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Online temperature monitoring of a grid connected induction motor

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ABSTRACT

This paper proposes a novel method for continuous temperature measurement of the stator winding of an induction machine. The method is based on measuring stator winding resistance by injecting a DC current test signal into the motor neutral point without interrupting its normal operation. The entire stator winding is used as a sensor without additional thermal sensors, while DC voltage and current need to be measured solely. Virtually equal currents are injected in each phase thereby minimizing the influence on the motor torque inherent to contemporary signal injection-based methods. The measurement results obtained using the proposed method are compared to results obtained using the standard resistance-based method and direct measurements obtained from thermocouples embedded in the windings. An excellent match is achieved under various loading levels and variable cooling conditions, thus proving the accuracy and robustness of the proposed method.

1. Introduction

Induction motors are widely used in various branches of industry. It is therefore essential to prevent their malfunction, due to large cost repairs and financial loss due to unexpected downtime. An exhaustive overview of most common faults and protection methods for induction motors is given in [1]. According to the authors, induction machine failures can most commonly be attributed to thermal destruction of stator insulation, caused by either overloading, impaired cooling, or ambient temperature rise.

Thermal protection of the machine needs to provide a compromise between two opposing conditions. On the one hand, the level of protection must not be set that low as to cause nuisance tripping, whereas on the other hand, it must not be set that high as to allow permanent operation at temperatures exceeding insulation rating. The most straightforward way of implementing thermal protection would be direct measurement of temperature in critical parts of the machine by means of sensors embedded in machine windings. However, this approach is seldom used in low and medium power drive systems, due to significant financial impact in these applications.

In the past decades, numerous approaches for thermal protection of induction machines suitable for low-cost applications have been developed. These approaches can be roughly classified into three groups [1]: methods based on the thermal model of the machine, methods based on estimation of machine's electrical parameters and hybrid methods, based on a combined thermal and electrical modeling approach.

An overview of thermal model-based methods is given in [2]. Traditional thermal-protection relays with a single time constant are often unreliable when dealing with cyclic loads or changes in cooling conditions. New generations of relays are microprocessor-based and provide possibilities of implementing high order lumped parameter thermal models (thermal networks), such as those described in [3,4]. Other advanced thermal modeling approaches, such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), are still mostly limited to the machine design stage, due to high computational demands involved. Application of FEA for improving the thermal model's accuracy has been proposed in [5,6]. Downsides related to all thermal model based methods are difficulties in determining thermal parameters and tuning of the model under variable cooling conditions. Development of complex thermal models requires either knowledge of the machine's design parameters [7] or temperature measurement data in different parts of the machine under various loading conditions [8]. This information is often unavailable, particularly for machines already in service. Reduced order thermal models which facilitate the process of calculating thermal parameters and are more suitable for real-time implementation have been proposed in [9,10]. An adaptive thermal model-based approach, which take variations of cooling conditions into account, is introduced in [11]. This approach requires measurement of motor speed and temperatures at several accessible points of the machine.

Methods based on the estimation of electrical parameters rely on calculation of rotor or stator resistance in order to estimate

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the average temperature of the corresponding winding. The main advantage over the thermal model-based approach is insensitivity to variations in cooling conditions and lack of requirement for additional temperature sensors. These methods can be subdivided into two groups: methods based on the electrical model of the machine and methods based on signal injection. The first group uses terminal voltage and current measurements combined with the electrical model of the machine to calculate the stator or rotor resistance [12,13]. Although convenient due to their non-invasive nature and little requirement for additional equipment, such methods suffer from sensitivity to difference between assumed and actual machine parameter values [14]. Resistance estimation based on signal injection provides a more accurate estimate, but it generally requires additional sources and measuring equipment. A majority of proposed methods are based on injection of DC current into the motor phases [15–18]. The DC current injection methods reported up to date result in undesirable torque oscillations [19]. In some recent publications, there have been reports of using Pulse Width Modulated (PWM) signals for estimating stator and rotor resistances [20,21]. These methods are only applicable to inverter-fed machines and require significant computational power for their implementation.

Hybrid methods which use a combined thermal and electrical modeling approach have recently been reported [22,23]. These methods have the merit of being robust to variations of the motor parameters. However, the problems of inaccuracy under very low load and under cyclic loads with rest periods, as well as the problem of accurate identification of thermal parameters, are still present.

Methods described in literature up to date do not provide a solution for accurately monitoring stator winding temperature in small- and medium-sized induction motors without disrupting normal machine operation or applying complex filtering procedures. In this paper, a new method for continuous stator winding temperature assessment of a grid connected induction motor without interruption of normal operation is proposed. The method is based on measuring the winding resistance and does not require installation of temperature sensors into the windings. A DC test signal is injected into the stator winding in such a way that it causes no adverse effects on the motor torque. Excellent performance is achieved under different operating modes and cooling conditions. Moreover, the method is suitable according to current standards, which assume the use of the resistance method for machines with a rated output below 200 kW [24].

2. Method description

The proposed method is based on measurement of stator resistance without interruption of machine operation. A schematic display of the measurement system is given in Fig. 1. A small DC current is injected into the neutral point of the motor. This can be achieved by connecting a DC voltage source between the neutral point and the neutral of the supply. In order to limit undesirable triplen harmonic and zero-sequence AC currents, a DC current source is created, by adding a large resistance in series with the voltage source, thus providing a constant DC current value. In order to enable current injection during rest intervals motor terminals need to be short-circuited upon disconnection from the supply. The DC voltage component across the windings is measured between the neutral point of the machine and an artificial neutral point, created by connecting three equal resistors to the machine terminals. A capacitor is added between the artificial neutral point and the machine neutral point in order to filter out the triplen harmonic and zero-sequence AC voltage components. This type of connection of the RC filter facilitates filtering in contrast to the

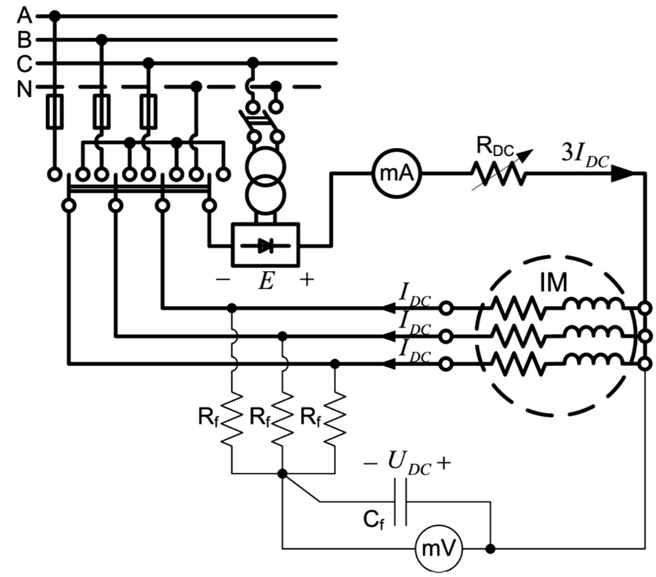

Fig. 1. Schematic display of the system for continuous measurement of stator winding resistance.

option of connecting an RC filter over a single phase, due to the following: 1. The amplitude of triplen harmonics and zero-sequence components is significantly lower than the first-order harmonic one, and 2. Triplen harmonics are easier to filter out than the first-order harmonic, due to their higher frequency. Once the voltage and current measurements have been obtained, the value of the winding resistance is simply calculated by the following equation:

$$R_1 = \frac{U_{DC}}{I_{DC}}, \tag{1}$$

where R_1 is the equivalent per-phase stator resistance. It has been shown in [25] that the DC zero-sequence impedance of an induction motor indeed equals R_1, as stated in (1).

In order to achieve accurate measurement, the DC current value should be set with the aim of providing sufficient voltage drop, but at the same time, a significant increase in winding temperature should not be caused. Appendix A examines thermal effects of the injected DC current in detail. Once the resistance value at an unknown temperature has been obtained, the temperature rise is calculated as in [24]:

$$\theta_h = \upsilon_h - \upsilon_a = \frac{R_1(\upsilon_h)}{R_1(\upsilon_c)} \cdot (k + \upsilon_c) - k - \upsilon_{amb}, \tag{2}$$

where υ_c and $R_1(\upsilon_c)$ are the cold-state temperature and resistance values, υ_h and $R_1(\upsilon_h)$ are the hot-state temperature and resistance values, θ_h is the corresponding hot-state temperature rise, υ_{amb} is the ambient temperature, and k is a constant which depends on the conductor material ($k = 235$ for copper). The cold-state resistance is measured when the motor is disconnected from the supply for a long time period, at a known temperature υ_c equal to the ambient temperature. The hot-state resistance is measured during motor operation.

The underlying assumption in the previous considerations was that the winding resistances were mutually equal. Even though this is generally the case, a slight mismatch between phase winding resistances may occur. A detailed examination of this mismatch on the systematic error of the proposed method is carried out in Appendix C.

It is commonly assumed that zero-sequence currents do not contribute to torque generation in induction machines [25]. How-