

Experimental Analysis of Thermal Behavior in Induction Motors Experiencing Single-Phase Open-Circuit Faults

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KEYWORDS

ABSTRACT

Induction motors are critical components in hybrid renewable energy systems, including wind-PV-fuel cell microgrids, due to their reliability and operational flexibility. However, their performance is highly sensitive to electrical faults, particularly single-phase open-circuit (SPOC) faults, which can induce significant thermal stress and compromise system stability. This study presents a comprehensive experimental analysis of thermal behavior in induction motors subjected to SPOC faults across varying load conditions and fault durations. High-resolution thermal imaging and embedded temperature sensors were employed to capture spatial and temporal temperature gradients in both stator and rotor components. The findings reveal pronounced asymmetrical heating in faulted phases, with localized temperature rises reaching up to 90°C under sustained full-load conditions, exceeding insulation class limits. Healthy phases exhibited secondary heating due to flux redistribution and circulating currents, demonstrating the complex interplay between electrical asymmetry and thermal dynamics. Comparative analysis with theoretical models confirmed strong correlation between phase current imbalance and localized heat generation, validating the predictive accuracy of existing thermal-electric analogies. The results also highlight the impact of load level and operational regime on hotspot formation, emphasizing the need for load-aware fault mitigation strategies. Implications for hybrid energy systems are significant: SPOC-induced thermal excursions can propagate to coupled power converters and energy storage units, potentially triggering inverter derating, energy inefficiency, or accelerated component degradation. The study provides critical insights for design considerations, recommending real-time thermal monitoring, enhanced insulation, and integration of intelligent fault management algorithms within energy management frameworks. Overall, this research advances the understanding of induction motor thermal behavior under fault conditions, offering empirical evidence to guide resilient motor design and fault-tolerant energy system operation, while establishing a foundation for future predictive thermal modeling in large-scale industrial applications. Keywords: Induction motor, single-phase open-circuit fault, thermal analysis, fault-tolerant design, hybrid energy systems, thermal gradient, insulation degradation, energy management, microgrid, distributed generation., and large-sal.

INTRODUCTION

Induction motors are widely utilized in industrial and renewable energy applications due to their robustness, low maintenance requirements, and high reliability. Their deployment in hybrid renewable energy systems—such as wind-photovoltaic (PV)-fuel cell microgrids—has increased significantly in recent years, driven by the global push toward sustainable energy solutions (C. Wang and M. Hashem Nehrir, 2008; G.K. Bayrak and M. Cebeci, 2014). Despite their operational advantages, induction motors remain highly sensitive to electrical anomalies, particularly single-phase open-circuit (SPOC) faults, which can significantly alter motor performance and introduce thermal stress that jeopardizes system longevity. These faults are characterized by the interruption of current flow in one stator phase, resulting in current asymmetry, flux imbalance, and redistribution of electromagnetic forces, which collectively produce uneven heating within the stator and rotor (S. Tamalouzt, et al., 2016). Understanding the thermal dynamics associated with SPOC faults is crucial for ensuring safe and efficient operation in both standalone and grid-connected configurations.

The thermal behavior of induction motors under fault conditions is a multidimensional problem that encompasses electrical, magnetic, and thermal interactions. During SPOC events, the disconnected phase experiences localized heating due to circulating currents induced in the stator slots and rotor laminations. Concurrently, healthy phases may undergo secondary heating caused by flux coupling, leading to significant temperature gradients across the machine (H. Yang, et al., 2007; X. Liu, et al., 2011). Such asymmetrical thermal stresses can accelerate insulation degradation, reduce motor efficiency, and trigger cascading faults within integrated hybrid systems, particularly when coupled with power electronic interfaces and energy storage units (N.A. Ahmed, et al., 2011; R. Balamurugan and R. Nithya, 2015).

While prior studies have extensively analyzed electrical fault detection and power quality in hybrid energy systems (C. Wang and M. Hashem Nehrir, 2008; A. Etxeberria, et al., 2012), comprehensive empirical investigation of thermal phenomena during SPOC faults remains limited. Most available literature relies on simulation-based approaches or theoretical modeling (A. Maleki and A. Askarzadeh, 2014; N.H. Samrat, et al., 2014), which may underestimate the localized hotspot formation and fail to capture transient thermal dynamics under real operating conditions. Moreover, the interaction between motor faults and hybrid energy management, including maximum power point tracking (MPPT) of renewable sources and energy storage control, has not been sufficiently addressed. Considering the growing penetration of induction motors in hybrid microgrids, a detailed experimental evaluation of thermal behavior under SPOC conditions is essential for both motor design optimization and system-level reliability.

This research aims to address these gaps by conducting a systematic experimental analysis of induction motor thermal behavior under SPOC faults, with a focus on the influence of load, fault duration, and coupling with hybrid renewable systems. The objectives of this study are fourfold: (i) to characterize temperature distribution across stator and rotor components during transient and sustained SPOC faults; (ii) to quantify the relationship between phase current asymmetry and thermal stress; (iii) to evaluate the implications of thermal excursions on hybrid system performance, including MPPT operation and energy storage; and (iv) to provide design recommendations for fault-tolerant operation, including insulation enhancement, thermal monitoring, and load-aware control strategies (C. Wang and M. Hashem Nehrir, 2008; S. Obara, et al., 2013; D. Rekioua, et al., 2014).

The scope of this study encompasses low- to medium-power induction motors representative of

those deployed in hybrid microgrids, integrating both empirical observations and theoretical interpretations. The findings are expected to contribute to the development of resilient induction motors capable of sustaining operational continuity during fault events, while informing hybrid energy system design to mitigate cascading effects of motor faults. By bridging the gap between theoretical modeling and experimental validation, this study provides a critical foundation for predictive thermal management, fault diagnosis, and long-term reliability assessment in renewable energy-integrated electrical systems.

METHODOLOGY

3.1 Experimental Setup

A three-phase, 3 kW squirrel-cage induction motor was instrumented for SPOC fault experiments. Thermal data were acquired using a high-resolution infrared camera, complemented by embedded thermocouples on stator windings and rotor surfaces. Electrical parameters, including phase currents, voltages, and torque, were simultaneously recorded using precision power analyzers. Motor load was varied from 0% to 100% rated load to capture a comprehensive thermal profile.

The SPOC fault was induced by disconnecting one stator phase under controlled conditions. Fault durations ranged from 1 to 30 seconds to emulate transient and sustained operational scenarios.

3.2 Measurement and Data Acquisition

Thermal gradients were mapped across stator and rotor components at 1-second intervals. Data acquisition software synchronized thermal and electrical measurements to allow correlation analysis between current asymmetry and temperature rise. Specific attention was paid to identifying:

1. Peak hotspot temperatures
2. Thermal time constants for winding and rotor elements

3. Phase imbalance impact on localized heating

3.3 Analytical Framework

Theoretical analysis of motor thermal behavior under SPOC faults follows the classical thermal-electric analogy. Heat generation Q in stator windings is expressed as:

$$Q = I^2 R(T) \quad Q = I_a^2 R(T) + I_b^2 R(T) + I_c^2 R(T)$$

where I is the instantaneous phase current and $R(T)$ is the temperature-dependent winding resistance. Thermal diffusion within the stator and rotor is modeled using lumped capacitance and finite element approximations to capture transient thermal gradients.

Electrical asymmetry under SPOC faults is represented as:

$$I_a \neq I_b = I_c \quad I_a \neq I_b = I_c \quad I_a \neq I_b = I_c$$

where I_a denotes the disconnected phase current (approaching zero), and I_b, I_c represent the healthy phases. The resulting torque ripple and unbalanced magnetic fields contribute to localized rotor heating.

3.4 Fault Condition Scenarios

Two operational scenarios were tested:

1. Transient SPOC Faults: Fault duration < 5 s to simulate short-term interruptions typical in grid-connected microgrids (T. Vigneysh, et al., 2013; S. Tamalouzt, et al., 2016).
2. Sustained SPOC Faults: Fault duration > 10 s representing severe insulation or switching failures, with implications for energy storage and power quality in hybrid systems (N.H. Samrat, et al., 2014).

3.5 Data Analysis

Thermal responses were analyzed to identify:

- Maximum permissible temperature rise

- Critical hotspots corresponding to insulation limits
- Correlation between asymmetrical currents and localized heating patterns

Quantitative metrics were derived using MATLAB-based post-processing, allowing visualization of spatial temperature distribution and temporal evolution under varying loads.

3.6 Validation

Experimental results were validated against simulated thermal profiles from IEEE-standard induction motor models (C. Wang and M. Hashem Nehrir, 2008; H. Yang, et al., 2007). Agreement within $\pm 5\%$ confirmed measurement accuracy and analytical reliability.

RESULTS

The experimental analysis produced comprehensive thermal profiles for the induction motor under both transient and sustained single-phase open-circuit (SPOC) fault conditions. The key findings are summarized below.

4.1 Temperature Rise under Fault Conditions

Under transient SPOC faults (< 5 s), the maximum observed temperature rise in the disconnected phase reached $38\text{--}42^\circ\text{C}$ above ambient at 100% load. Healthy phases experienced only $15\text{--}20^\circ\text{C}$ rise, indicating pronounced asymmetry in heat generation. Sustained faults (> 10 s) caused the disconnected phase winding temperature to exceed 85°C , approaching insulation class limits, while rotor core temperatures increased by $12\text{--}15^\circ\text{C}$ relative to normal operation. This confirms that SPOC faults induce rapid localized heating, with severity increasing with fault duration and load.

4.2 Thermal Gradient Distribution

Infrared imaging revealed pronounced hotspots in the stator slots corresponding to the disconnected phase. The thermal gradient across the stator surface exceeded 40°C under sustained faults, highlighting

areas at risk of insulation degradation. Rotor temperature distribution remained relatively uniform but showed minor concentration in regions aligned with the stator's faulted phase, suggesting electromagnetic coupling as a secondary heat source (C. Wang and M. Hashem Nehrir, 2008; S. Tamalouzt, et al., 2016).

4.3 Electrical-Thermal Correlation

Analysis confirmed a strong correlation between phase current asymmetry and local temperature rise. For instance, under 75% load, the faulted phase current dropped by over 90%, while corresponding stator winding temperature increased by 1.5 times compared to normal operation. The results validate the theoretical model:

$$Q = I^2 R(T) \quad Q = I^2 R(T)$$

demonstrating that reduced current in a disconnected phase paradoxically leads to higher localized heating due to magnetic flux imbalance and circulating currents (H. Yang, et al., 2007; X. Liu, et al., 2011).

4.4 Impact of Load Levels

Load-dependent thermal escalation was observed: at 50% rated load, temperature rise in the faulted phase remained within $40\text{--}45^\circ\text{C}$, whereas full-load operation induced up to 90°C increase. This highlights the importance of load-aware fault monitoring in hybrid energy systems where induction motors interact with distributed energy resources (N.A. Ahmed, et al., 2011; R. Balamurugan and R. Nithya, 2015).

4.5 Comparative Analysis

Comparison between experimental results and simulation data from IEEE-standard induction motor models confirmed consistency within $\pm 5\%$, validating the methodology. The results demonstrate that conventional protection schemes may underestimate thermal stress under short-term SPOC faults, emphasizing the need for integrated thermal monitoring (C. Wang and M. Hashem Nehrir, 2008).

DISCUSSION

5.1 Theoretical Implications

The observed thermal behavior under SPOC faults aligns with the theoretical foundation of induction motor asymmetrical heating. Magnetic flux redistribution due to phase disconnection creates circulating currents in healthy phases, generating additional localized losses in stator slots and rotor laminations. This validates the classical thermal-electric analogy and confirms the dependency of hotspot formation on electrical imbalance (A. Etxeberria, et al., 2012; S. Tamalouzt, et al., 2016).

5.2 Practical Implications for Hybrid Systems

In hybrid energy systems, such as wind-PV-fuel cell microgrids, induction motors are often coupled with power converters and energy storage units (C. Wang and M. Hashem Nehrir, 2008; G.K. Bayrak and M. Cebeci, 2014). Thermal excursions under SPOC faults can propagate to these coupled systems, triggering energy management inefficiencies or inverter derating. Consequently, thermal monitoring should be integrated with MPPT and microgrid control strategies to preemptively reduce motor load during fault conditions (N.H. Samrat, et al., 2014).

5.3 Design Recommendations

Experimental findings suggest that motor insulation selection and thermal derating must account for fault-induced hotspots. Design considerations include:

1. Enhanced insulation class for stator windings.
2. Incorporation of real-time thermal sensors for hotspot detection.
3. Load redistribution algorithms in hybrid energy management systems to reduce thermal accumulation (R. Sarrias-Mena, et al., 2015; F. Tazerart, et al., 2015).

5.4 Trade-offs and Limitations

While thermal monitoring mitigates risk, it introduces additional system complexity and cost. The study is limited to laboratory-scale motors (1–5 kW); scaling to industrial ratings requires careful thermal modeling. Moreover, fault durations beyond 30 s were not tested due to safety constraints, leaving extreme-event behavior to be addressed in future studies (S. Obara, et al., 2013; D. Rekioua, et al., 2014).

5.5 Comparison with Literature

Our findings corroborate prior simulation-based studies by Liu et al. (2011) and Maleki & Askarzadeh (2014) regarding hotspot formation. However, unlike previous works, this study provides high-resolution empirical evidence of thermal gradients, demonstrating that real-world asymmetrical heating is more pronounced than predicted by purely theoretical models. The integration with hybrid energy systems adds a novel dimension, connecting motor fault behavior to system-level energy management.

CONCLUSION

This study presents a detailed experimental investigation of thermal behavior in induction motors under single-phase open-circuit faults, revealing the critical impact of asymmetrical currents on localized heating and insulation stress. Key conclusions include:

1. SPOC faults induce significant thermal gradients, with hotspots reaching up to 90°C under full-load sustained faults.
2. Thermal escalation is strongly correlated with load level and phase current asymmetry, validating theoretical models.
3. Integration with hybrid renewable energy systems magnifies the implications of motor faults on system stability and power quality.
4. Real-time thermal monitoring, insulation enhancement, and load-aware fault management are

essential for fault-tolerant motor operation in microgrids.

Future research should extend the methodology to high-power industrial motors, explore predictive fault detection using AI-based thermal modeling, and assess long-term insulation degradation under repeated SPOC events. This work contributes to the design of resilient induction motors and energy management strategies within hybrid renewable systems.

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