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The Use of EKF to Estimate the Transient Thermal Behaviour of Induction Motor Drive

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Abstract: In this paper, a survey is conducted to examine the problem of estimating the states and parameters of an asynchronous machine when some of these measures are not available or the estimation approach is the best solution. The modeling is based on the theory of power dissipation; heat transfer and the rate of temperature increase the stator and the rotor, taking into account the effect of speed on trade. The first purpose of this article is displayed the effect of variable losses depending on the load and constant losses on the thermal behavior of asynchronous motor. According to the sensor's problems and the obtaining of the thermal information about the rotor, the second goal is the use of a sensorless method like the use of the EKF (extended Kalman filter), some simulation results are given and commented.

Key words: Induction machines, electrical machine losses, thermal models, thermal study, Kalman filter.

1. Introduction

Nowadays, the asynchronous machine is used more and more in the industrial domain. Indeed, it is appreciated for its standardization, its great robustness and its low costs of purchase and maintenance. For several years, we have noticed the widening of the scientific and manufacturer works concerning the drive of these machines [1]. The research of the electromechanical devices more and more flexible supported the appearance of the new particularly powerful systems. These systems generally rest on the association of an electronic device, allowing the control of the global system, and a rotating machine ensuring electromechanical conversion [1], however the increase in the specific powers and the use of novel control modes induce the harmonics of time [2] with frequencies beyond the audible aria, even with square wave voltages [1], the adaptation of our machines to this new applications generates more important internal heating. A rigorous study of the thermal behavior of the electric machines is increasingly necessary [2].

Many authors describe the use of sensor as solution to the thermal problems of the induction machine [3] like infra-red sensor [4, 5], thermocouple [4, 6-9], on the other hand, the first one gives a surface temperature measurement so the measurement is not accurate [3], and the second one can require some machining for a correct placement, but it has the merit to be able to provide internal temperatures in exiguous places of the machine [3].

The problem of obtaining the rotors thermal information gene the sensor measurement procedure to be successful, however some solutions in the specialized literature can be cited, an optical link between the stator and the rotor proposed in Refs. [4, 6, 10, 11] proposes an industrial rotary transformer, using a rings and brushes [4], a high frequency or infrared modules, all these methods are discussed in Ref. [3]. In addition to the stator and the rotor, the use of sensors

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increases the installation cost and practically all sensors are fragile and render the installation most complex. Access to the rotor flux, current, speed and temperature which eliminate all out sensors and make our installation less complex, these stats estimates can be used for the sensorless control. In addition, the resistances values derived from the corresponding estimated temperatures resolve the weak observability of the stator resistance at high speed and rotor resistance at low torque, so we will have a more robust control in all operating modem. The estimated temperatures may be used in the monitoring processes and avoid overheating of our machine therefore increased its operational life. Finally the advantages of this approach motor are reduced hardware complexity and lower cost, reduces size of the drive machine, elimination of the speed, current and thermal sensors.

2. Thermal Modeling Methods

In the specialized literature we can gather the thermal modeling methods of the electrical machines under the following three types.

2.1 Simple Modeling

We find many simple approaches in the literature in order to give bonds between the stator temperature and the rotor temperature. Beguenane and Benbouzid [12, 13] thus present an electrical rotor resistance identification method, which is unfortunately unable to identify the stator resistance; however these articles propose two thermal approaches to bind two resistances of the electric model:

(1) The first method is based on the EDF (French Electricity Board) experiment. It considers that the rotor has a temperature higher of 10 ℃ than that the stator temperature;

(2) The second method is based on work of Kubota. It gives a simple relation of proportionality between two resistances calibrated on the face values of the maker badge. We find the proportionality method in other articles like Ref. [14]. On the other hand, later works were realized on EDF model and put a flat as for its validity for all the operating processes, especially NEMA design D machines with 8-13% slip [15].

2.2 Fine Modeling

It is based on the use of the finite element method with a detailed model geometric and mechanics.

This makes it possible to obtain a complete cartography of the machine temperatures (Fig. 1). These results are very interesting since they make it possible to give an idea of the places where the temperature becomes critical according to the operations and answer the problems of the hot points [16, 17].

2.3 Electrical Equivalent Supply Networks (NODAL Method) [18, 19]

Those generally model the whole of the machine with nodes of temperature associated with each material used in Ref. [10]. The identification of this model is thus carried out either by finite elements, or by a great number of points of temperature measurement within the machine. These models are generally very detailed (Fig. 2) and thus too complex for our application in real time [10].

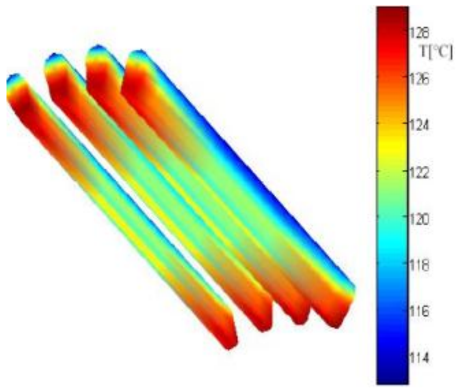
As our goal principal is the use of Kalman filter, these two types of models are not exploitable, because these methods do not give the formalism of state.

2.4 Simplified Models

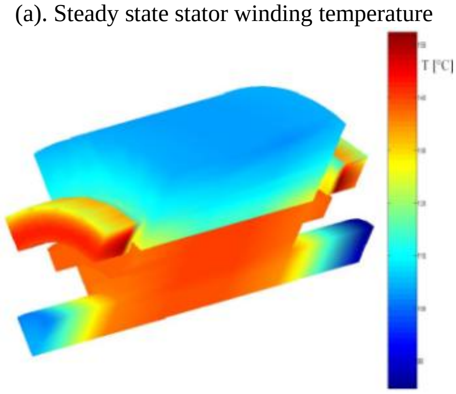
Other researchers sought to simplify the models by gathering the losses in subsets and by approximating the temperature in an unspecified point with a simple exponential answer that one can simply represent by a resistance and a heat capacity (Fig. 3) [7, 20].

3. Thermal Modeling of the IM in the State Space

In many cases, the model is the familiar steady-state equivalent circuit, but for high performance drives, a full transient model of the motor is required. Effective



(a). Steady state stator winding temperature



(b) Thermal cartography portion

Fig. 1 Thermal cartography portion of an asynchronous machine, obtained by finite elements [11].

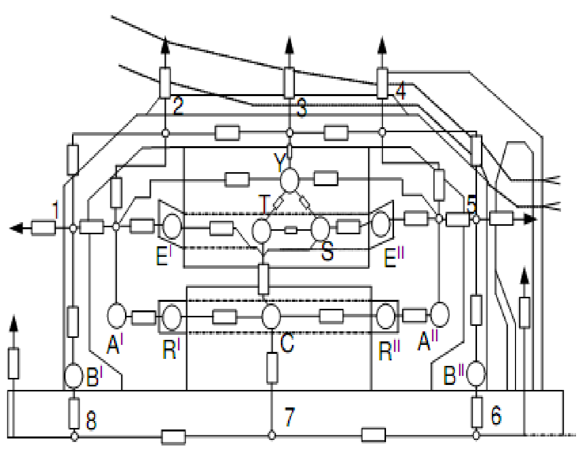


Fig. 2 Equivalent thermal models of the asynchronous machine [10].

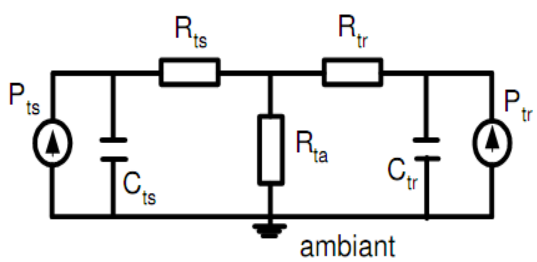


Fig. 3 Thermal model of the asynchronous machine [7].

modeling, and therefore the effectiveness of drive control and estimation, is limited by the complexity of the physical processes occurring within the motor. Frequency dependence of the rotor electrical circuit, nonlinearity of the magnetic circuit, and temperature dependence of the stator and rotor electrical circuits all impact on the accuracy with which the motor can be modeled [21]. The modeling of the IM taking all the real behaviors without hypothesis simplifications will be very difficult or impossible. For that, one will suppose a model with simplifying assumptions. This paper addresses the third of these effects (temperature dependence) by incorporating a thermal model of the motor in the estimation process. The frequency dependence of the rotor electrical circuit and nonlinearity of the magnetic circuit are not included.

Temperature estimation in the induction motor has been dealt with by many authors [11, 19], but most of these publications describe either a very complex lumped-parameter network or the finite-element method.

A state-variable model of the induction motor is required for the EKF algorithm. The twin-axis stator reference frame [21] is used to model the motor's electrical behavior, because physical measurements are made in this reference frame; the well-known linear relationship between resistance and temperature must be taken into account for the stator and rotor resistances:

$$\begin{aligned} R_s(\theta_s) &= R_{s0}(1+\alpha_s\theta_s) \\ R_r(\theta_r) &= R_{r0}(1+\alpha_r\theta_r) \end{aligned} \tag{1}$$

where, R_{s0}, R_{r0} stator and rotor resistance at the ambient temperature, α_s and α_r them coefficients thermal, respectively. In the IM traditional models, one replace R_s and R_r by $R_s(\theta_s)$ and $R_r(\theta_r)$ respectively, what can be rearranged in space of state on the format:

$$\begin{aligned} p\,\delta\, i_{qr} &= -L_1 L_m \omega_r\, i_{ds} - R_s(\theta_s) L_2 i_{qs} - L_1 L_2 \omega_r\, i_{dr} \\ &\quad + R_r(\theta_r) L_1\, i_{qr} + L_m V_{qs} \end{aligned} \tag{2}$$

$$\begin{aligned} p\,\delta\, i_{ds} &= -R_s(\theta_s) L_2\, i_{ds} + L_m^2\, \omega_r\, i_{qs} + R_r(\theta_r) L_m\, i_{dr} \\ &\quad + L_2 L_m\, \omega_r\, i_{qr} + L_2 V_{ds} \end{aligned} \tag{3}$$

$$p\delta i_{dr} = R_s(\theta_s)L_m i_{ds} - L_1 L_m \omega_r i_{qs} - R_r(\theta_r)L_1 i_{dr} - L_1 L_2 \omega_r i_{qr} + L_2 V_{qs} \quad (4)$$

$$p\delta i_{qs} = -L_m^2 \omega_r i_{ds} - R_s(\theta_s)L_2 i_{qs} - L_2 L_m \omega_r i_{dr} + R_r(\theta_r)L_m \omega_r i_{qr} + L_2 V_{qs} \quad (5)$$

where $\delta = L_1 L_2 - L_m^2$.

The mechanical behavior can be modeled by

$$T = b\omega_r + j\, p\omega_r + T_L \quad (6)$$

However, the electromagnetic torque of the motor T can be represented in term of stator and rotor current components:

$$T = p_n L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (7)$$

By equality of these two preceding equations, the equation speed of rotor in the space of state is

$$p\omega_r = p_n L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) - \frac{b}{j}\omega_r + \frac{T_L}{j} \quad (8)$$

The thermal model is derived by considering the power dissipation, heat transfer and rate of temperature rise in the stator and rotor. The stator power losses include contributions from copper losses and frequency-dependent iron losses [21].

$$p L_s = (i_{qs} i_{dr} - i_{ds} i_{qr}) R_s(\theta_s) + k_{ir}\, \omega_r \quad (9)$$

where K_{ir} is it constant of iron loss.

The rotor power losses are dominated by the copper loss contribution if the motor is operated at a low value of slip so

$$p L_r = (i_{dr}^2 - i_{qr}^2) R_r(\theta_r) \quad (10)$$

where, H_s, H_r are the stator and the rotor heat capacity respectively.

A simple representation of the assumed heat flow is given in Fig. 1. Heat flow from the rotor is either directly to the cooling air with heat transfer coefficient k_2, or across the air gap to the stator with heat transfer coefficient k_3.

$$p L_r = k_2\theta_r + H_r\, p\theta_r + k_3(\theta_r - \theta_s) \quad (11)$$

Heat flow from the stator is directly to the cooling air, with heat transfer coefficient k_1:

$$p L_s = k_1\theta_s + H_s\, p\theta_s - k_3(\theta_r - \theta_s) \quad (12)$$

For an induction motor with a shaft mounted cooling fan, the heat transfer coefficients are dependent on the rotor speed. This dependence has been modeled approximately by a set of linear relationships:

$$k_1 = k_{10}(1 + k_{1\omega}\omega_r) \quad (13)$$

$$k_2 = k_{20}(1 + k_{2\omega}\omega_r) \quad (14)$$

$$k_3 = k_{30}(1 + k_{3\omega}\omega_r) \quad (15)$$

where, k_{10}, k_{20} and k_{30} thermal power transfer coefficients at the zero speed. k_{1w}, k_{2w} and k_{3w} variation of thermal power transfer with speed.

The following equations are found with simple mathematical manipulations:

$$p\theta_s = \frac{R_s(\theta_s)}{H_s}(i_{ds}^2 + i_{qs}^2) + \frac{k_{ir}}{H_s}\omega_r^2 - \frac{k_{10}(1 + k_{1\omega}\omega_r)}{H_s}\theta_s + \frac{k_{30}(1 + k_{3\omega}\omega_r)}{H_s}(\theta_s - \theta_r) \quad (16)$$

$$p\theta_r = \frac{R_r(\theta_r)}{H_r}(i_{dr}^2 + i_{qr}^2) - \frac{k_{20}(1 + k_{2\omega}\omega_r)}{H_r}\theta_r + \frac{k_{30}(1 + k_{3\omega}\omega_r)}{H_r}(\theta_s - \theta_r) \quad (17)$$

The whole of preceding Eqs. (2), (5), (8), (16), and (17) give us the model of following state:

$$\begin{aligned}
p\delta i_{qr} &= -L_1 L_m \omega_r i_{ds} - R_s(\theta_s)L_2 i_{qs} - L_1 L_2 \omega_r i_{dr} + R_r(\theta_r)L_1 i_{qr} + L_m V_{qs} \\
p\delta i_{ds} &= -R_s(\theta_s)L_2 i_{ds} + L_m^2 \omega_r i_{qs} + R_r(\theta_r) L_m i_{dr} + L_2 L_m \omega_r i_{qr} + L_2 V_{ds} \\
p\delta i_{dr} &= R_s(\theta_s)L_m i_{ds} - L_1 L_m \omega_r i_{qs} - R_r(\theta_r)L_1 i_{dr} - L_1 L_2 \omega_r i_{qr} + L_2 V_{qs} \\
p\delta i_{qs} &= -L_m^2 \omega_r i_{ds} - R_s(\theta_s)L_2 i_{qs} - L_2 L_m \omega_r i_{dr} + R_r(\theta_r)L_m \omega_r i_{qr} + L_2 V_{qs} \\
p\omega_r &= p_n L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) - \frac{b}{j}\omega_r + \frac{T_L}{j} \\
p\theta_s &= \frac{R_s(\theta_s)}{H_s}(i_{ds}^2 + i_{qs}^2) + \frac{k_{ir}}{H_s}\omega_r^2 - \frac{k_{10}(1 + k_{1\omega}\omega_r)}{H_s}\theta_s + \frac{k_{30}(1 + k_{3\omega}\omega_r)}{H_s}(\theta_s - \theta_r) \\
p\theta_r &= \frac{R_r(\theta_r)}{H_r}(i_{dr}^2 + i_{qr}^2) - \frac{k_{20}(1 + k_{2\omega}\omega_r)}{H_r}\theta_r + \frac{k_{30}(1 + k_{3\omega}\omega_r)}{H_r}(\theta_s - \theta_r)
\end{aligned} \quad (18)$$

4. Simulation Results of the State Space Thermal Model

Eq. (18) is resolved by Matlab using the Runge-Kutta algorithm.

(1) Case of the temporary mode or a complete thermal cycle of the asynchronous machine (duty type S2):

This mode is characterized by the application of a constant load on a finite time interval followed by a rest leading to return to the ambient temperature. For this, a resistive torque of 5 Nm is applied, then we made a stop at t = 300 min.

In a general way, in transient and steady state modes, the temperature limit is reached in the stator before the rotor in the case of low power machines (< 37 kW) [14, 22].

At the starting the stator and rotor windings temperature is equal to the ambient temperature (0 ℃), the thermal transient is very slow over the thermal dynamics of the stator is faster than the rotors dynamics [23].

The interval of time (t = 0 min at t = 300 min) is an induction motor heating cycle, for against the time interval (t = 300 min to t = 650 min) is a time of deenergization to allow the motor to cool down before the next startup as presented on in Fig. 4.

(2) Slow continuous-operation periodic duty cycles: this operation mode can be identified by specification of the load period *tp*, no-load period *tv* and cycle duration Te, but also by the relative duty cycle *tr* in % write like this:

$$tr\% = tp/Te \times 100 \tag{19}$$

In this case the load torque is equal to 10 Nm.

For this application *tp* = 350 min, *tv* = 100 min and *Te* = 450 min, so *tr*% = 77.77%.

(3) Case of intermittent operation (duty type S3):

This cyclic regime is characterized by the application of a constant load over periods *tp* separate rest period *tv* without returning to ambient temperature, in our case we take the values *Te* = 150 min, *tp* = 100 min and *tv* = 50 min, so, *tr* = 66.66%.

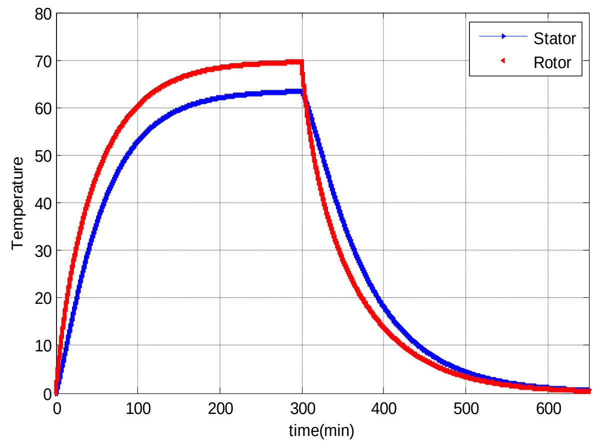


Fig. 4 Case of the temporary mode or duty type S2.

By comparison between the two duty operations mode slow (Fig. 5) and fast (Fig. 6), we can see that the IM in the slow operation mode is naturally itself cooled at Δ*tv* (100 min), but in the second mode the Δ*tv* is small (50 min) so the IM cannot cool naturally.

5. Application of the EKF

A reconstructor of state or estimator is a system having like entry, the entries and the exits of the real process, and whose exit is an estimate of the state of this process (Fig. 7). The extended Kalman filter algorithm takes account of process and measurement noise in a general nonlinear system:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + w(k) \\ y(k) = Cx(k) + v(k) \end{cases} \tag{20}$$

where, *w(k)*, *v(k)* represents the process and measurement noise respectively.

(1) The prediction stage is

$$\hat{x}(k+1) = f(\hat{x}(k), u(k)) \tag{21}$$

$$P(k+1) = F(k)P(k)F^T + Q \tag{22}$$

(2) The correction stage is

$$K(k+1) = P(k+1)C^T\left(CP(k+1)C^T + R\right)^{-1} \tag{23}$$

$$P(k+1/k) = P(k+1) + K(k+1)CP(k+1) \tag{24}$$

$$\begin{aligned} &\hat{x}(k+1/k) = \hat{x}(k+1) + \\ &K(k+1)\{y(k+1) - C\,\hat{x}(k+1)\} \end{aligned} \tag{25}$$

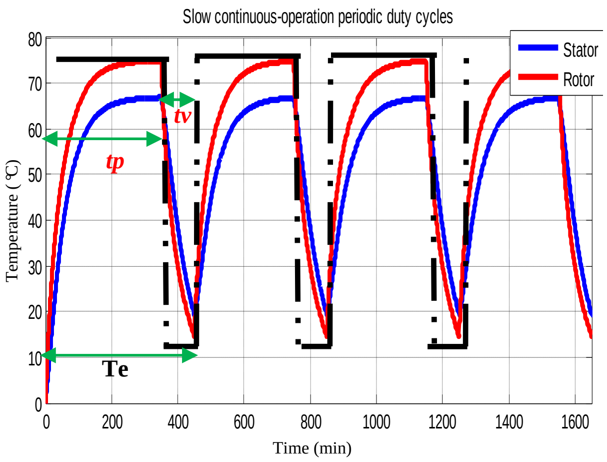


Fig. 5 Case of slow intermittent operation or duty type S3.

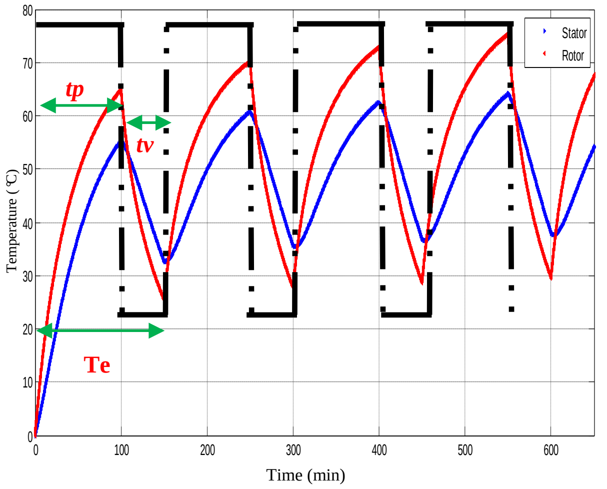


Fig. 6 Case of fast intermittent operation or duty type S3.

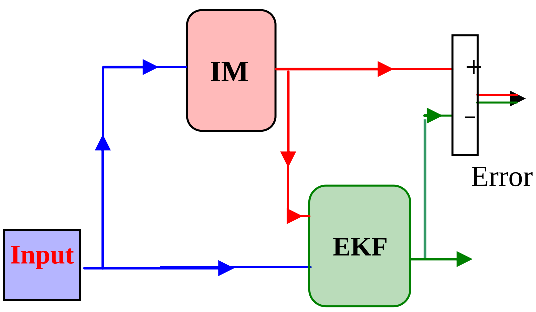


Fig. 7 Application of EKF in IM.

(3) Covariance matrices initial values

The matrix of covariance of error in estimation P and square of 7 × 7, translated the confidence that we can have in the adopted model [21] gives it:

$$p(0) = \text{diag}\,[5\ 5\ 5\ 5\ 2\ 1\ 1] \tag{26}$$

The matrix of covariance of the noise of state Q quantifies the precision of the model and allows the dynamic adjustment of the parameters. It is generally difficult to determine because the direct observation of the state of the system is impossible. It is given in Ref. [21] by

$$Q\% = \text{diag}([1.2\ \ 1.2\ \ 0.3\ \ 0.01\ \ 10^{-5}\ \ 10^{-4}]) \tag{27}$$

The matrix of covariance of noise of measurement R translated the level of noise to the measure is given in Ref. [21] by

$$R\% = 0.22\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{28}$$

6. Simulation Results

6.1 Constant Load

The two temperatures thermal model and estimation vary at different rates because of the differences in the losses, thermal capacities and the power transfer coefficients between the stator and rotor.

The stator and rotor temperature in the established mode reached the value 65 ℃, 72 ℃ respectively but their value considered to reach 62.3 ℃ and 69.6 ℃.

Fig. 8 shows that deference between the rotor and the stator temperature is about 10 ℃ verified EDF experiment (The EDF experiment which considers that the rotor has a temperature higher of 10 ℃ than that of the stator) [15].

6.2 Variable Load

In order to verify the model performance for variable load, some step of load variations are applied (100% → 120% → 50% → 75% of the rated load).

Figs. 9 and 10 show the simulation result of EKF and thermal model temperature of stator and rotor winding under the variable load condition, the deference between the thermal model temperature and EKF is about 2.4 ℃ and 2.7 ℃ for the stator and the rotor, respectively.

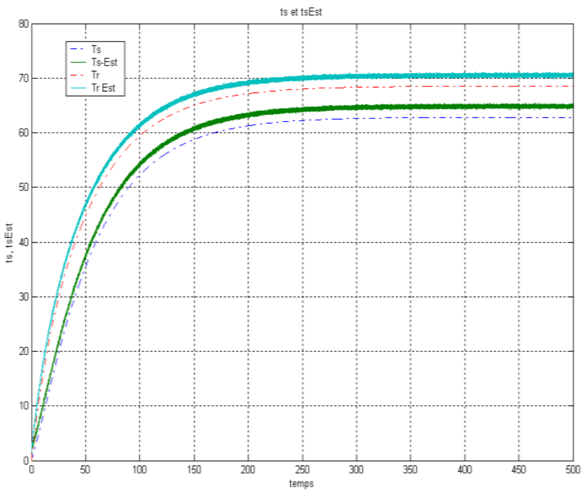


Fig. 8 Stator and rotor temperatures under constant load condition.

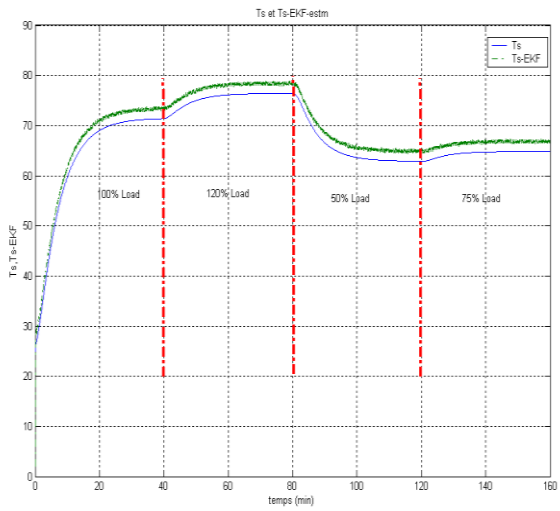


Fig. 9 Stator temperature under variable load condition.

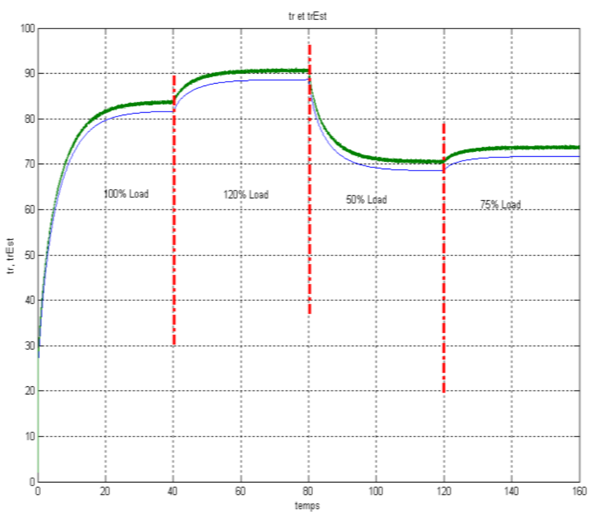


Fig. 10 Rotor temperature under the variable load condition.

7. Conclusions

In this article, we presented a thermal model of a cage induction machine. This model is based on the theory of power dissipation, heat transfer and the rate of temperature increase in the rotor and stator, taking into account the effect of speed on the exchange, simulation tests (duty type S2 and duty type S3) was done up to the validity of the thermal model.

Since the sensors can be not very reliable or expensive, in addition, the problems of the extraction to thermal information about the rotor are difficult or very expensive. The use of a sensorless approach is strongly recommended. The EKF makes it possible to achieve this goal, and the EKF enables to estimate simultaneously the rotor currents, speed, stator and rotor temperature using only the measurable states, a Gaussian noise has been added to take into account the stator current and voltage sensor noises to make a robust estimate.

The simulation study demonstrating that the temperature rise calculation with proposed simplified thermal model in this paper is feasible compared with similar researches. According to our results, the simplified thermal model can be used to estimate both steady state and transient state temperature. In the future, our works will be focused to the thermal monitoring by using EKF.

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