TEMPERATURE PROTECTION METHODS OF INDUCTION MOTOR

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Abstract
In conditions where induction motors are frequently started, overloaded and used in high inertia applications with long starting times, supplied from frequency converter, a temperature protection systems are more reliable to protect induction motor stator winding against thermal overloads. There are different types of temperature protections - thermostat, PTC thermistor, resistance temperature detector (RTD) and thermocouples, so it is important to know the properties of each type to choose an adequate protection system. Analyses of temperature sensor properties and their advantages and disadvantages show, that PTC thermistor is a cost-effective temperature protection solution, but for medium and high voltage induction motor protection RTD are commonly used. A virtual model has been represented to simulate the temperature sensor thermal time constant under different thermal conductivity and thickness of winding magnet wire insulation.
Key words: induction motor, protection, temperature sensor, thermal time constant, heating.

Introduction

Today in industrial and domestic environments moving and rotary mechanisms are mainly driven by electric motors, 90% of which are induction motors (IM). Because of simple construction, maintenance and variable frequency drive (VFD), IM with squirrel cage rotor are widely used. Three-phase induction motors (IM) are used as drive motors in pumps, lifts, cranes, compressors, fans, crushers, mills, cranes, conveyors, etc. Annual IM failure rate is estimated at 3-5% per year, and in extreme cases, up to 12% (Venkataraman et al., 2005), which cause essential direct and technological losses.

The failures of IM may be classified as following:

- electrical faults;
- mechanically related;
- environmental impact;
- other reason.

Statistics show that overheating of IM parts during operation is one of the common reasons of an IM failure (Venkataraman et al., 2005). Stator windings insulation is most sensitive to thermal overheating. Exceeding the thermal limit of the insulation will result in acceleration of the oxidation process that will decrease the insulation life or even cause IM failure. It is well known that the duration of insulation life is decreased by half for each increase of 10 °C temperature above its thermal limit temperature. In the past decades improved materials with better electrical, mechanical and thermal properties allowed manufactures to reduce the materials within motor and production costs of the IM (Glew, 1999). For example, reduced cross section of magnet wire (winding wire) increases the copper losses in IM winding thus increasing winding heating. Therefore, it is important to select an adequate protection system to protect critical IM parts from overheating and prevent failure.

One of effective techniques to detect contamination is direct winding temperature monitoring to archive temperature sensor measurements. Trending the stator winding temperature over time, and if there is a gradual increase in temperature, it may be cooling problems caused by contamination (Culbert, 2008). An operation review (Barbinyagra, 2007) from ammonia factory shows, that majority of IM failures are caused by vibration, overload and hazardous environment. To increase cycled loaded IM reliability, a temperature monitoring system with temperature sensors was installed in the factory. Experimental study on heating of 2.2 kW IM fed by pulse width modulation inverter (Benhaddadi et al., 1997) shows, that at rated load stator winding temperature is 7 °C higher than if IM is fed by sinusoidal voltage. Inverter fed IM stator winding insulation also needs to be resistant to partial discharge (PD). Therefore, magnet wires of IM contain nano sized metal oxides to impart PD resistance (Lynn et al., 1985). This very thin layer of metal oxide material is heat shock and thermal cycling sensitive and when the layer is cracked, the PD resistance property is reduced (Stone and Braswell, 2004). In high inertia application and application, where the rotor can lock or stall, the heating process of IM parts is very rapid and direct temperature sensing is considered to be more reliable than stator or armature current sensing. Studies (Staton et al., 2009; Gedzurs et al., 2014) show, that for low power IM (2.5 kW and 1.1 kW) the temperature rise speed is 6.2 $°C \cdot s^{-1}$ and 5 $°C \cdot s^{-1}$ respectively under locked rotor conditions. These studies show that in the mentioned operation conditions a direct temperature measurement of IM winding is more reliable for an adequate IM protection.

The objective of the study is to analyze temperature sensor properties for temperature protection of induction motors under extreme overloads and hazardous operation conditions.

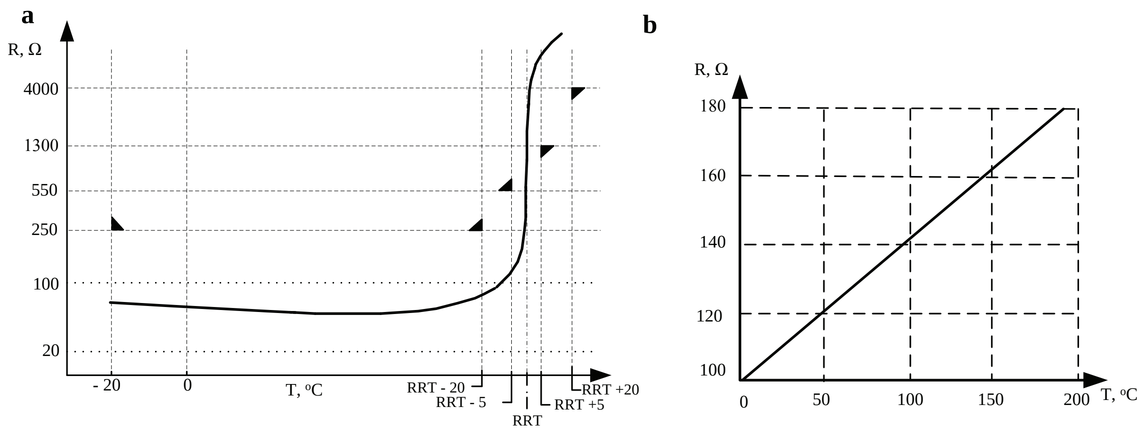

Figure 1. Temperature sensors resistance - temperature characteristics:
a - PTC thermistor; b - RTD PT100 sensor.

Materials and Methods

Induction motor temperature protection monitors the stator winding temperature by directly measuring the temperature using embedded temperature detectors. There are different types of temperature detectors (sensors), that are used for electric motor protection - thermostat, PTC thermistor, resistance temperature detector (RTD), thermocouples.

Winding thermostat is a temperature dependent device that uses bi-metallic strip to change the position of a pair of contacts at the preset rated response temperature. When temperature preset level is exceeded, the contacts switch a control device, relay or contactor. The control voltage can be applied directly to the thermostat, which makes a tripping mechanism unnecessary. The disadvantages of the thermostat are - long thermal delay, tripping temperature can be affected by careless fitting, large size compared to modern sensors.

Thermistor is a small resistance sensor with non-linear resistance - temperature relationship. There are two types of thermistors - negative temperature coefficient (NTC) and positive temperature coefficient (PTC) thermistors. The PTC thermistors are commonly used in IM motor protection systems. The resistance at normal temperature is relatively low and remains nearly constant up to the rated response temperature (RRT). As the RRT is exceeded, the gradient of the resistance increases sharply, giving the PTC thermistor a high sensitivity to small changes of temperature. At the set point, a temperature rise of a few degrees results in a large increase in resistance. The PTC thermistor resistance characteristic is shown in Figure 1(a). The resistance change of the PTC thermistor is monitored by a thermistor protection relay. The advantages of the PTC thermistor are small size, which allows them to be installed in direct contact with the stator winding and a low thermal inertia, which gives rapid and accurate response to the winding temperature changes.

Resistance temperature detectors (RTD) monitors temperature by measuring the change of resistance of an accurately calibrated resistive sensor, usually made of copper, platinum or nickel, but platinum RTD PT-100 is commonly used for stator winding temperature monitoring. RTD sensors can be of the wire wound type, or can be of the metal film type, which are lower cost with faster response but their characteristics can deteriorate over a time. A RTD has a linear resistance and temperature trend (Figure 1(b)), usually 0.4 $\Omega \cdot {}^{\circ}C^{-1}$ for PT-100 sensor. A very sensitive instrument, based on Wheatstone bridge, is required to measure the small changes in the resistance of RTD. The instrument passes a small excitation current through the resistive sensor.

Thermocouple is a temperature sensor that consists of two dissimilar metals, joined together at one end and for a junction (a couple). There are different types of thermocouples depending on the combination of metals used to make the sensor. Type J (iron and constantan), K (Chromel and Alumel), T (copper and constantan) and E (Chromel and Alumel) thermocouples are commonly used. The voltage-versus-temperature relationship of most types of the thermocouple is not linear. Thermocouple measurement devices need a cold junction compensation. The size of thermocouple is small so it can be placed between windings in small power IM.

To simulate changes of the thermal time constant of the temperature sensor at different IM stator winding insulation parameters, thermal conductivity and thickness, a virtual model is represented in MATLAB SIMULINK environment. The mathematical model is obtained from the following mathematical operations. Assuming that at start time there is no heat transfer from the sensor to environment, the heat transferred from the winding to the temperature sensor is described by the following equation:

$$\theta_t = h \cdot S \cdot (T_w - T\ ),\ \ \theta_a = c \cdot m \cdot \frac{dT}{dt},$$

$$h \cdot S \cdot (T_w - T) = c \cdot m \cdot \frac{dT}{dt}, \tag{1}$$

where θ_t – increment heat from windings to sensor, W;
θ_a – sensors accumulated heat flow, W;
h – heat transfer coefficient, W·(m^2 ·°C)$^{-1}$;
S – heat transfer surface, m^2;
T_w – winding temperature, °C;
T – sensor temperature, °C;
c – sensor specific heat, J·(kg ·°C)$^{-1}$;
m - mass of the sensor, kg.
t - time, s.

According to expressions (1) a differential equation of sensor`s heating in normal form is as follows:

$$\tau_s \cdot \frac{dT}{dt} = T_w - T, \tag{2}$$

where τ_s – sensor thermal time constant, s.

From equations, (1) and (2) it is possible to get thermal time constant τ_s of the temperature sensor:

$$\tau_s = \frac{c \cdot m}{h \cdot S} = \frac{c \cdot m \cdot R}{S}, \tag{3}$$

where R = 1·h^{-1} - thermal resistance, (m^2 ·°C)·W^{-1}.

Results and Discussion

Table 1 shows comparison of the temperature sensors. PTC thermistors have high sensitivity to small temperature changes in the rated response temperature range and due to higher resistance of the thermistor, lead wire resistance error has a very small effect, therefore, only two lead wires are required. A PTC thermistor can be used either for alarm or trip function. If both functions are needed, then the one thermistor is used for alarm and the second one for trip. Like RTD, thermistor needs a constant current/voltage source, but one controller can been used for several thermistors connected in series. This makes a PTC thermistor a cost-effective temperature protection method. RTD among above mentioned temperature sensors has the best accuracy due to linear resistance-temperature relationship and the highest stability. Lead wire resistance and self-heating errors affect the RTD measurements. Three lead wire configurations will been used to decrease the lead wire resistance effect and four lead wire configurations for very precise measurement needs. A Wheatstone bridge based instrument needs to measure small resistance changes of RTD. These facts make RTD a more expensive temperature protection system. Thermocouples are simple, self-powered and have wide temperature measurement range, but for temperature protection of medium and high voltage induction motors the RTD are more conformable, because of their better accuracy and stability.

Thermal time constant of temperature sensor.

As mentioned in (Venkataraman et al., 2005), due to thermal inertia of temperature sensors, the temperature protection system cannot react to fast heating process of the IM stator winding, such as locked rotor or prolonged starting of IM modes. It is important to know the thermal time constant of the temperature sensor to choose properly settings. Heating process model of the temperature sensor, placed on the surface of end winding, shown in figure 2 (Fraden, 2010).

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Table 1

Comparison of temperature sensors

Sensor	PTC Thermistor	Platinum RTD	Thermocouple
Advantages	- sensitivity; - 2 lead wires required; - can connect several thermistors in series to one relay; - cost-effective; - low thermal mass.	- accuracy; - linearity; - stability.	- self-powered; - less expensive than RTD; - small size and thermal mass; - wide temperature range - simple.
Disadvantages	- non-linearity; - each thermistor has pre-set switch point (can be used only for alarm or for trip); - current/voltage excitation.	- lead wire resistance error (3 or 4 lead wire required); - generally high response time for wire-wound RTD; - low vibration resistance; - self-heating; - current/voltage excitation; - requires very sensitive instrument to measure.	- cold-junction compensation; - non - linearity for most types; - least sensitive; - least stable; - low output signal.

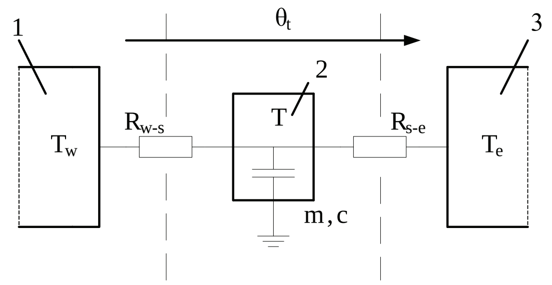

Figure 2. Heating process model of the temperature sensor:
1 - Stator winding of IM; 2 - temperature sensor; 3 - air gap between stator winding and IM case;
R_{w-s} - thermal resistance between winding and temperature sensor; R_{s-e} - thermal resistance between temperature sensor and air gap.

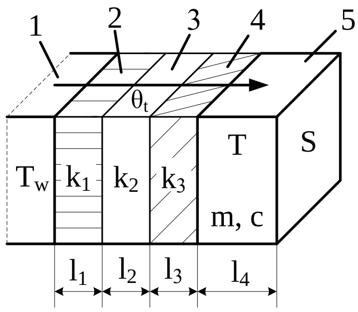

Figure 3. Simplified heating process models of the temperature sensor:
1 - stator winding of IM; 2 - magnet wire insulation; 3 - winding impregnation;
4 - sensor element insulation; 5 - sensor; l_1, l_2, l_3 - thickness of insulation layer;
l_4 - sensor thickness; k_1, k_2, k_3 - thermal conductivity of insulation layers.

thin-film RTD stator temperature sensor (model S200050PD) have been chosen as an example. The temperature sensor - PT100 has the following parameters: sensing element dimensions - 2 mm x 2.3 mm, thickness - 2 mm, insulation material of the sensing element (epoxy glass). If the sensor has been placed on the end winding surface and the contact is ideal, then there is a layer of insulation between stator winding and the sensor. The insulation layer consists of a winding magnet wire insulation, winding impregnation and sensor insulation layer. A simplified heating model of the sensor is shown in Figure 3. The thermal resistance of the each insulation layer can be calculated using equation 4.

$$R = \frac{l}{k}, \quad (4)$$

where k – thermal conductivity, $W^{.}(m\ ^{.}°C)^{-1}$;
l – insulation layer thickness, m;

Thermal conductivity of sensor epoxy glass insulation layer is $k_3 = 0.343\ W^{.}(m\ °C)^{-1}$ (Sarvar et al., 1990). Thermal conductivity of magnet wire and winding impregnation depends on the quality of insulation. According to (Dorrel et al., 2006) thermal conductivity $k_1 = k_2 = 0.2\ W^{.}(m\ ^{.}°C)^{-1}$ for normal raisin and $k_1 = k_2 = 0.2\ W^{.}(m\ °C)^{-1}$ for high performance insulation material. Thermal conductivity of platinum $k_4 = 71.6\ W^{.}(m\ °C)^{-1}$. According to (Stone and Braswell, 2004), the insulation thickness of magnet wire l_1 = 0.05 - 0.15 mm and thickness of winding impregnation usually is l_2 = 0.025 - 0.05 mm and rarely l_2 = 0.38 - 0.5 mm. Since the thickness of insulation layer of the temperature sensor is not given in specifications, it was assumed to be equal to the average thickness of the magnet wire insulation, i.e., l_3 = 0.1 mm.

Using equation (3) and parameters of insulation materials and the temperature sensor, a virtual model in MATLAB SIMULINK has been developed (Figure 4) to simulate effects of different insulation layer thickness and thermal conductivity on the thermal time constant of the temperature sensor. Thermal time constant τ_o = 4.69 s at the following parameters $l_1 = l_2$ = 0.05 mm, l_3 = 0.1 mm, $k_1 = k_2 = 0.2\ W^{.}(m\ °C)^{-1}$.

Figure 5 represents simulation results of the thermal time constant of the temperature sensor depending on the thermal conductivity k1 (0.2 - 1 W (m °C)$^{-1}$) of magnet wire insulation. At k1 = 0.2 W. (m °C)$^{-1}$ thermal time constant is τ_o = 4.69 s, at k1 = 1 W (m °C)$^{-1}$ - τ_s = 3.55 s, so the thermal time constant decreased by $\Delta\tau_s$ = 1.14 s. As Figure 5 shows the trend is not linear and from k_1 0.2 - 0.4 $W^{.}(m\ °C)^{-1}$ thermal time constant change is the biggest $\Delta\tau_s$ = 0.71 s.

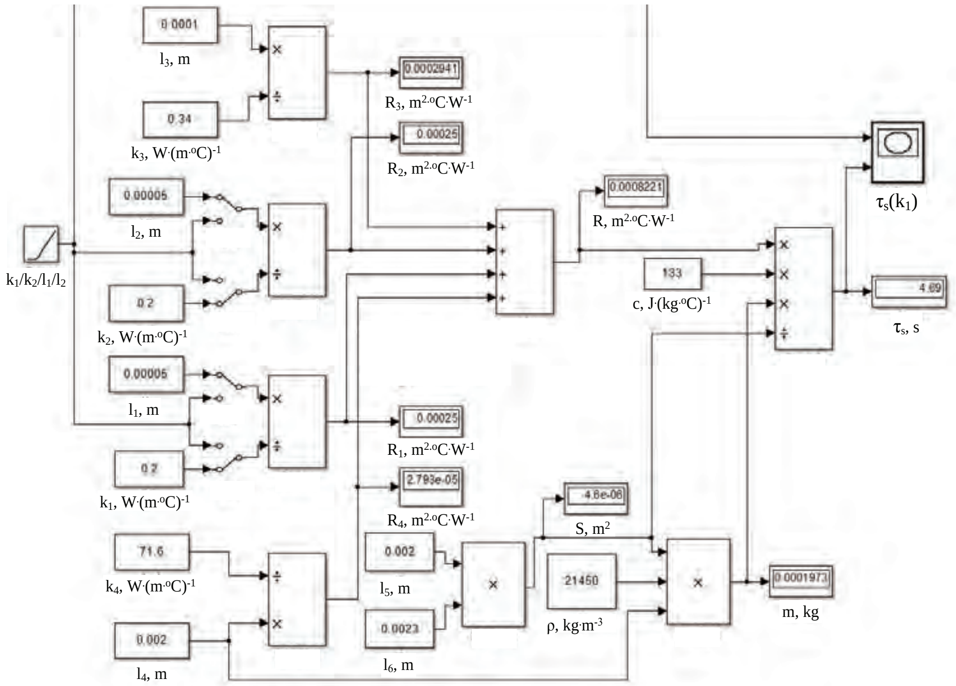

Figure 4. Simulation block diagram of thermal time constant of temperature sensor.

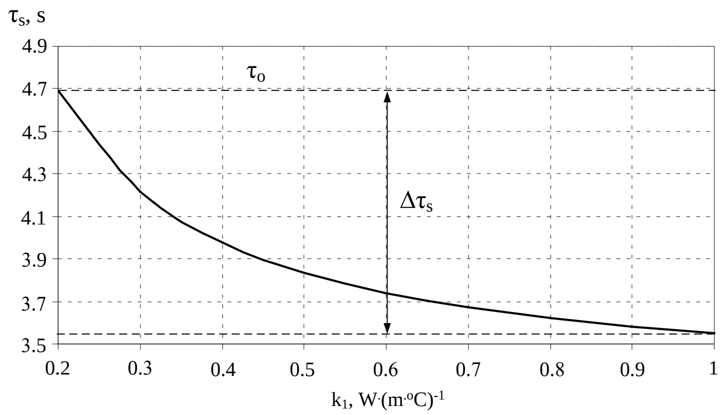

Figure 5. Simulation results of thermal time constant of temperature sensor at different thermal conductivity k_1 values of magnet wire insulation.

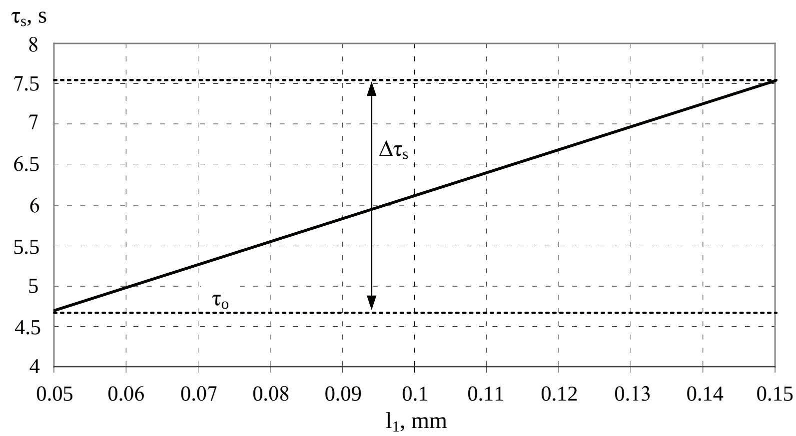

Figure 6. Simulation results of thermal time constant of temperature sensor at different insulation layer l_1 values.

Figure 6 represents simulations results thermal time constant of the temperature sensor τ_s and magnet wire insulation wire thickness l_1 relationship. Thermal time constant increase is linear from τ_o = 4.69 s at l_1 = 0.05 mm τ_s = 7.54 s at l_1 = 0.15 mm. The thermal time constant increased by $\Delta\tau_s$ = 2.85 s or by 64%.

Simulation results show that, the thickness changes of magnet wire insulation have a bigger influence on the thermal time constant than that of thermal conductivity.

Conclusions

1. Analyses of PTC thermistor sensor properties show that it requires mostly two wire leads, is very sensitive to temperature changes at rated response temperature range: several thermistors can be connected to one controller, small size of the sensor and low thermal mass, which makes PTC thermistor a cost-effective solution for induction motor temperature protection.
2. Analyses show that to measure small resistance changes of RTD a sensitive instrument and three or four lead wires are required for precise measurements, but accuracy, linearity and a long-term stability of the RTD makes it a conformable solution for temperature protection of medium and high voltage induction motors.
3. Thermal time constant simulation results of the thin-film RTD PT100 temperature sensor show that at stator winding magnet wire insulation thickness l_1 = 0.05 mm the thermal time constant is τ_o = 4.69 s and at insulation thickness l_1 = 0.15 mm thermal time constant increases to τ_s = 7.54 s. Therefore, insulation material thickness between the stator winding and temperature sensor has an essential impact on the thermal time constant of small size temperature sensors.

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