



Steady-State Thermal Modelling and Experimental Validation of a 1.5 kW Squirrel-Cage Induction Motor

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Abstract— *This study presents a steady-state thermal model of a 1.5 kW squirrel-cage induction motor and its partial experimental validation under rated-load operation. A coupled electromagnetic–thermal approach was implemented in ANSYS Motor-CAD, with electromagnetic losses applied as heat sources within a lumped parameter thermal network. The model was used to predict the steady-state temperature distribution of the motor components. The simulated results showed maximum temperatures of 80.54°C for the stator winding, 62.38°C for the stator back iron, 51.51°C for the rotor back iron, 51.67°C for the rotor bars, and 47.29°C for the housing. Experimental measurements of selected external components were compared with the corresponding simulated temperatures, giving percentage differences of 9.41%, 13.21%, and 8.35% for the housing, stator back iron, and rotor back iron, respectively. The mean absolute error was 5.63°C, with a root mean square error of 5.75°C for the three experimentally validated temperature points. The results indicate that the model provides reasonable prediction of the measured component temperatures, while the absence of direct measurements of internal winding and rotor-bar temperatures limits full experimental validation. The model therefore provides a computationally efficient framework for steady-state thermal assessment of induction motors.*

Keywords— *squirrel-cage induction motor, steady-state thermal modelling, ANSYS Motor-Cad, temperature prediction, experimental validation electromagnetic losses*

I. INTRODUCTION

Squirrel-cage induction motors (SCIMs) are widely used in industrial applications because of their robust construction, reliability, and low maintenance requirements. However, excessive temperature rise remains a major factor limiting their performance and service life by accelerating insulation ageing and restricting permissible loading [1]. Heat is generated

mainly by stator copper losses, rotor losses, and core losses, with the stator winding being the most thermally stressed component [2].

Accurate prediction of temperature distribution is therefore essential for improving motor reliability and cooling performance. Although finite element analysis (FEA) provides detailed thermal and electromagnetic information, its high computational cost limits its use for iterative design. Consequently, lumped parameter thermal network (LPTN) models have become widely accepted because they provide a good balance between computational efficiency and prediction accuracy [3], [6], [8].

Thermal modelling of induction motors has evolved from simplified analytical methods to integrated electromagnetic–thermal models. Okoro [1] demonstrated the capability of LPTN models for predicting steady-state and transient temperatures, while Ejiofor et al. [7] investigated thermal modelling of a 10-HP induction motor using the lumped parameter approach. More recent work has applied Motor-CAD and finite element techniques to the thermal analysis and experimental validation of 1.5 kW squirrel-cage induction

motors [15]. These developments demonstrate the continued use of coupled electromagnetic–thermal approaches for predicting component temperature distributions.

Recent studies have continued to investigate the thermal behavior of squirrel-cage induction motors using Motor-CAD and experimentally validated modelling approaches. Daffin et al. [15] investigated the thermal behavior of a 1.5 kW three-phase squirrel-cage induction motor using finite element analysis and experimental temperature measurements, while Daffin et al. [17] extended the thermal analysis by considering the influence of magnetic saturation. These studies demonstrate the continued development of experimentally assessed



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electromagnetic–thermal models for induction motor temperature prediction.

The effects of operating conditions on motor temperature have also been widely investigated. Studies have shown that varying load conditions, voltage unbalance, rotor design, and cooling arrangements significantly influence loss distribution and thermal behavior [13]–[20]. These findings highlight the importance of integrating electromagnetic loss calculations with thermal analysis to accurately predict motor temperatures under practical operating conditions.

Despite these advances, many existing models either oversimplify heat-transfer mechanisms or require substantial computational resources, while relatively few provide comprehensive experimental validation. Therefore, there is a need for a computationally efficient and experimentally validated thermal model capable of accurately predicting the temperature distribution of induction motors.

This study develops a steady-state lumped parameter thermal model of a 1.5 kW squirrel-cage induction motor using ANSYS Motor-CAD. Electromagnetic losses are coupled with a thermal network to predict component temperatures under rated operating conditions, and the model is validated experimentally to demonstrate its accuracy and suitability for thermal analysis, design verification, and performance evaluation of induction motors.

Although previous studies have demonstrated the application of lumped parameter thermal networks and Motor-CAD-based approaches to induction motor thermal analysis, fewer studies have focused on the coupled electromagnetic–thermal assessment and experimental evaluation of the specific 1.5 kW squirrel-cage induction motor considered in this study. The contribution of this work is therefore not the introduction of a new thermal modelling technique, but the development and application of a coupled Motor-CAD electromagnetic–thermal model for component-level steady-state temperature prediction, together with experimental comparison of selected externally measurable temperatures. The study further quantifies the prediction error and identifies the limitations associated with estimating internal component temperatures that cannot be directly measured during the experiment.

Mathematical modelling

The electromagnetic behaviour of the three-phase squirrel-cage induction motor was represented using the conventional dq-axis dynamic model in the synchronous reference frame. The model was employed in ANSYS Motor-CAD to compute electromagnetic quantities, including magnetic flux distribution, torque, and loss components required for thermal analysis. Similar Motor-CAD-based finite element modelling has been applied to the electromagnetic performance assessment of a 1.5 kW three-phase squirrel-cage induction motor, with experimental comparison of stator current and speed showing close agreement between simulation and measurement [16]. Since the dq formulation is well established

in the literature, the complete derivation is omitted for brevity.

The rotor dynamics are governed by

$$J \frac{d\omega_r}{dt} = T_e - T_L - T_B \quad (1)$$

where J is the rotor inertia, T_e is the electromagnetic torque, T_L is the load torque, and T_B represents friction and windage torque.

The heat conduction equation describes the thermal behavior of the machine

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \quad (2)$$

Where ρ is the material density (kg/m³), c is the specific heat capacity (J/kg·K), T is the temperature (°C or K), t is time(s), k is thermal conductivity (W/m·K), ∇ is the vector differential (gradient/divergence) operator, Q is the volumetric heat generation rate (W/m³)

The motor was modelled using a lumped parameter thermal network (LPTN), in which thermal resistances are given by

$$R_{th} = \frac{L}{kA} \quad (3)$$

Where R_{th} is the thermal resistance (K/W), L is the heat conduction path length (m), k is the thermal conductivity of the material (W/m·K), A is the cross-sectional area normal to heat flow (m²)

Total heat generation is given by:

$$Q = P_{cu} + P_{core} + P_{mech} \quad (4)$$

Where Q is total heat generated within the motor (W), P_{cu} is the stator copper loss (W), P_{core} is the core (iron) loss due to hysteresis and eddy currents (W), P_{mech} is the mechanical loss due to friction and windage

with stator copper losses calculated as

$$P_{cu} = 3I^2 R_0 [1 + \alpha(T - T_0)] \quad (5)$$

Where P_{cu} is three-phase stator copper loss (W), I is phase current (A), R_0 is the stator winding resistance at the reference temperature T_0 (Ω), α is the temperature coefficient of resistance for copper (°C⁻¹), T is the operating winding temperature (°C), T_0 is the reference temperature (°C)

Equations (1)–(5) constitute the coupled electromagnetic–thermal model implemented in ANSYS Motor-CAD to predict the steady-state temperature distribution of the induction motor.

The motor parameters used for this work are:

Table 1: Rated Parameters of the Studied Motor

S/No	Parameters	Value
1	Rated power	1.5 kW
2	Rated voltage	380 V
3	Rated current	3.83 A
4	Rated speed	1390 rpm
5	Frequency	50 Hz
6	Pole number	4
7	slots	24
8	Rotor bars	34
9	Airgap	1mm
10	Shaft diameter	28mm

The parameters in Table 1 were used as input data for developing the electromagnetic finite element model in Motor-CAD, which is used to compute the magnetic field distribution, electromagnetic torque, and associated losses of the machine.

Results and discussion

Electromagnetic Loss Distribution

Table 2 presents the electromagnetic loss components obtained from the Motor-CAD analysis under rated-load operation. The stator copper loss was 459.3 W, while the total FEA loss reported by Motor-CAD was 605.7 W. Therefore, the stator copper loss accounted for approximately 75.83% of the reported total FEA loss, indicating that it was the dominant loss component in the studied motor. The rotor cage loss was 123.1 W, while the stator and rotor iron losses were 19.03 W and 0.8527 W, respectively. The dominance of stator copper loss provides quantitative support for the higher temperature predicted in the stator winding.

Table 2: Electromagnetic loss distribution

S/No	Parameter	Value
1	Stator copper loss	459.30 W
2	Rotor cage loss	123.10 W
3	Stator iron loss	19.03 W
4	Rotor iron loss	0.8527 W
5	Total FEA loss	605.70 W
6	Stator copper loss contribution	75.83%

Thermal Transient and Steady-State Stabilization

Figure 1 presents the transient temperature response of the major motor components from startup to thermal stabilization under rated-load operation. The component temperatures increase rapidly during the initial heating period due to the generated electromagnetic and mechanical losses and gradually approach stable values as heat dissipation balances heat generation. The stator winding records the highest temperature and approaches approximately 80.54°C, while the housing reaches approximately 47.29°C. The temperature curves become nearly constant after approximately 40 minutes, indicating that thermal stabilization has been reached. The stabilized temperatures obtained from the transient analysis are consistent with the steady-state values reported in Table 2.

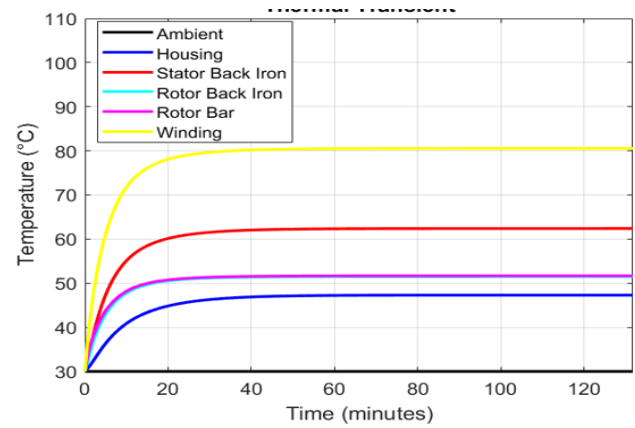


Figure 1: Thermal Transient and Steady-State stabilization

Steady-State Thermal Performance

The thermal results obtained from the coupled electromagnetic-thermal analysis are presented in Figures 2 and 3 and Table 3. The temperature distribution reflects the calculated loss distribution discussed in the preceding section. Since the stator copper loss represents approximately 75.83% of the reported total FEA loss, significant heat generation occurs in the stator winding, which consequently records the highest predicted temperature of 80.54°C. The stator winding records the highest temperature (80.54°C), confirming that copper losses dominate the thermal behaviour of the machine, whereas the housing remains the coolest component (47.29°C) due to effective heat dissipation. The stator back iron reaches 62.38°C, while the rotor back iron and rotor bars attain 51.51°C and 51.67°C, respectively. These results indicate that all components operate within acceptable thermal limits, demonstrating the effectiveness of the motor cooling system under rated operating conditions.

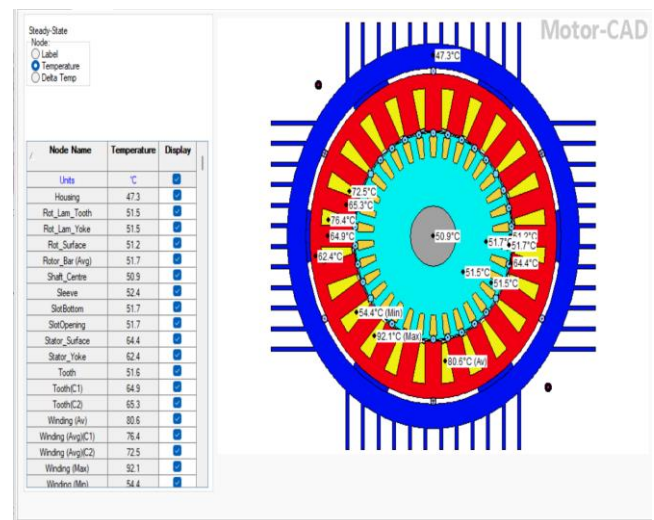


Fig. 2: Radial temperature distribution of motor components in steady-state

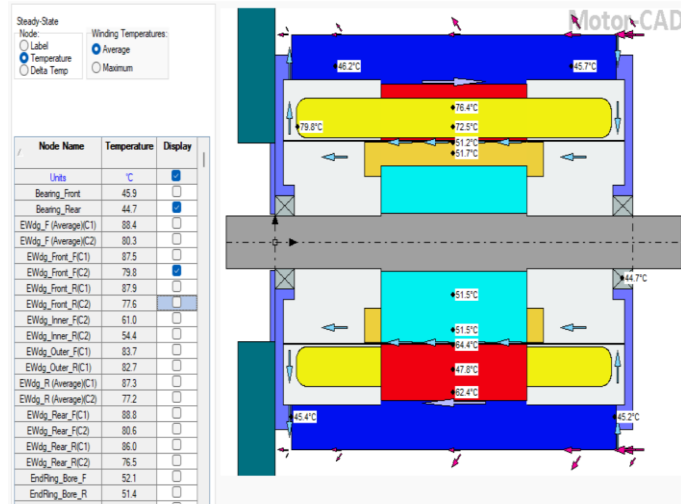


Fig. 3: Axial temperature distribution of motor components in steady-state

Table 3: steady-state temperature at rated load

S/No	Temperatures	Values
1	Ambient	30.00 °C
2	Housing	47.29 °C
3	Stator back iron	62.38 °C
4	Rotor back iron	51.51 °C
5	Rotor bar average	51.67 °C
6	Winding	80.54 °C

Experimentation

Experimental validation was performed on a 1.5 kW squirrel-cage induction motor operating under rated load. Voltage, current, output power, speed and temperatures were measured using a three-phase variac, digital multimeter, three-phase wattmeter, tachometer and infrared thermometer. Measurements were recorded after steady-state thermal conditions were achieved at an ambient temperature of approximately 30°C

Measurements were taken from no-load to rated load to establish thermal stabilization. Only the rated-load results are presented for validation.

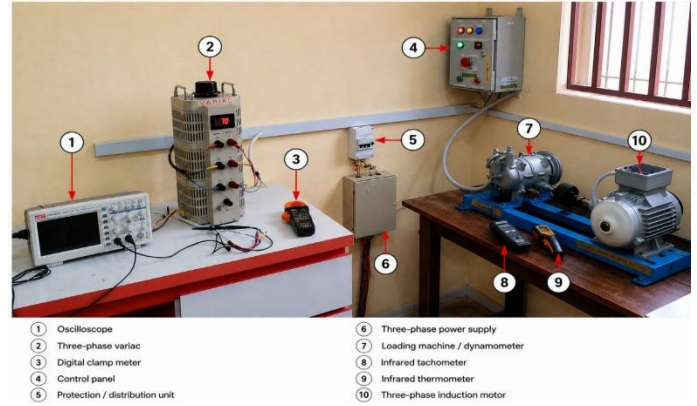


Plate1: Experimental setup

Comparison of simulation and experimental work

Table 3 presents a healthy comparison between the experimental and simulation result. The results demonstrate good agreement between experimental and simulated temperatures at rated load, with percentage differences of 9.41% (housing), 13.21% (stator back iron), and 8.35% (rotor back iron). The highest deviation occurs in the stator back iron, indicating limitations in core loss or heat distribution modeling.

The simulation slightly underestimates housing and rotor temperatures while overestimating the stator back iron. These differences are likely due to simplifications in cooling conditions and rotor heat transfer.

Experimental data for rotor bar and winding temperatures were unavailable, limiting validation for these components. The model accurately predicts the thermal behavior with acceptable accuracy, though improvements are needed in core and rotor thermal prediction.

Table4: Comparison of experimental and simulated temperatures.

S/ N	Temperatures	Experimental	Simulated	Absolute Error(°C)	Percentage Error (%)
1	Housing	52.2 °C	47.29°C	4.91	9.41%
2	Stator back iron	55.1 °C	62.38°C	7.28	13.2%
3	Rotor back iron	56.2 °C	51.51°C	4.69	8.35%
4	MAE	-		5.63	
5	RMSE	-		5.75	
6	MAPE				10.32



MAE – Mean Absolute Error

RMSE – Root mean square error

MAPE – Mean Absolute Percentage Error

Table 5: Comparison with previous study

Study	Motor	Method	Experimental validation	Maximum error
Okoro [1]	7.5KW	LPTN	No	NR
Ejiofor et al.[7]	10hp	LPTN	No	NR
Present study	1.5 kW	Motor-CAD/LPTN	partial	13.2%

Table 5 compares the present study with previous thermal modelling studies. Okoro [1] investigated a 7.5-kW squirrel-cage induction motor using a lumped parameter thermal network, while Ejiofor et al. [7] considered a 10-kW induction motor using an LPTN approach. In comparison, the present study considers a 1.5-kW squirrel-cage induction motor using a coupled Motor-CAD/LPTN approach. Experimental comparison of selected externally accessible temperatures resulted in a maximum error of 13.21%. The comparison demonstrates the application of the proposed modelling framework to the smaller 1.5-kW machine while providing experimental assessment of the predicted thermal behaviour.

Conclusion

The developed coupled electromagnetic–thermal model provides reasonable prediction of the steady-state temperatures of the experimentally accessible motor components. Experimental comparison showed percentage differences of 9.41%, 13.21%, and 8.35% for the housing, stator back iron, and rotor back iron, respectively. However, direct experimental measurements of the stator winding and rotor-bar temperatures were unavailable; hence, validation of the predicted internal component temperatures remains limited. Further work should incorporate suitable methods for measuring or indirectly estimating internal winding and rotor temperatures.

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