

# NEW METHOD FOR ROTOR TEMPERATURE ESTIMATION

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*Abstract: This paper presents a new method for observing the rotor temperature of high-power squirrel cage induction machines in measurable variables. The method is based on the fact that the rotor resistance depends on the actual rotor temperature. The main problem is to separate the changes in the rotor resistance due to temperature and skin effect. By comparing the input impedance with a known circle diagram measured in the start-up phase, it is possible to calculate changes in the rotor temperature. Further analyses also make it possible to obtain the absolute rotor temperature at any time.*

*Keywords: induction machine, thermal protection, rotor temperature, differential measurement.*

## 1 INTRODUCTION

Due to their high reliability and their robust construction, induction machines with a squirrel cage are installed in many areas of industrial practice. In the past decade, research in protection technique and instrumentation technology have brought some new methods for the measurement of protection-relevant variables, their link to instrumentation and control technology and, finally, their analysis. Effective supervisory systems have two positive effects: the lifetime of the machine can be prolonged and the working range of the machine and of the following process can be expanded. Still a critical variable for induction machines, in particular for those of high power, is the rotor temperature. Direct measurement of the rotor temperature requires considerable effort and it is not very reliable. During the last few years, a number of methods for calculating the rotor temperature have been published: prediction procedures calculate the actual rotor temperature by using thermal models [1-4] or neural networks [5], and other procedures use the effects of the rotor temperature on directly measurable variables [6-10]. Although a few of these ideas are very innovative, they still do not satisfy the practical requirements. The reason for this is on the one hand the lack of general applicability of some methods or the complexity of measurement, and, on the other hand, the sensitivity to disturbances or the ignoring of non-linear effects. The main problem in observing the rotor temperature in measurable variables is to separate the effects due to skin effect and temperature. Thus, even today a simple interlocking rule is implemented in most protection devices. The corresponding algorithm was developed on the basis of a very simple first order thermal model. This kind of modelling is quite conservative, so that the machine and the process are not used optimally.

At the Institute of Power Engineering at the Saarland University a new method for observing *changes* in the rotor temperature in measured variables has been developed. In the second section this new method, called compensation method, is described. Subsequently, a new algorithm using the results of this compensation method for calculating the absolute rotor temperature is presented. Finally the results obtained are shown.

## 2 COMPENSATION METHOD

The principle is based on the fact that during the start-up phase each induction machine has its own typical impedance circle diagram. This diagram is the "*fingerprint*" of the machine. The idea of this method is to determine the actual heating status of the rotor by evaluating changes in this circle diagram.

Figure 1 shows the well known equivalent circuit diagram of the induction machine. It is obvious that the input impedance depends on the values of the model parameters, on the temperature of stator and rotor and on the slip. An increase in the rotor temperature has the equivalent effect on the input impedance like a reduction of the slip. This fact gives the presented method the name "*compensation method*" and it is used in the following manner: by having two impedance circle diagrams with additional information about the slip, the temperature difference between points of identical slip can be

determined. In this article, the first impedance circle diagram is called "the reference diagram" and the other "the measurement diagram".

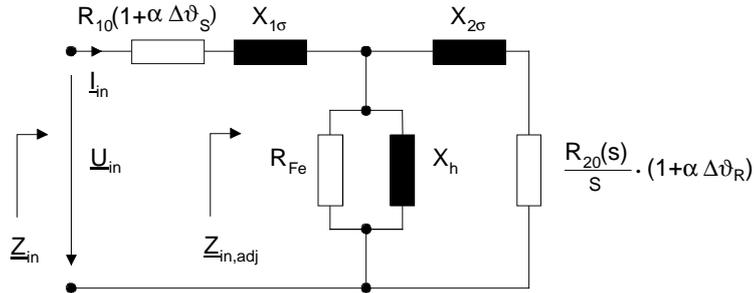


Figure 1. Equivalent circuit diagram of an induction machine

Both impedance circle diagrams are shown in Figure 2. The impedance phasor moves clockwise during the start-up phase. During the measurement the rotor of the machine was about 20 °C hotter than during the reference start-up. Therefore, the point x of the measurement circle diagram, which has the identical slip to the point p of the reference circle diagram, now corresponds to point q.

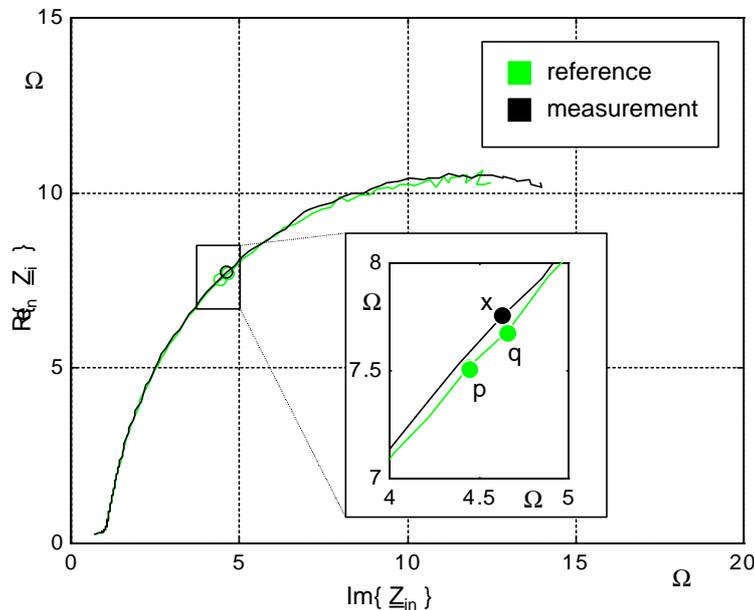


Figure 2. Impedance circle diagram of the reference and the measurement

The rotor temperature difference between the points with identical slip (points x and p) can now be evaluated. The input impedance and the rotor resistance are equal at the points x and q:

$$R_{R_{x,meas}} = R_{R_{q,ref}} \quad (1)$$

The indices "meas" and "ref" refer to measurement and reference impedance circle diagram, respectively.

In more detailed form, equation (1) can be rewritten as follows:

$$\frac{R_{20}(s_{x,meas})}{s_{x,meas}} \cdot (1 + \alpha \cdot (\vartheta_{R_{x,meas}} - \vartheta_0)) = \frac{R_{20}(s_{q,ref})}{s_{q,ref}} \cdot (1 + \alpha \cdot (\vartheta_{R_{q,ref}} - \vartheta_0)) \quad (2)$$

In (2)  $\vartheta_0$  is the reference temperature (generally  $\vartheta_0 = 20 \text{ }^\circ\text{C}$ ). The absolute difference of the electrical rotor frequency between the points x and q can be neglected:

$$R_{20}(s_{x,meas}) = R_{20}(s_{q,ref}) \quad (3)$$

Thus, the parameter  $R_{20}(s)$  is omitted from the equation (2). This implies that the skin effect has no influence on this method. Using the difference temperature as defined in equation (4), equation (3) can be converted into equation (5).

$$\vartheta_{DR,x} = \vartheta_{R_{x,meas}} - \vartheta_{R_{p,ref}} \quad (4)$$

$$\vartheta_{DR,x} = \frac{1}{\alpha} \left( \frac{s_{x,meas}}{s_{q,ref}} - 1 \right) + \vartheta_0 \left( 1 - \frac{s_{x,meas}}{s_{q,ref}} \right) + \left( \frac{s_{x,meas}}{s_{q,ref}} \vartheta_{Rq,ref} - \vartheta_{Rp,ref} \right) \quad (5)$$

It is obvious that the calculated rotor difference temperature  $\vartheta_{DR}$  depends on the measured slip  $s_{meas}$ , the temperature coefficient of the rotor material  $\alpha$  and the reference rotor temperature  $\vartheta_{R,ref}$ . The reference rotor temperature has no essential influence on the difference temperature. This dependence is used in the next paper section to estimate the reference rotor temperature with high accuracy. Another disturbance, the stator temperature  $\vartheta_s$ , can be eliminated by using an adjusted impedance on which the stator has no influence; see equation (6). The stator resistance  $R_{10}$  and the stator temperature  $\vartheta_s$  can easily be measured.

$$Z_{in,adj} = Z_{in} - R_{10} \cdot (1 + \alpha \Delta\vartheta_s) \quad (6)$$

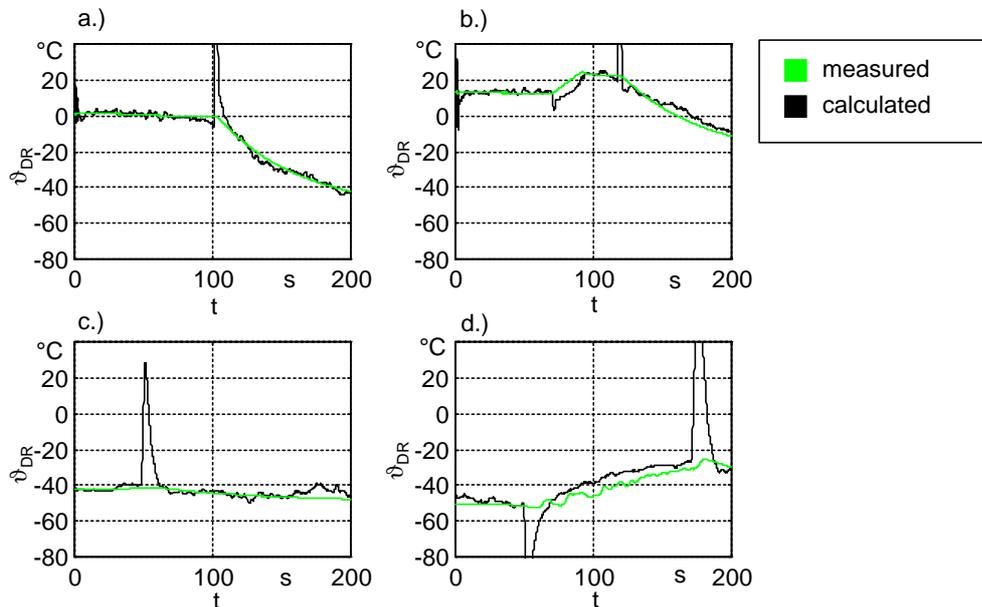
The presented method was tested with a 75 kW flywheel load induction machine under different operating conditions. The characteristics of the test-machine are summarised in Table 1. The results of the tests are presented in Figure 3. Table 2 shows the different operating conditions of the machine.

**Table 1.** Characteristics of the test-machine

Nominal voltage	$U_n$	380 / 220 V
Nominal current	$I_n$	150 A
Nominal power	$P_n$	75 kW $\Delta$
Power factor	$\cos\varphi$	0,82
Rated speed	$n_n$	1475 min <sup>-1</sup>
Pole pairs	$p$	2
Start-up time	$T_s$	100 s

**Table 2.** Operating conditions of the test-machine

Figure	Operating condition
3a.)	Start-up until 100 s, load application of 21 kW after 100 s.
3b.)	Load application of 45 kW during the start-up phase, after 70 s. Load rejection after 90 s. Load application of 45 kW after 120s.
3c.)	Steady-state operation, load change after 55 s from 45 kW to 26 kW.
3d.)	Steady-state operation, load change after 50 s from 26 kW to 61 kW and after 170 s from 61 kW to 29 kW.



**Figure 3.** Measured and calculated rotor difference temperature for different operating conditions

It can be concluded that the presented method gives excellent results under all tested operating conditions of the machine. Only for a short period after load changes, can the difference temperature not be observed. This is due to the electromechanical transient reactions which are caused by these load changes. If the absolute reference temperature was known in advance, it would also be possible to calculate the actual absolute rotor temperature by simple addition. In the following section, an algorithm for absolute reference temperature estimation is presented. Two similar start-ups represent the data basis of this algorithm. The evaluations have to be made only once during commissioning to obtain the absolute rotor reference temperature.

### 3 ALGORITHM FOR ABSOLUTE ROTOR TEMPERATURE ESTIMATION

The thermal transfer function in the Laplace-domain as shown in Figure 4 is the starting point of this algorithm. Here the input variable is a current dependent power loss  $P_V$  which is proportional to the square of the stator current  $I_s$ . The output variables are the stator and the rotor temperature ( $\vartheta_S, \vartheta_R$ ).

The key idea of the algorithm is to estimate the parameters of the rotor model  $F_R(p)$  by using the result of the compensation method and the stator model  $F_S(p)$ . The stator model can easily be identified by means of the measured stator temperature.

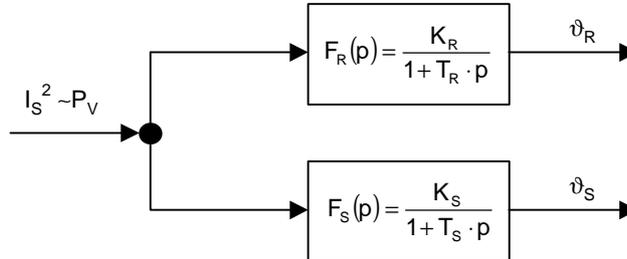


Figure 4. Thermal transfer function

The principle of the algorithm for the rotor temperature estimation is shown in Figure 5. It is assumed that the **proportions** of the model parameters for the heating of the machine during the start-up phase and for the cooling of the machine during the steady-state operation are identical. For identifying the thermal models, a least square algorithm is used.

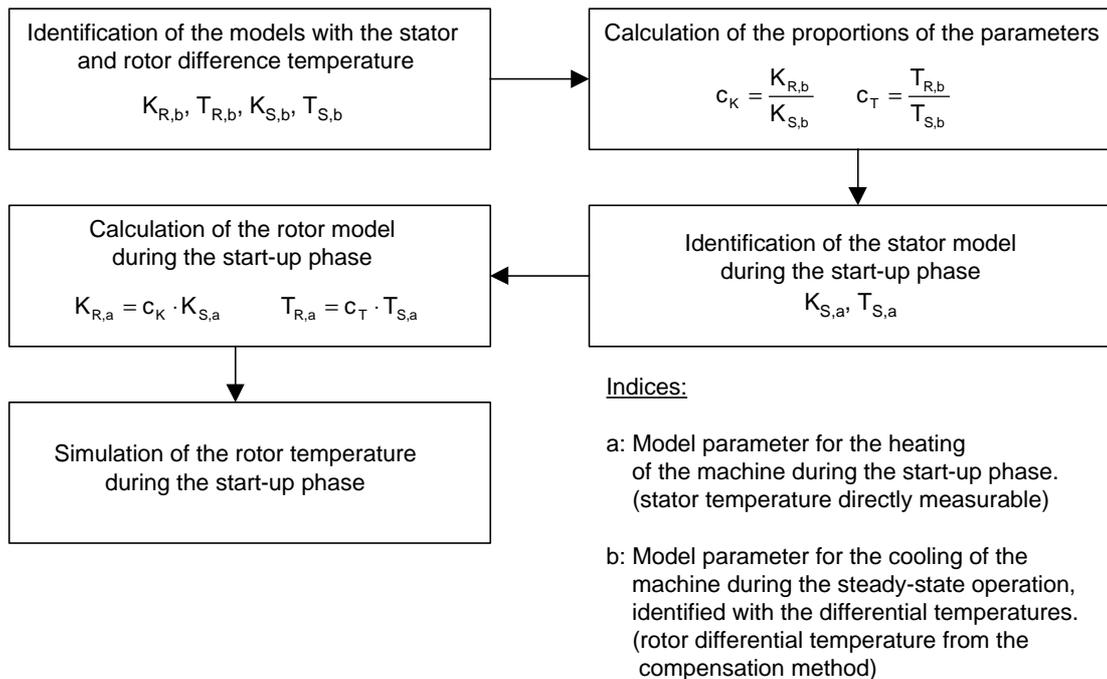


Figure 5. Algorithm for the rotor temperature estimation

In the next step, the dependency of the reference rotor temperature and the difference rotor temperature given by equation (5) can be used to estimate the reference rotor temperature. By combining the algorithm shown in Figure 5 with the compensation method described in section 2, it is possible to obtain an algorithm for adaptive calculation of the reference rotor temperature. As already mentioned, two similar start-ups represent the data basis of the algorithm. The principle of this adaptive reference rotor temperature estimation is shown in Figure 6. First, with a random reference rotor temperature  $\vartheta_{R,0}$ , the compensation method is started. The result of the compensation method, the difference rotor temperature  $\vartheta_{DR}$ , is used as an input variable for the algorithm described in Figure 5. The result of this procedure is the absolute rotor temperature  $\vartheta_R$  again. This loop is repeated until the calculated rotor temperature no longer changes. For testing the algorithm reliability, it is necessary to check that the finally calculated rotor temperature is independent of the algorithm initialisation. The results of two runs with different initial values are presented in Figure 7. The first

calculation (A) started with a rotor temperature increment from 20°C to 30°C, the second calculation (B) started with an increment from 20°C to 200°C.

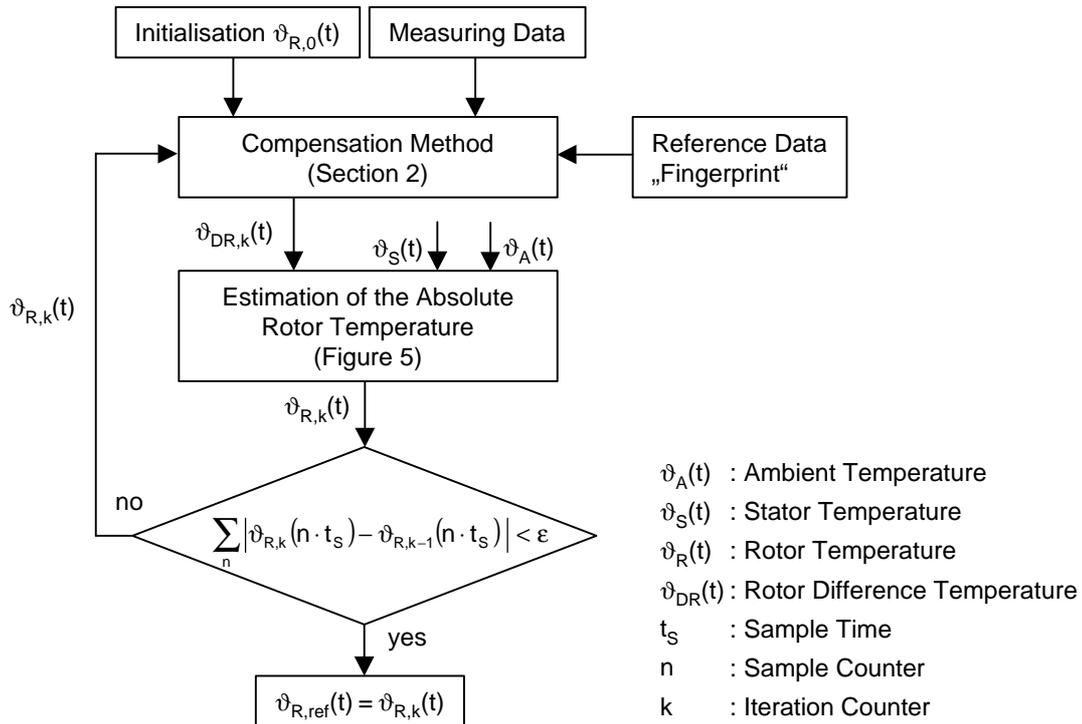


Figure 6. Principle for adaptive rotor temperature estimation

The simulations show that the calculated rotor reference temperatures converge to the same result after three iterations, independently of the selected initial values. Thus, the fingerprint of the machine is complete and it is possible to calculate the absolute rotor temperature by adding the rotor reference temperature and the result of the compensation method. As an example, the result of such a calculation - using the difference temperature from Figure 3a - is given in Figure 8.

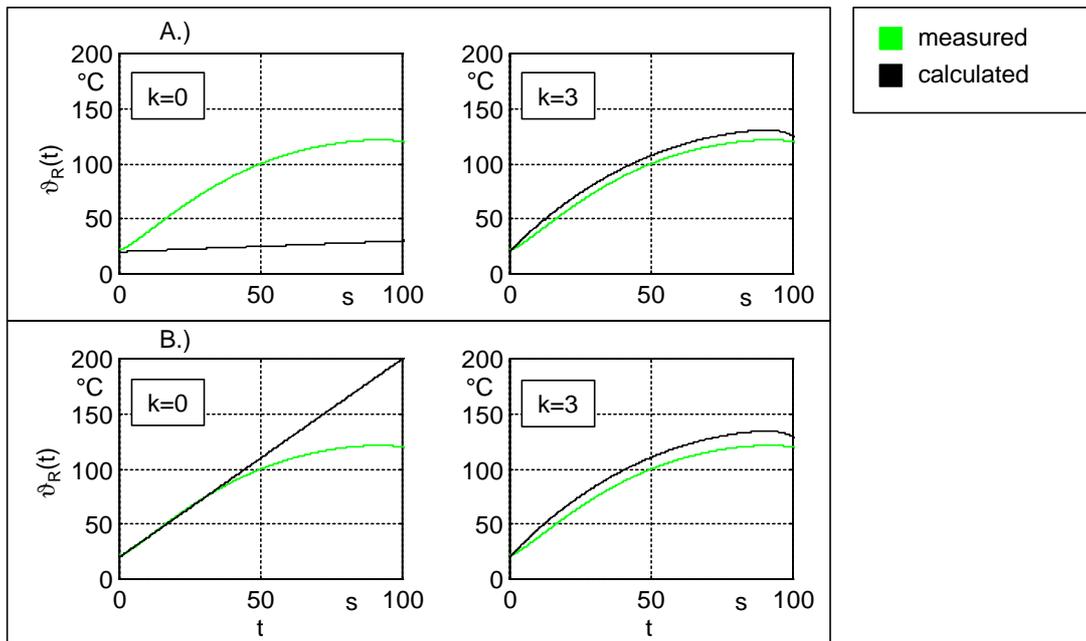
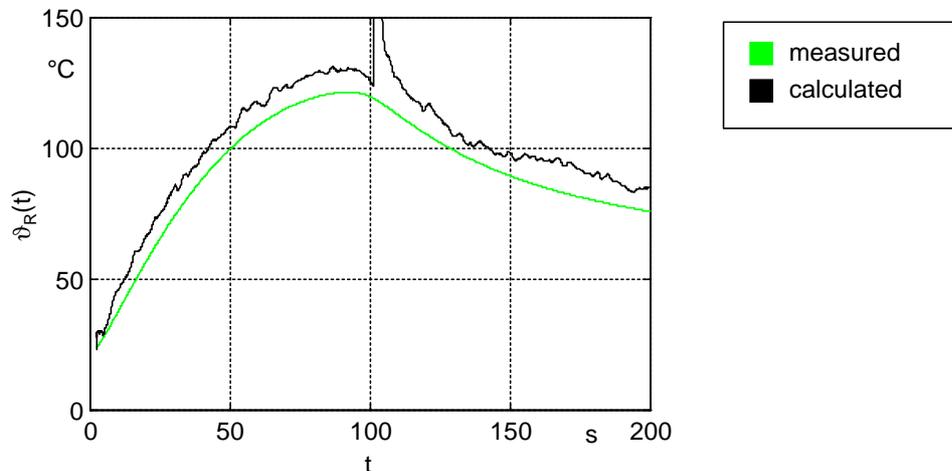


Figure 7. Results of the simulations

## 4 CONCLUSIONS

In this paper a new method for observing the rotor temperature in the input impedance of an induction machine is presented. In the first step, the temperature difference to a reference is detected by using the dependency of the impedance circle diagram on the rotor temperature. This method is called compensation method. Because this method has the characteristic of a differential measurement, the main problem, separating the changes of the rotor resistance due to skin effect and temperature, can be solved.



**Figure 8.** Measured and calculated absolute rotor temperature

In the second step, the result of the compensation method and the measured stator temperature are used in an algorithm for absolute rotor temperature estimation. Here the thesis was established that the proportions of the thermal stator and rotor model parameters for the heating of the machine during the start-up phase and for the cooling of the machine during the steady-state operation are identical. By combining these two procedures it is possible to calculate the absolute reference rotor temperature. Thus, the absolute rotor temperature can be obtained by addition at any time. The applicability of the method was demonstrated on a 75 kW induction machine.

## REFERENCES

- [1] A. Eltom, N. Moharari: Motor temperature estimation incorporating dynamic rotor impedance. *IEEE Transaction on Energy Conversion*, 6 (1991), No.1, 1991, p. 107-113.
- [2] A. Bousbaine: Thermal modelling of induction motors based on accurate loss density distribution. *Electrical Machines and Power Systems*, 27 (1999), No.3, 311-324.
- [3] E. G. Egorov, V. S. Genin, N. M. Mikhailov: Microprocessor thermal-safety relay for induction motors with short-circuit rotor. *Russian Electrical Engineering*, 68 (1997), No.1, S. 68-71.
- [4] M. S. Rajagopal; K. N. Seetharamu: Transient thermal analysis of induction motors. *IEEE Transaction on Energy Conversion*, 13 (1998), No. 1, S. 62-69.
- [5] R. Busch, S. Hilfert: On-line-Bestimmung der Temperatur von elektrischen Maschinen mittels Neuronaler Netze. *ELEKTRIE*, 52 (1998), Nr. 1-2, S. 56-61.
- [6] B. Amin: Principle of the direct determination of the temperature-dependant rotor and stator resistance of an induction motor. *ETEP*, 8 (1998), No. 1, pp 69-71.
- [7] M. Schrödl: Identifikation der Rotortemperatur einer Käfigläufer-Asynchronmaschine. *e&i* 105 (1988), Nr. 7/8, 315-318.
- [8] O. V. Thorsen, M. Dalva: Methods of condition monitoring and fault diagnosis for induction motors. *ETEP*, 8 (1998), No. 5, 383-395.
- [9] C. Ghita, H. G. Schuster: Short-circuit/overload protection of induction motors using a calorimetric method. *Proc. of the 31<sup>st</sup> Internat. Intelligent Motion Conf.*, Nürnberg 1997, 317-321.
- [10] Th. Vetter: Überwachung und Prädiktion des Erwärmungsverhaltens einer ASM mit Käfigläufer mittels Parameterschätzung. *TH Darmstadt, Diss.* 1988.

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