OPERATION IMPROVEMENT OF INDUCTION MOTOR TEMPERATURE PROTECTION DEVICE UNDER EXTREME OVERLOAD

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Abstract. The aim of the research was to improve the operation quality of a temperature protection device (TPD) for an induction motor (IM) under extreme overload conditions – locked rotor mode. The analytical and experimental research showed that under extreme overload the temperature of the stator windings reaches 5-10 ºC·s^{-1}. Due to thermal inertia and the imperfect nature of the embedded temperature sensors this causes an increase of the winding temperature above the critical value for electrical insulation at the switch off point. This leads to a shorter lifespan of the stator winding insulation. A virtual model was created in the MATLAB-SIMULINK environment to simulate the transient heating process of the embedded temperature sensor under locked rotor mode of the IM. The simulation results showed that if the stator windings temperature increase speed is 10 ºC·s^{-1} and the thermal time constant of the sensor is 6 s then at the switch off point of the conventional TPD the winding temperature exceeds the permissible level of a B class insulation by 56 ºC, this is the primary cause of shorter lifespan in insulation. To compensate the impact of the temperature sensors thermal inertia on to the measurement accuracy under rapidly rising temperature of the stator winding, an output electrical signal should be formed as a sum of the measured electrical signal and of its varying speed signal. The simulation showed that it can be realized by the first order differential filter with the time constant T_d equal to the thermal time constant of the temperature sensor ($T_s = T_d$). Therefore, a differential filter should be used to ensure adequate accuracy and fast operation of the temperature protection device to effectively protect the IM under prolonged start up and locked rotor mode.

Keywords: induction motor, stator windings, temperature sensor, thermal time constant, measurement error correction.

Introduction

In an industrial environment induction motors (IM) are commonly used to drive essential systems including pumps, fans, compressors, mills, cranes, conveyors, crushers, etc. IMs have a simple construction and high reliability. But the statistics show that the annual motor failure rate is conservatively estimated at 3-5 % per year, and in extreme cases, up to 12 % [1], this causes interruption to the motors primary task and losses in operation time in production processes while it is maintained or repaired.

IM failures can be classified as follows: 1) electrical related failures ≈ 35 %; 2) mechanical related failures ≈ 31 %; 3) environmental impact and other reasons ≈ 34 % [1]. Other studies classify IM failures as follows – 1) bearing faults ≈ 40 %; 2) stator related ≈ 38 % 3) rotor related ≈ 10 %; 4) other failures ≈ 12 % [2]. The analysis of the failures shows that many of them are caused by a prolonged thermal overload of the IM stator winding.

There are different types of devices to protect against over temperature. The most commonly used are bi-metal type overload relays, but these do not protect against thermal overloads caused by high ambient temperature, IM ventilation faults, unbalanced voltage and high negative-sequence currents can lead to nuisance tripping and under-protection of the relay [2; 3]. Microprocessor-based thermal overload relays estimate the stator winding temperature based on a thermal model. The first order thermal model is commonly used, which is generally inaccurate to IMs operation conditions. Higher order thermal models are developed to increase accuracy [4; 5], but they are complex and require additional parameter identification and computation time. Also stator winding resistance estimation methods are used to calculate temperature by using an equivalent electrical model of the IM or estimation using direct current (DC) injection [6]. The active thermal protection technique using DC injection to estimate the stator resistance and calculate the winding temperature can provide acceptable accuracy, but it requires a DC injection circuit and causes moderate torque pulsations. Temperature protection devices that measure the IMs stator winding temperature directly by using a temperature sensor are more reliable if the IM is operated in high ambient temperature, cycled load, blocked ventilation or dusty conditions.

Under extreme overload, such as in locked rotor, the temperature increase speed of the stator windings is V_θ = 5-10 °C·s^{-1}. The experimental study [7] shows that for a 1.1 kW IM V_θ =5 °C·s^{-1}, but for a 2.5 kW IM – V_θ = 6.2 °C·s^{-1} [8]. As mentioned in [1; 7], due to thermal inertia of the temperature sensor under locked rotor conditions the temperature measurement will have an error proportional to the thermal time constant T_s of the temperature sensor and winding temperature increase speed V_θ. Therefore, the temperature protection device will trip when the winding temperature exceeds the thermal limit of the IM stator winding insulation.

The aim of the research is to improve the operation quality of a temperature protection device for an induction motor under extreme overload conditions - locked rotor condition.

Materials and methods

To simulate heat transfer from the stator winding to the temperature sensor in the MATLAB SIMULINK environment the following algorithms are used:

$$T_t \frac{d\Delta\theta_t}{dt} + \Delta\theta_t = \Delta\theta_s, T_t \cdot \Delta\theta_t(s) \cdot s + \Delta\theta_t(s) = \Delta\theta_s(s),\ W(s) = \frac{\Delta\theta(s)}{\Delta\theta(s)} = \frac{1}{T_t \cdot s + 1}, \quad (1)$$

where T_t – thermal time constant of the temperature sensor, s;
$\Delta\theta_t$ –temperature sensor temperature increase, °C;
$\Delta\theta_s$ – stator windings temperature increase, °C;
$\Delta\theta_t(s)$ – Laplace transform of temperature sensor temperature increase, °C;
$\Delta\theta_s(s)$ – Laplace transform of stator temperature increase, °C;
$W(s)$ – transfer function of the temperature sensor;
t – operation time, s.

Results and discussion

Figure 1 shows simulation results of the heating process of an IM stator winding and temperature sensor under a locked rotor condition. The simulation is done for 2 conditions – IM rotor was locked during operation and the winding temperature θ_o = 100 °C and then the IM was locked at the start up with the initial temperature θ_o = 20 °C.

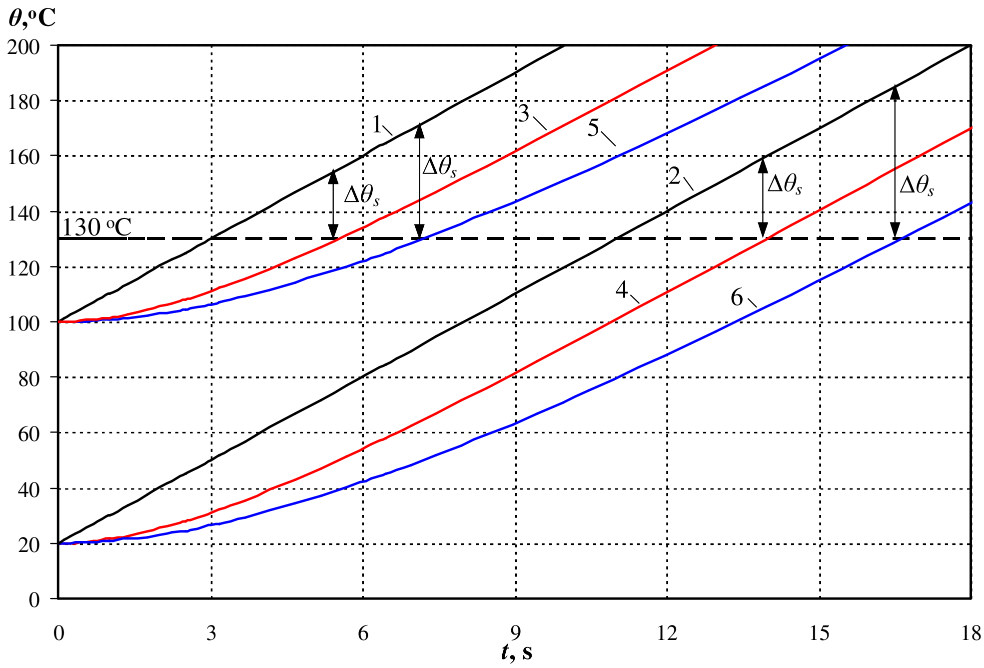

Fig. 1. **Simulation results of the induction motor winding and temperature sensor heating process under locked rotor condition:** 1, 2 – temperature of stator winding at θ_o = 20 °C and θ_o = 100 °C; 3, 4 – temperature measurement of temperature sensor with a T_s = 3 s at θ_o = 20 °C and θ_o = 100 °C; 5, 6 – temperature measurement of temperature sensor with a T_s = 6 s at θ_o = 20 °C and θ_o = 100 °C; $\Delta\theta_s$ – sensor measurement error, °C

The stator winding temperature increase speed is V_θ = 10 ºC·s^{-1}, the temperature sensor thermal time constants T_s = 3 s and T_s = 6 s and thermal limit of a B class winding insulation θ_{max} = 130 ºC.

The simulation results show that at θ_o = 100 ºC when the temperature sensor with T_s = 3 s reaches 130 ºC the winding temperature is 155 ºC and the measurement error is $\Delta\theta_s$ = 25 ºC, for the temperature sensor with T_s = 6s – $\Delta\theta_s$ = 43 ºC. At θ_o = 20 ºC the measurement error is $\Delta\theta_s$ = 30 ºC for the temperature sensor with T_s = 3 s and $\Delta\theta_s$ = 56 ºC with T_s = 6 s.

To compensate the impact of the temperature sensors thermal inertia and to increase the measurement accuracy, a differential filter can be used (Fig. 2). Adapter 2 monitors the resistance/voltage change of the temperature sensors and converts it into an electrical signal U_a. Then the electrical signal U_a from the adapter is applied to adder 6 input and the compensation circuit 5, which consist of an amplifier 3 and differential filter 4. The differential filter responds to rapid measured electrical signal increase and forms the compensation voltage ΔU_k, which is applied to the adder second input. Then the added output signal U is applied to the solid state relay of the TPD.

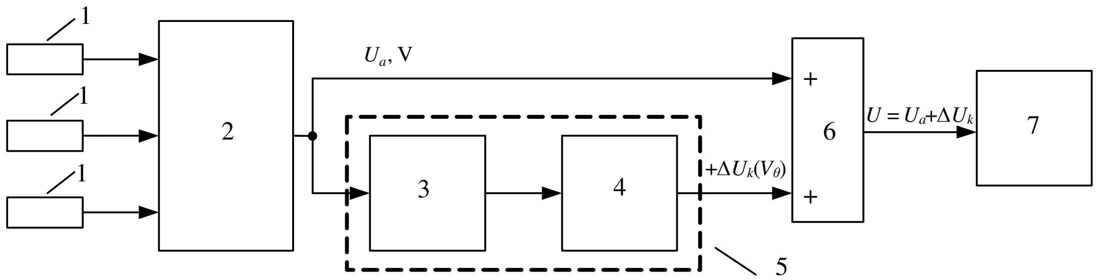

Fig. 2. **Temperature measurement block diagram of TPD with compensation circuit:**
1 – temperature sensor; 2 – adapter; 3 – amplifier; 4 differential filter; 5 – compensation circuit; 6 – adder; 7 – solid state relay

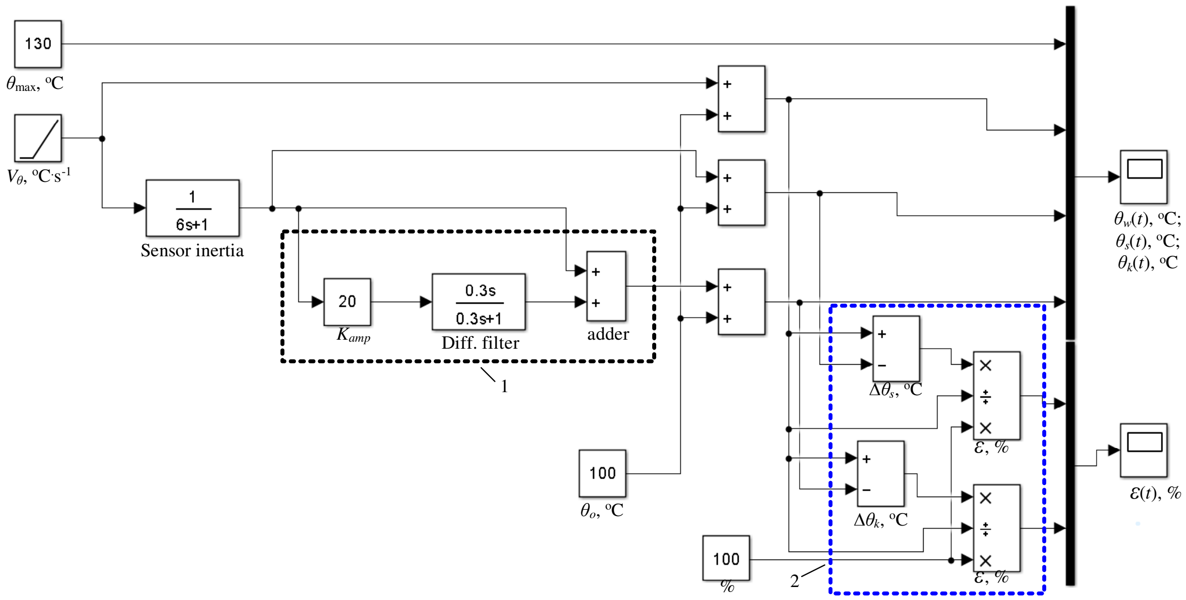

Fig. 3. **Simulation block diagram of temperature measurement of temperature sensor:**
1 – simulation block of differential filter; 2 – simulation block of measurement relative error; V_θ – IM stator winding increase speed, ºC·s^{-1}; θ_{max} – thermal limit of IM stator winding insulation, ºC; θ_o – initial temperature, ºC; θ_w – IM winding temperature, ºC; θ_s – temperature measurement of temperature sensor, ºC; θ_k – temperature measurement of temperature sensor with differential filter, ºC; $\Delta\theta_s$ – measurement error of temperature sensor, ºC; ε – measurement relative error of temperature sensor, %

To analyse the measurement accuracy of the temperature sensors with a differential filter under IM locked rotor condition, the simulation block diagram of the IM stator winding temperature measurement in the MATLAB SIMULINK environment has been compiled (Fig. 3). Simulation is done under the following parameters – initial IM stator winding temperature θ_o = 100 ºC, stator winding temperature increase speed V_θ = 10 ºC·s^{-1}, temperature sensor thermal time constant T_s = 6 s. The simulation diagram includes a calculation block of relative error to analyse the effectiveness of the differential filter on the temperature measure accuracy. The compensation circuit is described by the following transfer function:

$$W(s) = k \cdot \frac{T_f \cdot s}{T_f \cdot s + 1} = \frac{T_d \cdot s}{T_f \cdot s + 1}, \tag{2}$$

where T_f – thermal time constant of filter, s;
T_d – thermal time constant of differentiation, s;
k – amplifier gain;
$W(s)$ – transfer function of filter.

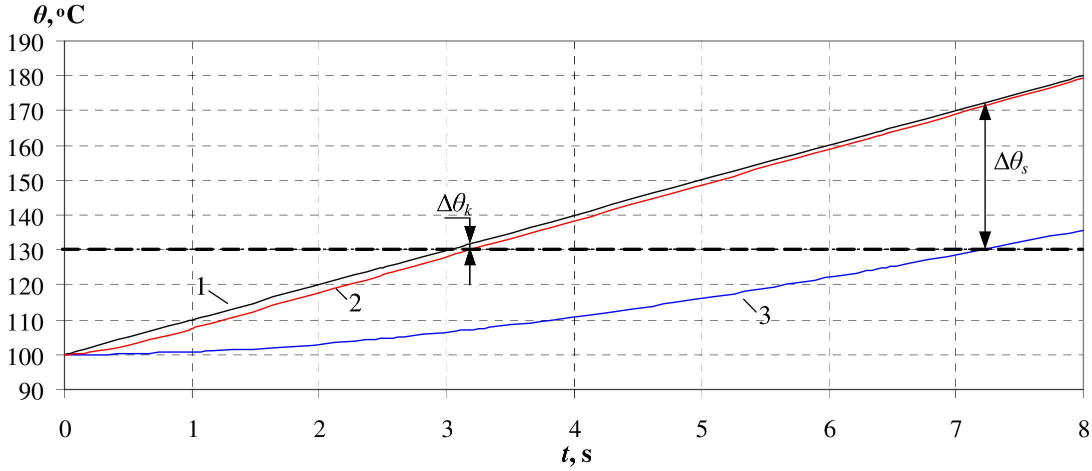

Fig. 4. **Simulation results of temperature sensor heating process with a differential filter:** 1 – temperature of IM stator winding, ºC; 2 – temperature measurement of temperature sensor with differential filter and T_s = 6 s, ºC; 3 – temperature measurement of temperature sensor with T_s = 6 s, ºC; $\Delta\theta_k$ – measurement error of temperature sensor with differential filter, ºC; $\Delta\theta_s$ – measurement error of temperature sensor, ºC

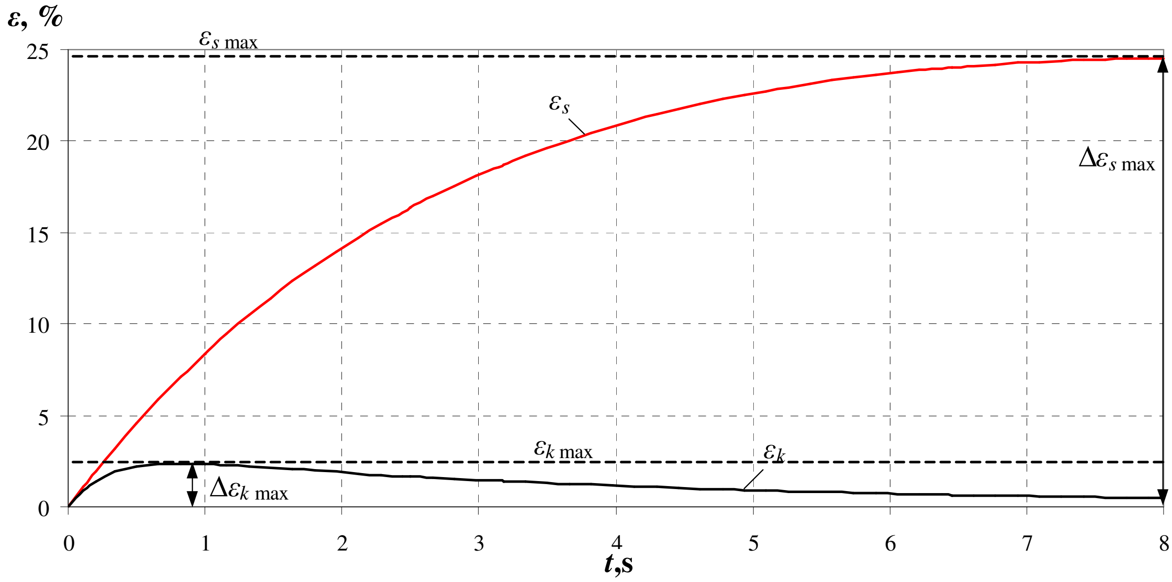

Fig. 5. **Simulation of temperature measurement relative error of temperature measurement:** ε_s – measurement relative error of temperature sensor, %; ε_k – measurement relative error of temperature sensor with differential filter, %

The simulation results show that the time constant of differentiation should be equal to the thermal time constant of the temperature sensor $T_d = T_s$ and the time constant of the filter should be $T_f = 0.05T_d$, to ensure adequate accuracy and response of the temperature sensor to the rapid heating process of the IM stator winding. Figure 4 shows the simulation results of temperature measurement with the compensation circuit. The temperature measurement error is $\Delta\theta_k = 2$ ºC for the temperature sensor with the compensation circuit and $\Delta\theta_s = 43$ ºC without the compensation circuit. The relative error of the temperature measurement calculations (Fig. 5) shows a significant improvement in measurement accuracy and response to the rapid heating process of the IM stator winding. Therefore, a compensation circuit with a differential filter can be used in TPD to provide fast response protection of the IM under extreme overloads.

Conclusions

1. Under extreme overload of the IM the thermal inertia of the temperature sensor causes a temperature measurement error. Simulation shows that at the stator winding temperature increase speed $V_\theta = 10$ ºC·s^{-1} and at critical insulation temperature the measurement error is $\Delta\theta_s = 25$ ºC for $T_s = 3$ s. For $T_s = 6$ s the error is $\Delta\theta_s = 43$ ºC. Therefore, IM stator winding temperature will be higher than the insulation thermal limit when the temperature protection device will trip causing shorter lifespan of the stator winding insulation.
2. To increase the temperature measurement accuracy of TPD the compensation circuit should be used with an amplifier and differential filter. The differentiation time constant should be equal to the temperature sensor thermal time constant $T_d = T_s$ and the filter time constant $T_f = 0.05T_d$.
3. The simulation results of the temperature sensor measurements show that the compensation circuit decreases the temperature measurement error from $\Delta\theta_s = 25$ ºC to $\Delta\theta_s = 2$ ºC under IM locked rotor and 100 ºC conditions and calculations of the measurement relative error also show a significant reduction. It proves that a compensation circuit can be used in TPD to ensure adequate protection of the IM under extreme overload.

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