ACTIVE STATOR WINDING THERMAL PROTECTION FOR AC MOTORS

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Abstract—AC motors are the main workhorses in process industries. Their malfunction may not only lead to repair or replacement of the motor, but also cause significant financial losses due to unexpected process downtime. Reliable thermal protection of ac motors is crucial for reducing the motor failure rate and prolonging a motor’s lifetime. In this paper, conventional thermal protection devices and state-of-the-art thermal protection techniques are reviewed with their advantages and limitations discussed. Since 2001, the research team at the author’s company and at the Georgia Institute of Technology has been cooperatively developing a series of active motor thermal protection methods, as a low-cost alternative approach to the traditional passive and sensor-based methods. These active thermal protection methods monitor the average stator temperature via stator resistance estimation based on the dc equivalent model of ac motors, using only motor stator voltage and current measurements. In this paper, an overview of the active thermal protection techniques for line-started, soft-starter-connected and inverter-fed ac motors is presented, with their advantages and drawbacks discussed. The active thermal protection techniques are capable of providing accurate, and non-invasive thermal protection of ac motors.

Index Terms – AC motor, inverter, starter, stator resistance, stator temperature, temperature estimation, thermal protection.

I. INTRODUCTION

In North America, ac motor systems play a critical role in industrial process, while consuming more than a half of all the electric power produced. Due to their effectiveness, ruggedness and low maintenance requirements, these ac motors are widely used in applications of pumps, fans, mills, compressors, etc. The malfunction of a motor may not only lead to the repair or replacement of the individual motor, but also cause significant financial losses due to unexpected process downtime. Therefore, reliable motor protection is essential for minimizing the motor failure rate, increasing the mean time to a destructive motor breakdown, and prolonging a motor’s lifetime. Over the years, substantial efforts have been made in developing preventive monitoring and protection techniques for ac motors. As an important feature of any motor protection system, thermal protection is crucial for avoiding thermal overload and prolonging a motor’s lifetime.

As one of the major underlying root causes of motor failures, thermal overload can lead to deterioration of key components of a motor, including stator winding insulation, bearing, motor conductors, and core, etc [1-5]. The stator insulation is typically the most vulnerable component during thermal overload, since its thermal limit is reached before that of any other motor component. About 35-40% of induction motor failures are related to stator winding insulation failure [1-3]. Stator insulation failures are normally the results of long-term thermal aging [6]. A high stator winding temperature, which also depends on the insulation class, gradually and irreversibly reduces the electrical and mechanical performance of the insulation materials due to chemical reactions, and eventually leads to insulation failures. The typical thermal limits of the stator winding for different insulation classes are listed in Table I [7]. As a rule of thumb, it is estimated that a motor’s life is reduced by 50% for every 10°C increase above the stator winding temperature limit. Therefore, a motor must be de-energized immediately when the thermal limit is reached. As a result, accurate and reliable thermal protection of ac motors is essential for prolonging a motor’s lifetime and preventing unexpected process downtime.

TABLE I. TEMPERATURE LIMITS FOR DIFFERENT INSULATION CLASSES.

<table>
<thead>
<tr>
<th>Insulation Class</th>
<th>Ambient Temperature (°C)</th>
<th>Rated Temperature Rise (°C)</th>
<th>Hot Spot Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40</td>
<td>60</td>
<td>105</td>
</tr>
<tr>
<td>B</td>
<td>40</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>F</td>
<td>40</td>
<td>105</td>
<td>155</td>
</tr>
<tr>
<td>H</td>
<td>40</td>
<td>125</td>
<td>180</td>
</tr>
</tbody>
</table>

Motor thermal overload is typically caused by the following reasons [8]:
1. transient/starting thermal overload;
2. motor overload;
3. unbalanced supply voltages;
4. high ambient temperature;
5. impaired cooling capability.

(a) unbalanced supply voltage  (b) overload

Fig. 1. stator winding damage due to thermal overload [9].
The stator winding damages caused by unbalanced supply voltage and overload are shown in Fig. 1 (a) and (b), respectively. It can be observed that the stator winding may be totally damaged due to thermal overload.

Since the start of the utilization of ac motors, thermal protection has drawn special attention due to the relatively severe consequences of stator insulation failures. To preventively protect the motor from stator winding insulation failure and extend a motor’s lifetime, the stator winding temperature often needs to be continuously monitored during operation. Such monitoring is particularly important for medium- to large-size motors due to relatively larger capital costs the costs of the associated process downtime due to unexpected failures. Direct measurements of the stator winding temperature using embedded thermal sensors, such as thermocouples, resistance thermal detectors (RTDs), infrared thermal sensors, etc, are the most reliable approach for thermal protection. However, their applications are limited due to economic reasons, especially for small- to medium-size motors, since the installations of the embedded thermal sensors are difficult and costly.

Many different types of thermal protection devices have become commercially available, which by design are not directly measuring the motor temperature. Their operating principles and drawbacks are discussed in Section II and III. The basic concept of an alternative type of thermal protection techniques: active thermal protection techniques, is presented in Section IV. The active thermal protection techniques for line-started, soft-starter-connected, and inverter-fed ac motors, which are previously proposed by the authors, are summarized and compared in Sections V, VI, and VIII, respectively. Their advantages and drawbacks are also discussed. The active thermal protection techniques are capable of providing accurate and non-invasive thermal protection of ac motors.

II. CONVENTIONAL THERMAL PROTECTION DEVICES

The most commonly used conventional motor thermal protection devices are: dual-element time-delay fuses and eutectic alloy or bi-metal type overload relays. Motor thermal protection in industry typically relies on using a combination of these devices. They are designed based on the thermal limit curves, which define the safe operating time for different magnitudes of input currents under both transient and running overload conditions. The typical thermal limit curve of an ac motor is shown in Fig. 2 [10].

Although these low-cost thermal protection devices have been proven to work over the years, they can only roughly emulate the thermal limit curve. Besides, even the thermal limit curve is also only a rough and conservative representation of the thermal characteristic of ac motors, since the effects of ambient temperature, unbalanced supply voltage and the changes of the cooling capability of ac motors are neglected. In addition, since only the magnitude of the input current is monitored, these devices are not capable of protecting motors when high negative-sequence currents are present. Therefore, nuisance tripping and under-protection are both common when these devices are used [8, 11].

III. MICROPROCESSOR-BASED THERMAL OVERLOAD RELAYS

To overcome the aforementioned drawbacks of conventional fuses and relays, microprocessor-based thermal overload protective relays are often applied. They represent the state of the art in the thermal protection of ac motors. These microprocessor-based relays typically estimate the power losses in ac motors using current measurements, and then calculate the stator winding temperature based on the thermal model of ac motors. The motor is tripped immediately when a predetermined maximum permissible temperature is reached.

![Fig. 3. First-order thermal model of ac motors.](image)

The first-order thermal models are the most commonly used thermal model in this type of relays. An example of the first-order thermal model is shown in Fig. 3. The stator winding temperature and the ambient temperature are denoted as $T_s$ and $T_A$, respectively; $C_{th}$ represents the equivalent thermal capacitance, which models the intrinsic thermal characteristic of the stator winding; $R_{th}$ represents the equivalent thermal resistance, which models the cooling capability from the stator winding to the ambient; $P_{loss}$ represents the heat dissipation in the stator winding, which is mainly the copper loss. Since identification of the thermal parameters are typically difficult without embedded thermal sensors, methods have been developed to roughly estimate the thermal parameters using the motor’s nameplate information, including Service Factor and Trip Class [12]. The
The first-order thermal model of induction motors is broadly used due to its implementation simplicity: only the motor current needs to be measured. However, as these approaches neglect the temperature rise caused by the other motor losses and the change of the motor’s thermal behavior under different operating conditions, these thermal models are generally inaccurate and conservative, and therefore often times use of this approach will trip the motor long before the actual thermal limit is reached.

To improve the stator temperature estimation accuracy by considering the effect of different losses on stator temperature, high-order thermal models are also developed [13-19]. These methods can model the thermal effects of the losses in different motor components, such as winding, core, etc, and therefore are capable of providing more accurate stator temperature estimation than the first-order thermal models. An example of a second-order thermal model is shown in Fig. 4 [16], where the stator and the rotor are modeled separately, so that the thermal effects of the rotor losses and the rotor temperature rise on the stator temperature rise can be estimated. The complexity of the thermal model is a tradeoff between the accuracy of temperature estimation and the complexity in parameter identification and required computational effort. The losses in different motor components are either calculated online using the current measurement, or estimated via offline testing. The thermal parameters in these high-order thermal models are normally determined based on the measured temperature at different locations in the motor using embedded thermal sensors. The applications of high-order thermal models are limited due to the difficulty in thermal parameter identification, when embedded thermal sensors are not available. Another inherent drawback of the thermal model-based approaches is their negligence of the changes in the cooling capability of ac motors. Therefore, using a thermal model with fixed thermal parameters can lead to rapid motor failures when the cooling capability of the ac motor is significantly reduced.

\[ T_s = T_{s0} + \frac{R_s - R_{so}}{\alpha R_{so}}, \]  

where \( T_s \) and \( R_s \) are the stator temperature and resistance at room temperature; \( T_{s0} \) and \( R_{so} \) are the estimated \( T_s \) and \( R_s \) at room temperature; and \( T_{s0} \) and \( R_{so} \) are the estimated \( T_s \) and \( R_s \) at room temperature.

Many stator resistance estimation approaches have been proposed based on the equivalent electrical model of induction motors [20-22]. However, these techniques are mainly used for improving the field-oriented control performance at low speed or improving the sensorless speed estimation accuracy. It is shown in [23] that these approaches are inherently too sensitive to the variations of motor parameters due to different operating conditions, and therefore, are not capable of providing accurate stator resistance estimation for thermal protection purposes.

IV. OVERVIEW OF ACTIVE THERMAL PROTECTION TECHNIQUES

The development of active thermal protection techniques can be traced back to the early 80’s. It is first proposed in [24] to use the dc model of ac motors to estimate the stator resistance and temperature, by creating a dc bias in the motor’s input voltage and current. Since the dc component does not “pass through” the air-gap, stator resistance can be calculated using only the dc component in the input voltage and current, as,

\[ R_s = \frac{2 \cdot v_{ab}^{dc}}{3 \cdot i_{ab}^{dc}}, \]  

where, \( v_{ab}^{dc} \) and \( i_{ab}^{dc} \) are the dc components of the motor line voltage \( v_{ab} \) and phase current \( i_{ab} \), respectively, when a dc bias is injected between phase \( a \) and \( b \), phase \( b \) and \( c \), of a Y-connected ac motor. However, since power diodes are typically used to create the dc bias in this approach, dc bias can only be injected continuously and the magnitude of the injected dc bias can not be adjusted online, which induces continuous and uncontrollable torque pulsation and extra heat dissipation in both the power diodes and also the motor itself.

One novel approach to resolve these design limitations is by use of a newly developed signal-injection-based active thermal protection technique. To minimize the torque pulsation and heat dissipation caused by the injected dc bias, controllable dc signals are intermittently injected to estimate the stator temperature. The period of stator temperature update depends on the requirement of practical applications. Active thermal protection approaches have been proposed by the authors for different applications: ac line-started motors [25, 26], soft-starter-connected motors [27, 28], and inverter-fed motors [29]. These techniques are capable of providing accurate and non-invasive thermal protection of ac motors, with adaptation to the changes in a motor’s cooling capability.

V. ACTIVE THERMAL PROTECTION FOR AC LINE-STARTED MACHINES

A. DC Signal Injection for AC Line-started Motors

To inject a controllable dc bias between two phases of ac motors, a dc injection circuit is proposed in [26]. It consists of a controllable switch (e.g., a mechanical contactor or a solid-state power switch) and an external resistor \( (R_{ext}) \) connected in parallel, as shown in Fig. 5-(a). In [26], the controllable switch is implemented using an n-channel enhancement type power MOSFET. Under dc signal injection mode, the controllable switch is turned open when \( i_{ab}>0 \), and turned closed when \( i_{ab}<0 \); the equivalent circuits are shown in Fig. 5-(b) and (c). The asymmetrical resistance causes the voltage drop across the circuit to be asymmetrical, resulting in injection of a dc current component into the motor. The magnitude of the
The injected dc signal is dependent on the value of $R_{ext}$, which can be adjusted depending on the nominal $R_s$ and the rated $I_{nom}$ so that the torque distortion and power dissipation caused by dc signal injection is within an acceptable level. Under normal operation, the controllable switch is kept closed to minimize the heat dissipation in the circuit. Therefore, the effects of dc signal injection can be minimized by using periodic operation of the circuit: dc signals are only periodically injected for a small amount of time, which is sufficient to obtain an accurate estimate of the stator temperature. As one of the few laboratory prototypes built to validate the dc injection approach, a prototype using a commercial mechanical contactor as the controllable switch is shown in Fig. 5-(d).

![Fig. 5. DC injection circuit.](image)

**B. Experimental Testing**

A series of lab testing has been conducted to validate this stator temperature estimation approach using both mechanical and solid-state switches. Fig. 6 shows the overall experimental setup using a MOSFET-based dc injection circuit [26]. A dc generator supplying a resistor bank serves as the dynamometer. Thermocouples are installed at different locations of the induction motor to measure the stator winding temperature for comparison purposes. The estimated stator resistance and the measurement stator temperature are shown in Fig. 7. The motor is operated under load variation conditions: no load $\rightarrow$ 100% $\rightarrow$ 50% $\rightarrow$ 75% of the rated load. The estimated stator resistance with different values of $R_{ext}$ is shown in Fig. 7-(a), (b) and (c); the measured stator temperatures with thermocouples at different locations are shown in Fig. 7-(d).

![Fig. 6. Experimental Setup [26].](image)

**VI. ACTIVE THERMAL PROTECTION FOR SOFT-STARTER-CONNECTED MACHINES**

A. DC Signal Injection using Soft-starters

The soft-starter normally contains multiple anti-parallel solid-state power switches (e.g., thyristors) to control the current flow and, in turn, the terminal voltages of the motor. The soft-starter limits the transient voltages and currents, reduces the inrush currents, and results in a “soft” motor start. After starting, the soft-starter typically enters the “bypass” mode, when integrated contactors are closed to minimize the power dissipation.

A new thyristor gate drive control scheme has been developed by the authors to inject dc components in the motor line voltages and phase currents [28]. This scheme periodically switches the soft-starter operation between two states after the soft-starter completes the ramp-up mode: a normal bypass operation state and a dc signal injection state. During the dc signal injection state, only one contactor (corresponding to only one phase, e.g., phase a) in the soft-starter is kept open, while the other two contactors still work normally as in bypass mode. Instead of using symmetrical gate drive signals for all three phases, a short delay is introduced to the gate drive signal of only the forward-conducting thyristor of phase a ($V_{G0}$), after the phase a current’s rising zero-crossing. After the dc signal injection state, the phase a contactor is closed, so that the soft-starter
returns to normal bypass operation state. The equivalent model of the motor system during dc signal injection state is shown in Fig. 8. Fig. 9 shows the typical waveforms of the motor line voltage, $v_{ab}$, phase current, $i_a$, while a small delay angle of $\alpha$ ($\alpha < 40^\circ$) is added. The torque pulsation caused by the injected dc signal can be controlled under acceptable level by adjusting the delay angle.

Fig. 8. DC equivalent circuit of motor, source and soft-starter.

Fig. 9. Motor line voltage, phase current during dc signal injection.

**B. Experimental Testing**

![Experimental setup](image)

The lab setup for the validation of this stator temperature estimation technique is shown in Fig. 10. The motor is operated under variable load conditions: no load $\rightarrow$ 50% $\rightarrow$ 75% $\rightarrow$ 100% of the rated load. To test the feasibility of this approach when the cooling capability of the motor is reduced, the motor’s cooling fan is removed under the same variable load condition. The estimated stator temperature and the mean measured temperature using thermocouples under normal condition and cooling capability deterioration condition are shown in Fig. 11-(a) and (b), respectively.

**VII. ACTIVE THERMAL PROTECTION FOR INVERTER-FED MACHINES**

**A. DC Signal Injection using Motor Drives**

Open-loop ac motor variable frequency drives are widely used for controlling the rotor speed of ac motors. In such drives, motor input voltage commands are generated at a certain fixed ratio to the frequency (or speed) command to control the switching of solid-state power switches, e.g. IGBTs. To inject dc signals, a dc voltage offset can be simply added to the original input voltage command, which then adjusts the switching of the power switches automatically. An example of
dc signal injection method using space vector pulse width modulation (SVPWM) is shown in Fig. 12 [29]. Similar to the soft-starter dc injection method, this scheme also periodically switches the drive operation between two states: a normal operation state and a dc signal injection state. The typical input current waveform during dc signal injection state is shown in Fig. 13, where a clear dc component is shown in the motor current. Since the dc voltage command is constant, the stator temperature can be estimated using only current measurements, as,

$$T_s = T_s^0 + \frac{1}{\alpha} \frac{1}{\alpha} \frac{d}{dt} i_{dc}^0,$$

where $i_{dc}^0$ represents the dc component in the phase current when the stator temperature is $T_s^0$. Therefore, the voltage measurement can be avoided, which is highly desirable since voltage sensors are typically not present in variable frequency motor drives.

![Fig. 12. Modified space vector PWM for dc signal injection.](image)

![Fig. 13. Stator current with dc signal injection.](image)

![Fig. 14. Experimental setup [29].](image)

![Fig. 15. Impaired cooling by blocking ventilation.](image)
B. Experimental Testing

The lab setup for the validation of this approach is shown in Fig. 14. The motor is then operated under variable load conditions: no load → 100% → 50% → 75% of the rated load. To test the effectiveness of this approach when the motor’s cooling capability is deteriorated, the ventilation is blocked, when the motors is operated under the same variable load condition, as shown in Fig. 15. The estimated stator temperature and the average temperature measured using thermocouples under normal condition and cooling capability deterioration condition are shown in Fig. 16-(a) and (b), respectively. The value of the stator resistance estimated using this technique can also be further used for improving the field-oriented control performance at low speed or improving the sensorless speed estimation accuracy.

VIII. SUMMARY OF ACTIVE THERMAL PROTECTION TECHNIQUES

Conventional passive thermal protection devices, including dual-element time-delay fuses, eutectic alloy or bimetal type overload relays and microprocessor-based overload relays, are typically inaccurate due to the difficulty in the accurate modeling of a motor’s thermal behavior. The error in the stator winding temperature estimation may be more than 30°C [28]. Therefore, nuisance tripping is common when these devices are used.

On the other hand, the active thermal protection techniques are capable of providing accurate monitoring of the stator temperature without embedded thermal sensors, as shown in Section V, VI and VII. The errors in the stator winding temperature estimation can be smaller than 3°C, depending on the magnitude of the injected dc signals. The torque pulsation and extra heat dissipation caused by dc signal injection can be controlled within acceptable levels. The dc signals are intermittently injected to minimize the effects of the dc signal injection. The period of dc signal injection depends on the frequency of stator temperature estimation updates required by the practical application, given a motor’s typical thermal time constant.

Because of their accuracy in the stator winding temperature estimation, their robustness to the variations in the electrical/thermal parameters of ac motors and their capability of adaptation to the changes in a motor’s cooling capability, these active thermal protection techniques are highly preferred over conventional thermal protection techniques for the reliable thermal protection of ac motors.

IX. CONCLUSIONS

Thermal protection of ac motors is crucial for preventing catastrophic motor breakdown, prolonging motor’s lifetime, and avoiding the extraordinary financial losses due to unexpected industrial process downtime caused by motor failures. A review of available thermal protection devices and techniques has been presented in this paper. The principle and drawback of conventional overload relays and microprocessor-based thermal relays have been discussed. It has been concluded that these thermal protection techniques are not capable of providing reliable thermal protection for ac motors under different operating conditions, due to:

1. inaccurate modeling of the thermal characteristics of ac motors under different operating conditions;
2. negligence of the changes in a motor’s cooling capability.

To overcome the drawbacks of conventional thermal protection techniques, an alternative type of thermal protection technique: active thermal protection, has been proposed by the authors for ac line-started, soft-starter-connected, and inverter-fed ac motors. By intermittently injecting dc signals into the motors, the dc model of ac motors has been used for the estimation of the stator winding resistance and temperature. It has been clearly shown that these techniques are capable of providing accurate monitoring of the stator temperature without embedded thermal sensors. The errors in the stator winding temperature estimation can be within 3°C, depending on the magnitude of the injected dc signals. The torque pulsation caused by the injected dc signals can be
controlled under acceptable level. The importance of these techniques lies in their non-invasive nature:

1. only current and voltage measurements are required;
2. motor’s normal operation is not disturbed.

Therefore, the active thermal protection techniques are capable of providing non-intrusive, low-cost and reliable thermal protection of ac motors, when moderate torque pulsation is acceptable for the practical applications.

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XI. REFERENCES


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