

# Online Stator End Winding Thermography using Infrared Sensor Array

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**Abstract**—Temperature monitoring is vital for protection and online health assessment of winding insulation of rotating electrical machines. The conventional method of embedding temperature sensors into the stator winding is reliable for localized measurements but could be blind to hot-spots depending on sensor proximity and fault severity. The more recent Infra-red (IR) camera based thermographic techniques are non-invasive and non-contact in obtaining machine's casing temperature distribution. However, they suffer from low sensitivity in detecting incipient winding faults. To overcome these limitations, a sensor array composed of discrete IR thermopile sensors mounted along the inner wall of the stator's casing is proposed in this paper. Although the system is invasive, it is non-intrusive and provides direct temperature distribution along the end-winding region in a non-contact way. The effectiveness of the sensor array in providing temperature distribution and inter-turn short circuit hot-spot detection is validated with experiments conducted using an induction motor.

**Index Terms**—Condition monitoring, induction motor, infrared sensor, temperature measurement, winding fault

## I. INTRODUCTION

Insulation degradation has been identified as one of the major cause for stator related faults in electrical machines [1]. Thermal stress is the chief contributor for insulation degradation, as such, monitoring the winding temperature would aid in reliable continuous assessment of insulation health [2] [3]. Conventional condition monitoring systems for electrical machines are predominantly based on non-invasive measurements [4]. The internal signals could be more sensitive as the fault phenomenon originates inside the machine. However, these signals are less explored in the past due to the limitation on the availability of reliable, cost-effective and non-intrusive technology for internal probing. With the availability of small rugged electronics, miniature self-sustaining sensors capable of withstanding harsh environment can be deployed to explore signals even from tight spaces [5] [6]. The current work explores the application of IR temperature sensor technology for monitoring electrical machine's winding temperature distribution, which could help in accurate detection and prognosis of insulation related winding faults.

The conventional stator temperature monitoring is based on embedding localized temperature detectors (thermocouples/resistance temperature detectors) into the winding [3] [7]. The localized sensing nature coupled with limited sensor numbers due to cost and cabling constraints makes it less

suitable for assessing winding temperature distribution. With the advent of affordable IR thermal cameras, thermography is emerging as a promising temperature monitoring method for electrical machines [8] [9] as they are non-invasive and non-contact. However, external casing temperature distribution captured by the camera is more suitable for detecting severe faults and may not correlate well with internal winding temperature, especially for detecting incipient faults. Moreover, thermal imaging could easily be affected by external environmental factors [10] [11].

This paper proposes a sensor array system consisting of circularly distributed IR thermopile sensors mounted along the inner stator casing, facing the end-winding region. Although the system is invasive, it is non-intrusive to the machine's operation and enables the measurement of winding temperature distribution in a non-contact manner. Direct measurement of winding temperature and ease of obtaining surface temperature distribution are the key benefits of using embedded temperature detector and an IR camera respectively. These benefits are achieved in the proposed sensing scheme, albeit with lower resolution in temperature distribution. The proposed Infrared Sensor Array (IRSA) is demonstrated using commercially available IR sensors in an induction motor modified to introduce stator inter-turn faults (SFs). SF has been identified as the incipient stage for winding insulation failure [4] [12] and hence is used to assess the fault detection capability of IRSA. The key contributions of this paper are,

- Development and deployment of an end winding infrared sensing array in an induction motor with stator inter-turn winding fault emulation capability.
- Comparison of the effectiveness of the IRSA in detecting incipient winding inter-turn faults with end winding thermocouples and an IR thermal camera.

The organization of the paper is as follows: Section II briefly reviews the sensor based temperature monitoring methods for electrical machines. An overview of infrared based temperature sensing and IR sensor array is discussed in Section III. The hardware test rig developed for fault diagnosis study using IRSA is presented in Section IV. The experimental results comparing the performance of IRSA and thermal camera in winding fault detection is presented and discussed in Section V. Finally, Section VI concludes the paper.

## II. STATOR WINDING TEMPERATURE MONITORING

The winding insulation subjected to high electrical and thermal stresses degrades gradually leading to inter-turn short circuit fault [2]. This causes the flow of high short circuit loop currents and heating up of the shorted winding portion. This heating effect would further accelerate the degradation of the neighboring winding's insulation and could lead to catastrophic phase-to-phase or phase-to-ground faults [1]. The inter-turn fault has been identified as the main reason for insulation failure in electrical machines [4]. The time taken for an inter-turn fault to progress to a catastrophic stage has not been well established, but it is more probable that it will not be instantaneous [13]. Therefore, detecting the fault at the earliest could help prevent unexpected machine failure. In this section, we briefly review two major sensor based temperature monitoring schemes for electrical machines and its effectiveness in detecting inter-turn faults.

### Point-based Sensors

Point-based temperature sensors (embedded temperature detectors) provide temperature information from highly localized regions. These sensors include thermistors, thermocouples, and resistance temperature detectors (RTDs). The ideal installation location for these sensors is in the stator slots and end winding region, close to the hottest part [3]. They provide a direct winding temperature reading and is considered most reliable for thermal protection [14] [7].

The sensors installed on the winding of the machine would be uniformly distributed to get overall temperature profile and the number of sensors would usually be lower than the number of stator coils. Although this setup would be sufficient for detection of thermal overloads and asymmetric heating between phase windings, it could be ineffective for detecting inter-turn faults. In the case of an inter-turn fault, the heating is localized to the faulty coil, and depending on the proximity of the sensor, the increase in temperature due to the fault may go undetected.

### Infra-red Camera

An infrared (IR) camera based temperature monitoring system captures the thermal image of an area under observation in a non-contact and non-invasive manner. Their deployment had been limited due to the expensive nature of thermal cameras. However, with decreasing costs of IR camera systems, the deployment for continuous monitoring of electrical machines is explored more in recent years [8] [9]. Due to the wider sensing area, IR camera can be used to monitor more components and detect different faults, such as bearing issues, thermal overloads, cooling defects, and coupling misalignments. The fault detection mechanism is through discerning the anomalous temperature increase and/or thermal patterns caused by the faults [15] [8].

For the application of stator winding temperature monitoring, the external casing temperature distribution may not ideally reflect the internal winding temperature. Although IR thermography has been used for detecting thermal overloads,

asymmetric winding heating [9] and inter-turn fault conditions [16], it can be argued that the detection would not be possible at incipient stages. Also, interpreting the fault from the heat map may not be straightforward. Historical thermal data of the machine with considerations to various external parameters and an expert interpretation would be necessary for arriving at a diagnostic conclusion [10] [9].

To overcome the limitations of embedded temperature detectors and the thermal camera, this paper proposes the use of an array of discrete IR thermopile sensors for winding temperature monitoring. The proposed array-based sensing system is to be deployed inside the machine for measuring the temperature distribution of stator's end winding region. The system provides a direct measure of the end winding temperature distribution in a non-contact way.

## III. IR SENSOR ARRAY

Infrared temperature sensors measure temperature by interpreting the thermal radiation energy emitted by the object [8]. The key specifications that characterize the measurements are the field of view (FoV) and surface emissivity. The FoV determines the region in which the sensor is sensitive to radiation. The FoV and position of the object determine the surface area exposed to the sensor. The measured temperature is the average of the exposed surface temperature. Surface emissivity denotes the amount of thermal IR energy radiated by the object at a given temperature. The computation of the surface area; approximating the object to be perpendicular to the sensor by a distance  $d$ , is depicted in Fig. 1, where  $\phi$  represents the angular FoV of the sensor. The diameter of the circular area covered is given by,

$$D = 2d \tan(\phi/2) \quad (1)$$

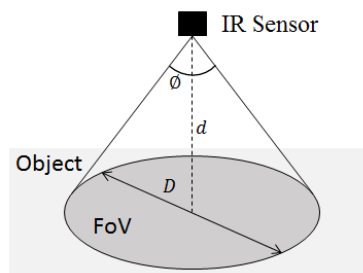


Fig. 1: FoV of a discrete IR sensor

The proposed IRSA system should be capable of resolving temperature of individual coils exposed in the end-winding region. To achieve this, the design of the array system should take into consideration the geometry of the end-winding, sensor FoV, number of sensors and sensor positioning. A typical linear sensor array is depicted in Fig. 3, where the individual sensor's FoV is confined to the object of interest. More often, the FoV would encompass multiple objects and additional processing will be required to resolve individual

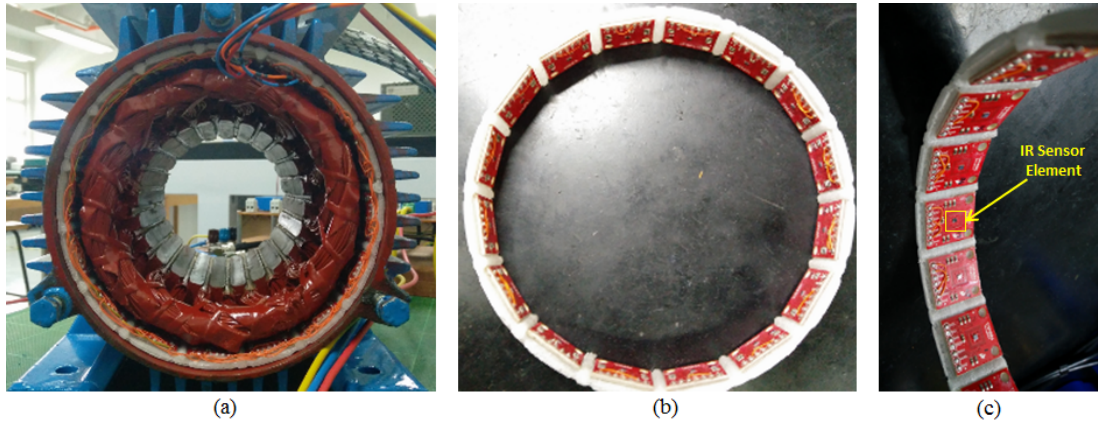


Fig. 2: IR sensor array prototype validation: a) IRSA in an induction motor b) IRSA c) TMP006

object's temperature. For an oversimplified case, the number of sensors required for IRSA is given by,

$$n = L_{ew} / D \quad (2)$$

where,  $L_{ew}$  is the circumferential length of the outer end-winding region. The proposed IRSA system is built using Texas Instrument's TMP006 IR temperature sensors. They are sensitive to passive infrared energy at  $4 \mu\text{m}$  to  $16 \mu\text{m}$  wavelengths, with operating temperature range from  $-40^\circ\text{C}$  to  $+125^\circ\text{C}$  [17]. Assuming the sensors have a uniform sensitivity with fixed FoV of  $120^\circ$ , the number of sensors required to cover the end-winding periphery of the chosen induction motor using (2) is found to be 16. Hence, a circular sensor array with 16 sensors is constructed as shown in Fig. 2. As the sensors utilize I2C bus, four wires are sufficient for powering and reading data from IRSA.

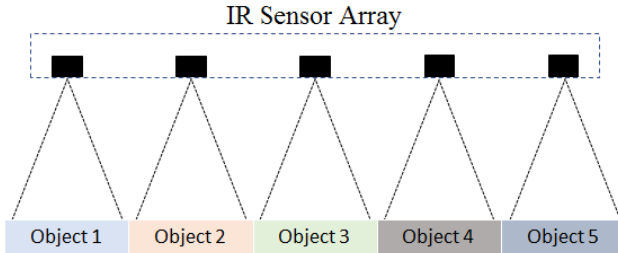


Fig. 3: FoV of linear IR sensor array

#### IV. EXPERIMENTAL SETUP

The IRSA system is validated using a totally enclosed fan-cooled, 1.5 kW induction motor with the stator armature winding rewound to include tap-outs for introducing inter-turn short circuit faults. Additionally, each coil is embedded with a thermocouple (TC) at the end-winding region. The winding configuration consists of four coils per phase, and 12 thermocouples are embedded to provide a reference to validate the performance of the IRSA. The sensor array is mounted on one side of the end-winding region as depicted in Fig. 2 a). To

accelerate the rise in temperature, the fan was removed during the experiments. An IR thermal camera is used to record the motor's external casing temperature. The experiment setup is depicted in Fig. 4.

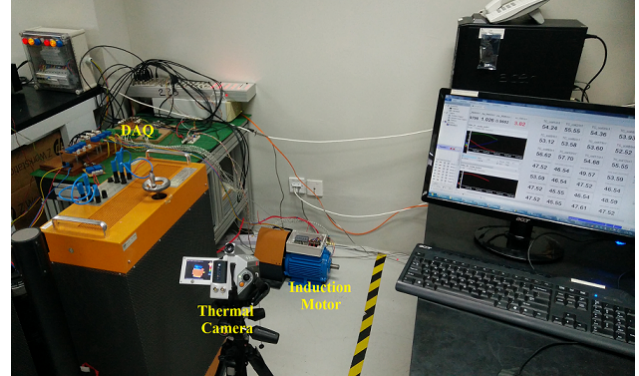


Fig. 4: Experiment test rig

Experiments are conducted in a no-load condition for healthy state and stator inter-turn fault (SF) with 5% of the windings shorted. The SF is introduced separately in two different phases (U and V) to compare the fault localization capability. The tap-outs were shorted using a power resistor in order to limit the inter-turn fault current. In each state, Healthy, SF-Uphase and SF-Vphase, the machine is run for 60 minutes to attain thermal steady state and temperature data from sensors and camera are collected. Before the start of each experiment, it is made sure that the machine is at the surrounding ambient temperature.

#### V. RESULTS AND DISCUSSION

The end winding coil temperature distribution from the TC and IRSA system is presented in Fig. 5. The first row represents the TC and the second, the IRSA data. Each segment of the wheel corresponds to one sensor. We can observe that the temperature profile from the TC and IRSA follows a similar trend. The average temperature deviation

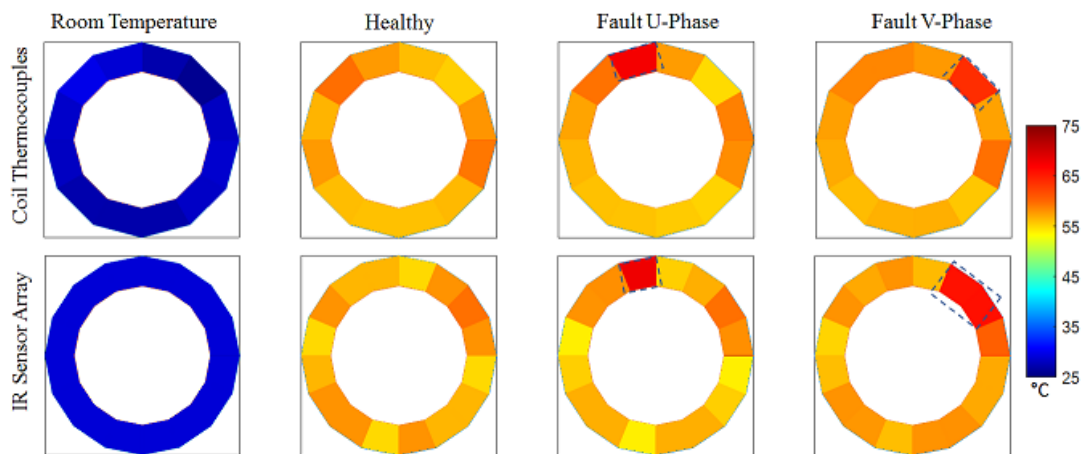


Fig. 5: End-winding temperature distribution

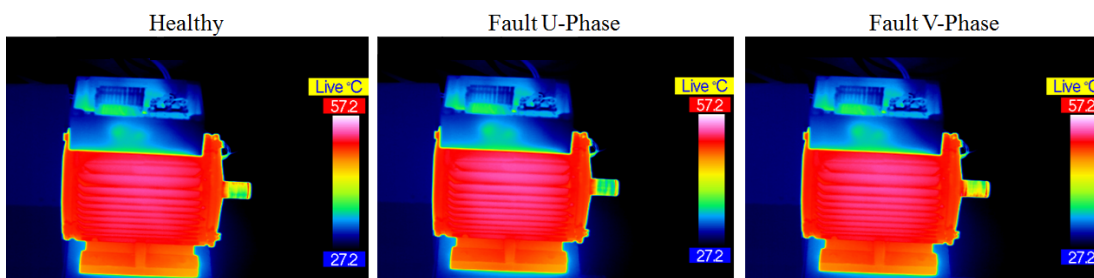


Fig. 6: Thermal image of the motor casing under different conditions

between the TC and IR sensors for the healthy case is found to be less than  $2^{\circ}\text{C}$ . This validates the ability of IRSA to measure the end winding temperature accurately. During an inter-turn fault condition, IRSA is able to detect hot-spot temperature rise due to the flow of high fault current localized to the shorted coil. Under similar circumstances, the thermal images (Fig. 6) cannot differentiate between healthy and inter-turn condition, much less infer the hot-spot temperature.

#### A. Comparison between Thermocouples and IRSA

From Fig. 5, we can observe that both the IRSA and the thermocouple system are able to detect the temperature increase due to the inter-turn fault. However, in real-world applications, the number of thermocouples used to measure winding temperature would be less than the number of coils. Under such conditions, the inter-turn fault temperature rise may go undetected. To demonstrate this, a 3-thermocouple based configuration is chosen. The 3 sensors are distributed spatially among the three phases. With this scheme, 4 different sensing configurations are possible in a 12-coil stator machine. The temperature measurements from different sensing locations under healthy and inter-turn fault conditions are presented in Fig. 7. Each configuration (config.) corresponds to a different combination of 3-phase coils. The temperature deviation among the sensors within each configuration is depicted on top of the bar plots. Setting the fault detection

threshold as  $3^{\circ}\text{C}$  deviation, it can be observed that the inter-turn fault, being a localized event, cannot be detected in all configurations. Configurations 2 and 4 are able to detect fault in the U-phase and V-phase respectively. This is due to the fact that the corresponding sensor is located in that fault coil.

On the other hand, installation of 12 TC sensors, which represents one sensor for each coil is also not feasible as it increases deployment complexity and cost. Moreover, the TC based system has to be installed during the machine's manufacturing stage, whereas, the IRSA can be deployed as an add-on system even to an existing machine during maintenance. As the IRSA uses a digital bus, it does not suffer from electrical noise from PWM drives compared to the TC system [18], and the digital bus greatly reduces the number of wire leads. Alternatively, with the recent exploration of wireless communication for monitoring electrical machines, the sensed data from IRSA can be transferred through wireless RF communication as well [19] [20].

#### B. Comparison between Thermal Camera and IRSA

Fig. 6 presents the machine's casing temperature data under different fault conditions. From Fig. 6, we can observe that there is no discernible change in temperature distribution between the healthy and faulty cases. This is to be expected as the temperature rise in the faulty coil compared to the other windings is only about  $5.5^{\circ}\text{C}$ . Such low temperature

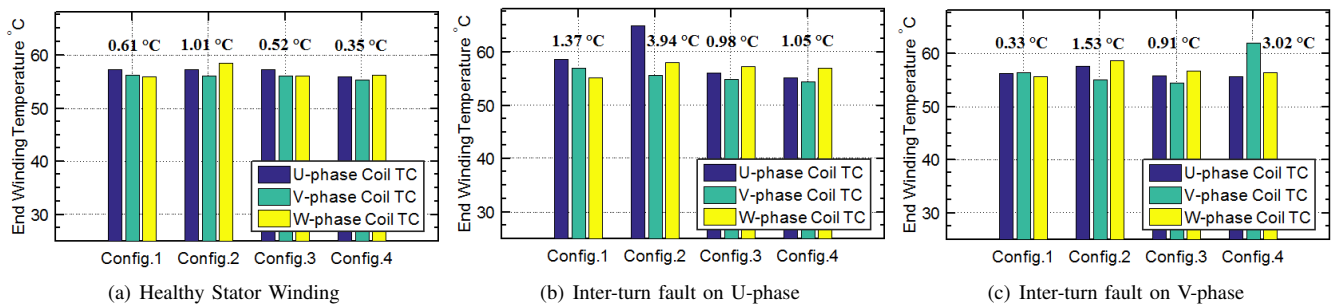


Fig. 7: Comparison of different thermocouple deployment configurations (config.1 to config.4)

differences will not produce appreciable changes in the motor's casing temperature. Thus, an IR camera based monitoring might not be suitable for detecting incipient winding fault conditions. On the other hand, the IRSA, with the capability to directly measure the end winding temperature distribution, is able to localize the fault and provide hot-spot temperature. This would be very useful for fault diagnosis and winding insulation prognostics.

The thermal camera, with its wider coverage area, would be able to monitor the drivetrain along with the electrical machine. However, the fault could go undetected if the abnormal thermal signature were to develop in parts of the machine not within the FoV of the camera. Also, for accurate fault diagnosis with an IR camera, the environmental factors such as wind, humidity, emissivity and other thermal sources should be taken into account [11]. Such complexities may not arise with IRSA as the environment is relatively constant, considering the deployment inside the machine. Moreover, using IRSA, the fault detection algorithm can be straightforward as the actual winding distribution is obtained from the end-winding region.

## VI. CONCLUSION

This paper demonstrated the application of an IR sensor array in developing a stator end winding temperature monitoring system. The proposed system was able to provide accurate temperature distribution of the end winding and in detecting local hot-spot, even under incipient faults. In comparison, the conventional point based method with the fewer number of sensors and the casing thermal imaging could not provide coil temperature distribution and could leave hot-spots undetected.

The findings of this paper can be further explored for the design of optimal sensor array for the end winding temperature monitoring. A general framework for the sensor array design can be developed by considering the sensor FoV, the number of sensors, winding arrangement and end-winding geometry.

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