines and Drives
University of Technology, A-8010 Graz, Austria

Abstract: This work attempts to find values of thermal resistances for the heating simulation of an induction motor by measurement on this motor. This article works with the assumption of a special case in that it is not possible to bring up an external load torque on the shaft. Nevertheless it should be possible to measure temperatures according to the insulation class of the motor. These claims can be met by the reversing duty of the induction motor with different periods and duty factors. The very useful measurements of rotor temperatures were realised by a measurement transmission with silver sliprings. The base of the equivalent thermal network is a four body model. The thermal capacities were specified by measurement of the different masses and by calculation from drawings. The different losses are broken down by calculation in different parts and used as input for the equivalent thermal network in which only the thermal resistances are unknown. A set of several different measurements (and equations) are available which allow the specification of the thermal resistances.
Keywords: temperature measurement, induction motor, thermal network.

1 INTRODUCTION

For the heating of an induction motor an equivalent thermal network of a four body model was to be developed. It is not possible to weigh the masses of the four bodies separately. So it is necessary to make the possible mass measurements and break down these results by calculation from drawings into the four interesting parts. The thermal capacities of these four bodies are specified as product of these masses and the specific thermal capacities defined for the bodies. In operation the total electric power of the motor can be measured. To split this power into the different losses heating the machine it is necessary to make basic experiments (no-load and short circuit).

The general loss balance is:

$$P = P_{vCuS} + P_{vCoR} + P_{vFeS} + P_{vFeR} + P_{v\rho} \quad [W] \tag{1}$$

P	total losses	$P_{v\rho}$	friction losses
P_{vCuS}	copper losses of the stator	P_{vCoR}	conductor losses of the rotor
P_{vFeS}	iron losses of the stator	P_{vFeR}	iron losses of the rotor

In the equivalent thermal network only the thermal resistances are unknown after these calculations. It is very difficult to determine the thermal resistances by a calculation with physical quantities because the structure of the motor is highly inhomogenous. With measurements of the thermal heating of an induction motor, the thermal resistances might be determined out of experiments. In this paper, there is an additional restriction in the experiments as no mechanical load at the shaft is possible and allowed to support the heating. One possibility to carry out heating measurements in spite of this restriction is the reversing duty of the induction motor.

1.1 Reversing duty

The reversing duty is characterised by a no-load run and a following change of the direction of rotation. Two phases of the induction motor are changed during no-load operation to start the process of reversing the direction of rotation. The essential quantity for the consumed power at the reversing duty is the ratio of the time at no-load t_L and the sum of deceleration time t_B and acceleration time t_A. To specify the motor specific deceleration and acceleration time it is necessary to read the speed-torque characteristic from the current circle diagram.

In weak supply conditions, the currents would be too high for the supply at the nominal voltage of 400V and delta connection. Therefore temperature rise tests at reversing duty were performed at star connection. The current circle diagram and the speed-torque characteristic subsequently were drawn for a phase voltage of U_1 = 231V.

No-load point I_0 = 3.096A, φ_0=78.98° Short circuit point I_k = 63.56A, φ_k=58.4°

With the current and torque value diagrams the rotational speed and the quadratic mean value of the current over time can be determined approximately (for example by graphical integration). Of course this only works with the simplifying assumption, that M(s) and I(s) during the deceleration and acceleration process are in accordance with the current circle diagram, which is regarded only valid for quasi stationary but not for dynamical processes.

So n(t) can be calculated from

$$t=\Theta\cdot\int\frac{1}{\mathrm{M}-\mathrm{M}_{vr}}\cdot d\omega_m \quad \text{with } \Theta = 0.0773\text{kgm}^2;\; \mathrm{M}_{vr}=\frac{\mathrm{P}_{vr}}{\omega_m}=1.443\text{Nm} \text{ and } n=\omega_m\cdot\frac{60}{2\pi} \tag{2}$$

The time for the deceleration process from no-load rotating speed to standstill results to t_B=0.211s, the acceleration time from standstill to the no-load speed results to t_A=0.151s and the reversing duty without time at no-load run results to t_B+t_A=0.362s.

To specify the value of the whole reversing duty t_{Rev} with the premise that the loss power consumed in the motor is approximately the loss power at nominal load it is necessary to calculate the different losses during the deceleration and the acceleration.

The quantity of heat generated in the rotor circuit during the acceleration can be calculated to [2]:

$$W_2=\int P_2\cdot dt=\int 2\pi n_2\cdot M\, dt=2\pi n_{syn}\cdot\Theta\int s\, d\omega_m=-\Theta\,\omega_{syn}^2\cdot\int_{s_1}^{s_2} s\, ds=\frac{\Theta\cdot\omega_{syn}^2}{2}\cdot\left(s_1^2-s_2^2\right) \tag{3}$$

Now the quantity of heat of the rotor circuit for the reverse of the direction of rotation, corresponding to the change of slip from s_1=2 to s_2=0, is calculated to

$$W_2=4\cdot\frac{\Theta\cdot\omega_{syn}^2}{2} \tag{4}$$

The quantity of heat generated in the stator winding can be calculated approximately by the product of the heat in the rotor and the ratio of the ohmic resistances R_1 and R_2'. So the energy deposed in the stator and the rotor windings during the reverse of the direction of rotation results to:

$$W_{Rev}=4\cdot\frac{\Theta\cdot\omega_{syn}^2}{2}\cdot\left(1+\frac{R_1}{R_2'}\right)=7551.55\text{Ws} \tag{5}$$

The consumed power during the reverse duty is calculated to:

$$P_{Rev}=\frac{W_{Rev}}{t_B+t_A}=20768.8\text{W} \tag{6}$$

With the knowledge of the no-load losses P_{v0} = 410.05W, the nominal losses $P_{vN} = P_N(1-\eta)$= 1950W (for η = 0.87) and the following equation

$$P_{vN}\cdot t_{Rev}=P_{Rev}\cdot\left(t_B+t_A\right)+P_{v0}\cdot t_L \tag{7}$$

the duration of the whole reversing duty results to:

$$t_{Rev}=t_L+t_B+t_A=\frac{\left(P_{Rev}-P_{v0}\right)\cdot\left(t_B+t_A\right)}{P_{vN}-P_{v0}}=4.79\text{s} \tag{8}$$

It can be recognised that the power can be controlled by modification of t_{Rev} respectively t_L.

2 MEASUREMENT

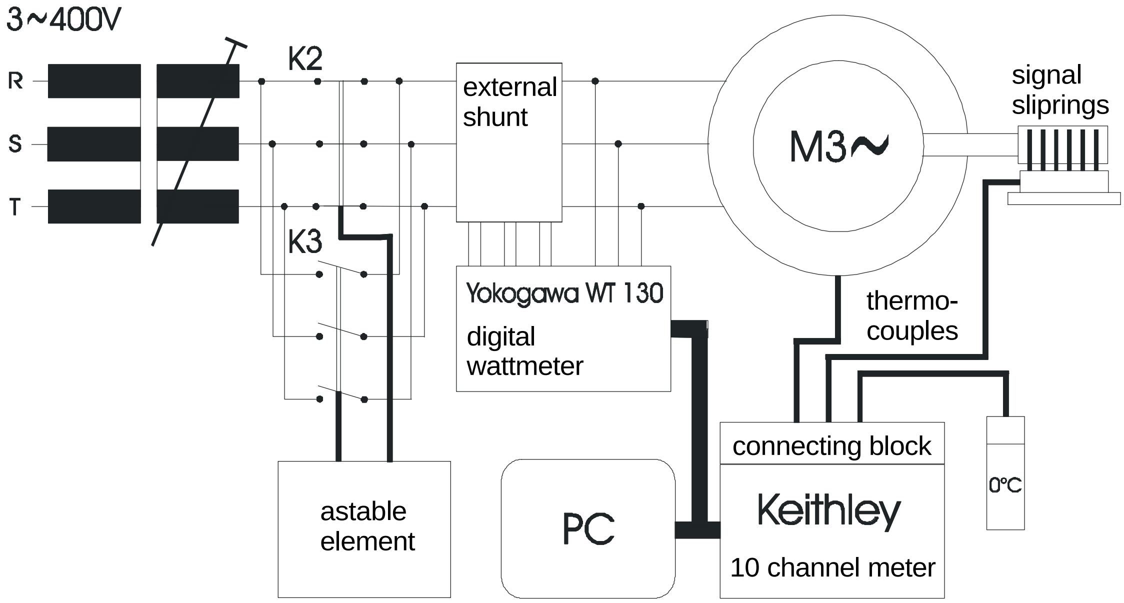

Figure 1. measurement circuit

At reversing duty the exchange of two phases is performed by two 63A-contactors connected in reversing combination. The supervision of the 230V-control circuit at reversing duty is taken over by a 10A/230V-centre-zero relay which is triggered by a standard oscillator circuit with a timer NE 555D.

Because of the high currents exceeding the upper range limit of 20A (wattmeter) at the short circuit test as well as at the reversing duty, the currents are measured with an external shunt [4] which provides a voltage of 2.5V corresponding to a current of 50A. The calibration ratio of the shunt was detected by an experimental current voltage measurement over the whole interesting measurement range.

The wattmeter works with a scanning frequency of 45kHz and refreshes the display every 250ms. To get stable measurement values during the temperature rise test at reversing duty a floating (linear) averaging over the last 64 measurement values was performed.

Eight copper constantan thermocouples measure the overtemperatures of the induction motor. A thermocouple generates a voltage in mV range if there is a temperature difference between the welded contact point of copper and constantan and both other ends, in this case screwed to the connecting block. This voltage is measured by a digital meter with a built in 10-channel multiplexer. For the polarity it is necessary to note that copper has a higher potential than constantan if the temperature of the contact point (measuring spot) is higher than the temperature of the connecting point.

All measured temperatures represent temperature differences between the particular absolute temperature of the body and the temperature of the connecting block (10 channel meter). However the temperature of the connecting block is not stable because of the environmental conditions and is not suitable as a reference temperature. The heat emission of the induction motor to the surrounding is warming the connecting block where the thermocouples are plugged in. The effect is that the measured overtemperatures of the induction motor are too low. To shield the connecting block from the heat emission of the induction motor the connecting block was installed into a polystyrene container. To ascertain the temperature drift of the connecting block temperature, one of the thermocouples is dipped into ice water. This thermocouple generates the temperature of the connecting block against the temperature of 0°C with high accuracy. The measured motor temperatures can be corrected according to the temperature drift of the connecting block by adding the apparently increase of the ambient temperature $\vartheta_{U,abs}$ to the measured motor temperatures:

$$J_k = J + J_{A,abs} - J_{A,abs}^{\text{begin of measurement}} \qquad (9)$$

The next equation is an example for the calculation of the overtemperatures from the thermal electromotive force. The shown numerical coefficients are valid for the thermocouples of the induction motor, but not for the thermocouple dipped into the ice water which is working in an other temperature range. The coefficient K($\vartheta_{A,abs}$) depending on the ambient temperature was determined experimentally.

$$J = 23370 \cdot U_{th} - \underbrace{0.0411}_{K(J_{A,abs})} \cdot J_{A,abs} + 1.1147 \qquad [°C] \qquad (10)$$

All measured values were transferred via the GPIB-Bus to the PC and used for different calculations in LabView. In principal the LabView program consists of three modules handled in a temporal order:

- Reading the impulse frequency of the incremental encoder and conversion into the number of revolutions per minute
- Reading the electrical voltage, current and active power
- Reading the eight thermal e.m.f. and conversion into °C

The overtemperatures of the rotor are transmitted over sliprings. For this purpose a bore was drilled from the end of the shaft till behind the bearing to thread the thermocouples into the shaft. The sliprings are mounted at the end of the shaft. The brushes transferring the thermal e.m.f from the rotating system to the stationary environment heat up during the run of the motor. So the temperatures of the rotor would be measured also too low. Therefore a thermocouple is used to measure the temperature of the brushes used for correcting the measured temperatures of the rotor.

2.1 Measurement at reversing duty

The duration of the reversing duty cycle at this measurement amounts t_{Rev}=3.6s. The measured total active power is P_{vTotal} = 2381.08W as mean average over all measurements. To assign this power to the machines different loss sources the following considerations and calculations are necessary.

We assume that the iron losses in the stator and the friction losses are approximately constant during the whole duty cycle, because they are not constant over only 10% of the cycle time. They can be calculated in the following way:

with P_{v00}= 381.72W (from a no-load measurement for U_1=231V) and $P_{v\rho}$= 226.06W
results $P_{vFeS} = P_{v00} - P_{v\rho}$ = 155.66W

The iron losses in the rotor for f_2 = 50Hz are calculated from the iron losses in the stator with the ratio of the iron masses:

$$P_{vFeR}^{reverse} = P_{vFeS} \cdot \frac{m_{FeR}}{m_{FeS}} = 92.82W \qquad (11)$$

The iron losses in the rotor change their value proportional to the frequency in the rotor. The calculated value can be taken as mean value for a change of the rotating direction from f_2 = 100Hz to f_2 = 0Hz. As these iron losses occur only in the short time of reversing but are negligible during the no-load run they are calculated for the whole reversing duty to be:

$$P_{vFeR} = P_{vFeR}^{reverse} \cdot \frac{t_B + t_A}{t_{Rev}} = 9.34W \qquad (12)$$

The conductor losses in the rotor for the entire reversing duty amount to:

$$P_{vCoR} = \frac{4 \cdot \frac{\grave{E} \cdot \grave{u}_{syn}^2}{2}}{t} = 1063.1W \qquad (13)$$

The copper losses in the stator can be calculated from the mean value of the measured total active power over all measuring points (P_{vTotal}). The fan and friction losses are not assigned to any of the four heating sources in the simulation. They are retarding during the acceleration and increase the rotor conductor losses, but they support the deceleration and decrease the rotor conductor losses. As these effects are approximately in balance the fan and friction losses are first be calculated by the factor $[t_{Rev} - (t_B+t_A)]/t_{Rev}$ before subtracted from the losses.

$$P_{vCuS} = P_{vTotal} - P_{vCoR} - P_{vFeS} - P_{vFeR} - P_{v\rho} \cdot \frac{t_{Rev} - (t_B + t_A)}{t_{Rev}} = 949.66\,W \quad (14)$$

Another possibility to determine the copper losses in the stator and the conductor losses in the rotor for verification of the preceding calculation is the calculation with current readings. The wattmeter displays and transmits current as the arithmetic mean value of measured root mean square values during the entire reversing duty. This is not equivalent to the root mean square value which is responsible for the Joule heating in the motor. From the current circle diagram we find that the current $I_{eff,reverse}$=58.643A flows almost all the time of reversing the rotating direction (t_B+t_A=0.362s) and the no-load current I_{10}=3.096A flows during the remaining time of no-load ($t_{Rev}-t_B-t_A$=3.6s), that implies:

$$I_{eff} = \sqrt{\frac{1}{t_{Rev}} \cdot \int_0^{t_{Rev}} I^2 \cdot d\tau} \approx \sqrt{\frac{1}{t_{Rev}} \cdot \left[I^2_{eff,reverse} \cdot (t_B + t_A) + I^2_{10} \cdot (t_{Rev} - t_B - t_A) \right]} = 18.83 \quad (15)$$

giving the arithmetic mean value

$$\bar{I} = \frac{1}{t_{Rev}} \cdot \left[I_{eff,reverse} \cdot (t_B + t_A) + I_{10} \cdot (t_{Rev} - t_B - t_A) \right] = 8.683\,A \quad (16)$$

which corresponds very good to the mean value measured I_{mean} = 8.758A.

Now, with this I_{eff} the losses can be calculated:

$$P_{vCuS} = 3 \cdot R_{1,W1-W2}^{20°C} \cdot I^2_{eff} = 979.13\,W \quad (17)$$

$$P_{vCoR} = 3 \cdot R'_2 \cdot I^2_{eff} = 1014.22\,W \quad (18)$$

These results are similar to the earlier results.

3 SIMULATION

The higher the order of the body model the more complicated is the calculation and the search for the relevant thermal capacities, the thermal resistances and the loss sources. As the most interesting temperatures are the mean temperatures of the rotor conductor, the rotor iron, the stator copper and the stator iron we choose a four body model for simulation.

The thermal capacities are calculated as described before. The measured losses are broken down to element parts and used as input for the equivalent thermal network. There are different ways to determine the thermal resistances. For example they can be calculated from the measured prominent thermal time constants of each measured channel (each channel consists all time constants).

The four body model was simulated with PSPICE™.

3.1 Measurement at reversing duty

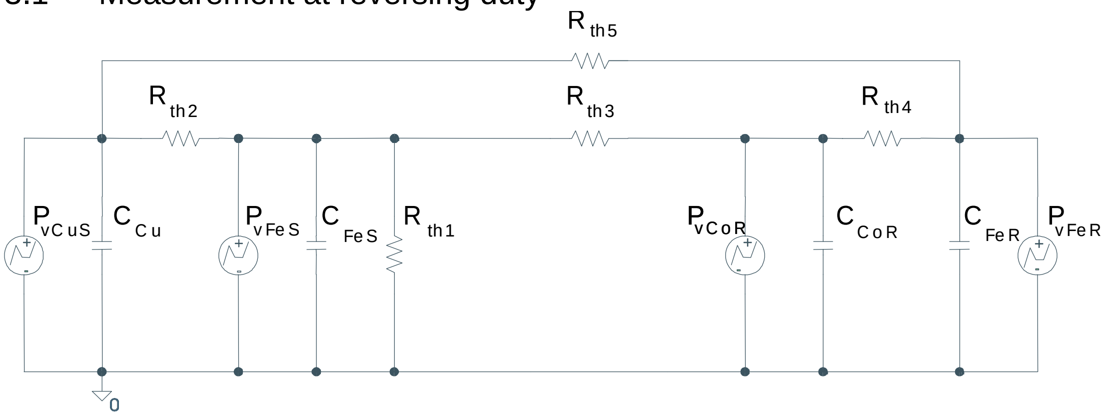

Figure 2. simulation circuit of the thermal network

The values of the thermal resistances are:

$R_{th1} = 0.033 - 0.000209\ \vartheta_{FeS}$ [°C/W] $R_{th2} = 0.040$ [°C/W] $R_{th4} = 0.002$ [°C/W]
$R_{th3} = 0.13$ [°C/W] $R_{th5} = 0.2$ [°C/W]

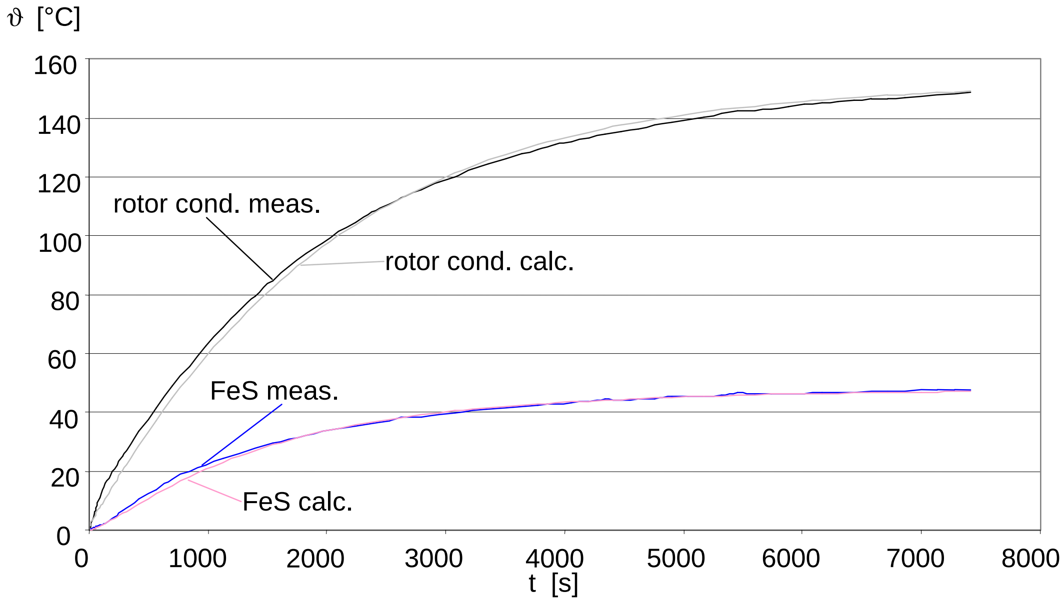

Figure 3. measurement and simulation result at reversing duty U3S1

4 DISCUSSION

Comparing the simulation results and the measured temperatures in figure 3 we see that the four body model delivers temperatures in good agreement with the experimental tests. The restricted place in this paper does not allow to discuss the problems of the measurement and the simulation in detail. The measurements performed at different fictitious loads have proved very useful in testing various methods to determine thermal resistances of induction motors.

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AUTHOR(S): Univ. Ass. Dipl.-Ing. Udo TRAUSSNIGG, A.o. Univ.-Prof. Dr. Hansjörg KÖFLER, Institute for Electrical Machines and Drives, TU Graz, Kopernikusgasse 24, A-8010 Graz, Austria, Phone Int ++43 316 873 8102, Fax Int ++43 316 873 8103, E-mail: traussnigg@ema.tu-graz.ac.at