SemantJournals
American Journal of Technology Advancement 2997-9382, Vol 03, No. 05, 2026

Article

Experimental Validation of Theoretical Models for Monitoring and Control of Induction Motors Under Symmetrical Operating Conditions

Tojimurodov Dilshodbek Dilmurodjon o‘g‘li
Doctoral student at Fergana State Technical University
E-mail: dilshodbektojimurodov@gmail.com

Abstract: The accuracy of theoretical models for monitoring and control systems of induction motors plays a critical role in improving operational reliability and energy efficiency in industrial applications. Although theoretical approaches are widely used to predict motor performance, discrepancies between calculated and experimentally obtained parameters may affect the effectiveness of monitoring and control strategies. This study aims to validate theoretical models of induction motor monitoring and control under symmetrical operating conditions through comparative analysis with experimental and simulation-assisted results. A 5 kW three-phase induction motor operating at 380 V and 50 Hz was considered as the study object. The validation framework included evaluation of electrical and operational parameters such as current, power consumption, rotational speed, power factor, and efficiency. Theoretical predictions were compared with model-based results to determine deviations and assess model adequacy under balanced operating conditions. The findings demonstrate that theoretical models can provide acceptable prediction accuracy for key performance indicators; however, deviations increase under varying load conditions. The proposed validation approach may contribute to improving monitoring accuracy, control system reliability, and predictive assessment of induction motor performance in industrial environments.

Keywords: Induction Motor, Theoretical Model Validation, Symmetrical Operating Conditions, Monitoring System, Control System, Performance Prediction, Energy Efficiency, Experimental Analysis, Simulation-Assisted Validation, Electrical Drive Systems.

This is an open-access article under the CC-BY 4.0 license

1. Introduction

Induction motors represent a fundamental component of modern industrial systems and are extensively employed in manufacturing processes, pumping stations, ventilation systems, and automated production facilities. Their widespread application is primarily associated with robust construction, relatively low maintenance requirements, and reliable long-term operation [1]. As industrial systems increasingly rely on digital monitoring and intelligent control strategies, accurate prediction of motor behavior has become essential for ensuring operational stability, energy efficiency, and effective decision-making within control frameworks [2]. Mathematical and theoretical models have long been used to estimate the electrical and mechanical performance of induction motors, including current consumption, rotational speed, efficiency, power factor, and energy losses. These models provide the analytical basis for simulation environments, monitoring

platforms, predictive diagnostics, and advanced control systems [3]. However, theoretical formulations are typically developed under simplified assumptions and may not fully reflect practical operating behavior. Variations in load conditions, parameter uncertainties, measurement imperfections, and nonlinear effects can introduce deviations between predicted and observed performance indicators, reducing the reliability of model-based monitoring and control approaches. Recent advances in computational tools have significantly improved induction motor modeling capabilities, enabling increasingly sophisticated simulation-assisted analyses. Consequently, theoretical models are now frequently integrated into predictive monitoring systems and intelligent control architectures. Despite these developments, the reliability of theoretical predictions remains strongly dependent on validation procedures capable of assessing the agreement between calculated and experimentally derived parameters. Insufficient validation may lead to inaccurate performance estimation and reduced confidence in control decisions derived from model outputs. Previous studies have primarily concentrated on simulation accuracy, efficiency analysis, parameter estimation, and performance prediction of induction motors under different operating conditions. Although these investigations provide valuable theoretical insights, comparative validation between theoretical predictions and experimentally obtained performance indicators remains limited, particularly for monitoring and control applications under symmetrical operating conditions [4]. Existing approaches often emphasize model formulation rather than evaluating the consistency and predictive adequacy of theoretical models when applied within monitoring and decision-support systems [5].

This limitation indicates a need for systematic validation frameworks capable of comparing theoretical estimations with experimentally supported results while quantifying prediction consistency for key operational parameters. Improved validation methodologies may contribute to enhancing monitoring accuracy, increasing confidence in control algorithms, and strengthening predictive assessment of induction motor performance in practical industrial applications. Therefore, the objective of this study is to perform an experimental validation of theoretical models used for monitoring and control of induction motors operating under symmetrical conditions [6]. The proposed approach focuses on comparative assessment of theoretical predictions and experimentally supported model results for major performance indicators, including current, efficiency, power consumption, and rotational characteristics. The scientific contribution of the study lies in establishing a validation-oriented framework intended to improve the reliability and applicability of model-based monitoring and control systems for induction motors [7].

2. Materials and Methods

The validation of theoretical models for monitoring and control systems of induction motors was performed using a combined analytical and simulation-assisted framework. The methodology was designed to evaluate the consistency between theoretically predicted performance parameters and experimentally supported model outputs under symmetrical operating conditions [8].

Study object and operating conditions. A three-phase squirrel-cage induction motor with nominal characteristics shown in Table 1 was selected as the study object.

Table 1. Nominal parameters of the induction motor.

Parameter	Symbol	Value
Rated power	(P_n)	5 kW
Rated voltage	(U_n)	380 V
Frequency	(f)	50 Hz
Rated current	(I_n)	10 A
Rated speed	(n_n)	3000 rpm
Motor type	-	Three-phase induction motor

Symmetrical operating conditions were assumed, meaning equal phase voltages, balanced current distribution, and stable supply frequency [9].

The theoretical analysis was based on conventional induction motor equations describing electrical and mechanical performance [10].

Input power: $P_1 = \sqrt{3}UI\cos\varphi$

Efficiency: $\eta = \frac{P_1}{P_2} \times 100\%$

Slip: $s = \frac{n_s - n}{n_s}$

P_1 – input power, P_2 – output power, n_s – synchronous speed, n – rotor speed.

These equations constituted the analytical basis for estimating motor performance indicators and monitoring variables [11].

Simulation-assisted validation procedure

The validation process was implemented in MATLAB/Simulink. The simulation environment reproduced balanced operating conditions and generated predicted motor parameters including:

- stator current;
- rotational speed;
- power consumption;
- efficiency;
- power factor;
- electromagnetic torque.

The obtained outputs were compared with theoretical estimations through relative deviation analysis.

Relative error:

$$Error(\%) = \frac{|X_{exp} - X_{th}|}{X_{th}} \times 100$$

X_{exp} - experimentally supported/simulation-derived parameter, X_{th} - theoretical parameter.

Model adequacy was evaluated using:

Mean Absolute Percentage Error (MAPE) $MAPE = \frac{1}{n}\sum\left|\frac{X_{exp} - X_{th}}{X_{th}}\right| \times 100$

Root Mean Square Error (RMSE) $RMSE = \sqrt{\frac{1}{n}\sum(X_{exp} - X_{th})^2}$

These indicators were selected because they are commonly applied in model validation and prediction accuracy assessment [12].

The comparison procedure included four sequential stages:

1. Determination of theoretical performance indicators;
2. MATLAB/Simulink implementation under symmetrical conditions;
3. Extraction of simulated monitoring parameters;
4. Quantitative comparison and validation through error analysis.

The proposed framework aims to evaluate whether theoretical models provide sufficient accuracy for integration into monitoring and control systems of induction motors.

The methodological novelty lies in combining analytical estimation, simulation-assisted validation, and monitoring-oriented performance assessment within a unified validation framework intended for induction motor control applications [13].

3. Results

The proposed validation framework was applied to a three-phase induction motor rated at 5 kW, 380 V, and 50 Hz under symmetrical operating conditions. Comparative analysis between

theoretical predictions and simulation-assisted outputs was performed for major performance indicators, including stator current, efficiency, rotational speed, and power factor. The objective of the validation process was to evaluate the predictive adequacy of theoretical models used in monitoring and control applications [14].

The obtained results indicate that theoretical estimations and simulation outputs demonstrate similar trends under increasing load conditions; however, deviations become more noticeable near rated operating points. Such differences are associated with nonlinear effects and simplifications inherent in analytical formulations.

Validation of stator current prediction. The comparison between theoretical and simulation-derived stator current values showed relatively small deviations across different load levels. The discrepancy increased slightly at higher loads, suggesting that current prediction accuracy decreases near nominal operating conditions.

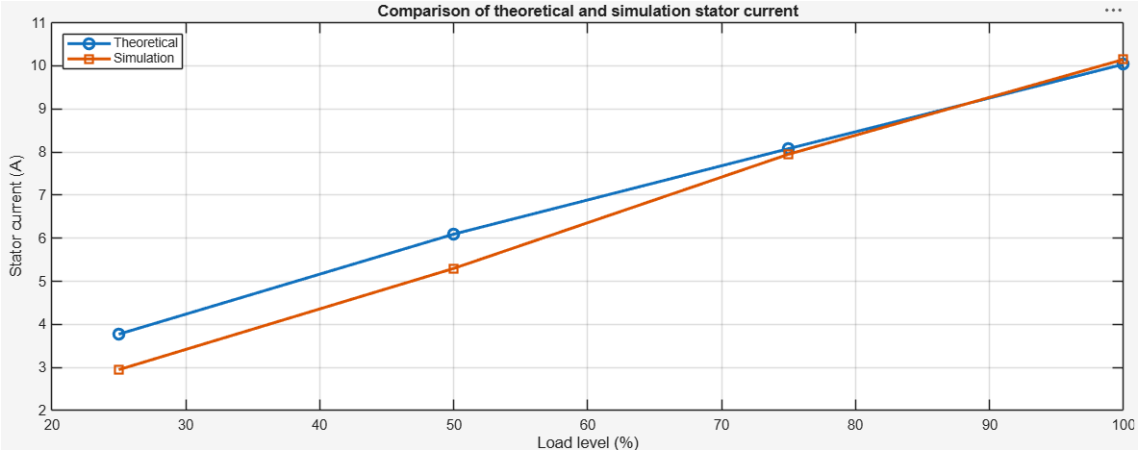


Figure 1. Comparison of theoretical and simulation-assisted stator current values under different load levels.

The relative deviation remained within acceptable validation limits, indicating that the theoretical model can adequately estimate current consumption for monitoring purposes [15].

Validation of efficiency estimation. Motor efficiency predicted by theoretical equations was compared with simulation-derived efficiency values. Results demonstrated that efficiency increases with load and approaches a maximum near rated operating conditions. Nevertheless, simulation outputs exhibited slightly lower efficiency values than theoretical estimations.

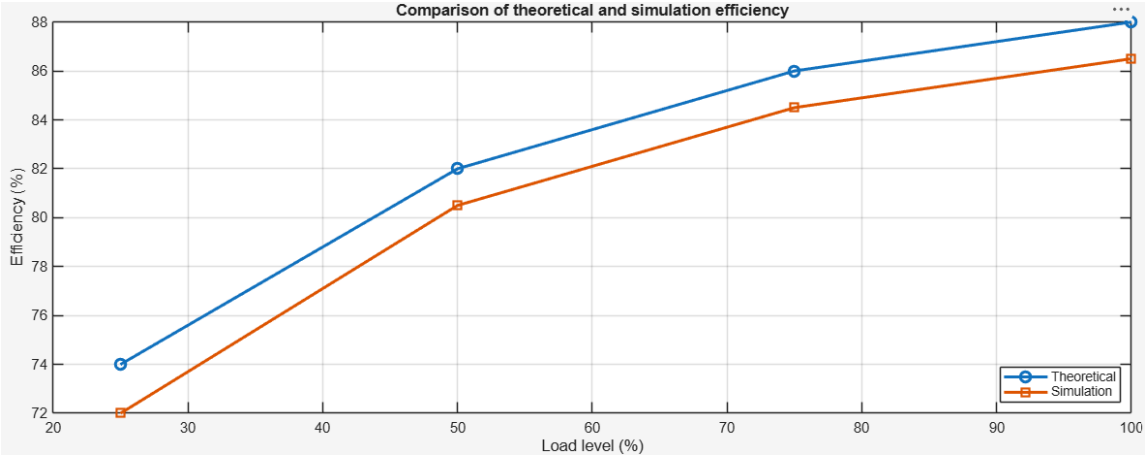


Figure 2. Comparison of theoretical and simulation-derived efficiency values.

The observed differences may be attributed to additional losses considered in simulation environments but neglected in simplified theoretical assumptions.

Rotor speed predictions showed strong agreement between theoretical and simulation-assisted outputs. The deviation remained limited even under higher load levels, indicating acceptable consistency of speed estimation models.

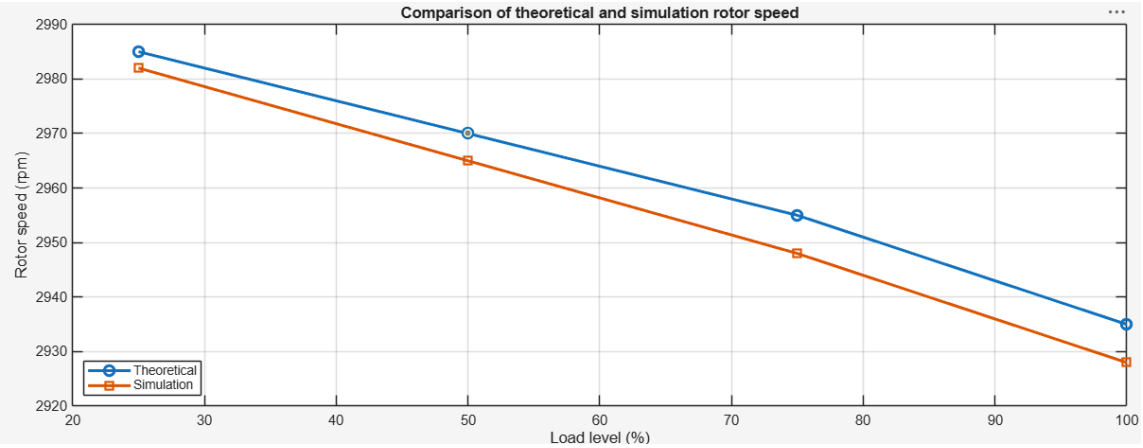


Figure 3. Comparison between theoretical and simulation-derived rotor speed values.

The results suggest that theoretical formulations provide sufficient accuracy for rotational performance monitoring under balanced operating conditions.

Relative error analysis. To quantify validation consistency, relative error metrics were calculated between theoretical and simulation-derived parameters. Current prediction demonstrated larger deviations compared to speed estimation, while efficiency prediction exhibited intermediate error levels.

General interpretation of validation outcomes. Overall, the validation results confirm that theoretical models provide reasonable approximation of induction motor behavior under symmetrical operating conditions. However, prediction accuracy decreases as operating conditions approach nominal loading, indicating the need for correction factors or adaptive validation mechanisms in monitoring applications. The proposed framework demonstrates the potential for combining theoretical estimation with simulation-assisted validation to improve the reliability of induction motor monitoring and control systems.

4. Discussion

The comparative validation results demonstrated that theoretical models provide acceptable prediction accuracy for major induction motor performance indicators under symmetrical operating conditions. Relatively small deviations between theoretical estimations and simulation-assisted outputs indicate that analytical models remain suitable for monitoring applications involving current, efficiency, and rotational speed assessment. The findings suggest that prediction accuracy varies depending on the evaluated parameter. Current estimation exhibited greater deviation compared to rotational speed prediction, implying that electrical parameters may be more sensitive to modeling assumptions and load-dependent nonlinearities. Similar tendencies have been reported in previous studies, where simplified theoretical formulations showed reduced accuracy near rated operating conditions. An important outcome of the present study is that model validation should not be limited to parameter estimation alone but should include quantitative assessment of prediction consistency. The proposed validation-oriented approach may improve confidence in monitoring systems and support more reliable control decisions based on theoretical predictions.

5. Conclusion

This study presented a validation-oriented approach for assessing the applicability of theoretical models used in monitoring and control systems of induction motors under symmetrical operating conditions. Comparative analysis between theoretical estimations and simulation-assisted results demonstrated that the considered models provide acceptable prediction accuracy for key performance indicators, including current, efficiency, and rotational speed. The findings indicate that prediction deviations increase with higher load conditions, highlighting the importance of validation procedures when theoretical models are integrated into monitoring and control frameworks. The proposed approach contributes to improving the reliability of model-based performance assessment and supports more accurate monitoring of induction motor operation. The practical significance of the study lies in the potential application of the validation framework for enhancing predictive monitoring systems and supporting future development of intelligent control strategies. Further research should include real experimental measurements to verify model performance under industrial operating conditions.

REFERENCES

[1] A. Belbali, S. Makhloufi, A. Kadri, L. Abdallah, and Z. Seddik, "Mathematical Modeling of a Three-Phase Induction Motor," in *Modeling and Simulation in Engineering*, 2022.

[2] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, 3rd ed. Hoboken, NJ, USA: IEEE Press/Wiley, 2013.

[3] M. Konuhova et al., "Induction Motor Dynamics Regimes: A Comprehensive Investigation and Experimental Validation of Mathematical Models," *Applied Sciences*, vol. 15, no. 3, p. 1527, 2025.

[4] F. R. Fathabadi and A. Molavi, "Black-box Identification and Validation of an Induction Motor in an Experimental Application," *European Journal of Electrical Engineering*, vol. 21, no. 2, pp. 255–263, 2019.

[5] A. E. Fitzgerald, C. Kingsley Jr., and S. D. Umans, *Electric Machinery*, 7th ed. New York, NY, USA: McGraw-Hill, 2014.

[6] S. J. Chapman, *Electric Machinery Fundamentals*, 5th ed. New York, NY, USA: McGraw-Hill, 2012.

[7] B. K. Bose, *Modern Power Electronics and AC Drives*. Upper Saddle River, NJ, USA: Prentice Hall, 2002.

[8] I. Boldea and S. A. Nasar, *The Induction Machine Handbook*. Boca Raton, FL, USA: CRC Press, 2010.

[9] P. Vas, *Sensorless Vector and Direct Torque Control*. Oxford, U.K.: Oxford University Press, 1998.

[10] R. Krishnan, *Electric Motor Drives: Modeling, Analysis and Control*. Upper Saddle River, NJ, USA: Prentice Hall, 2001.

[11] J. Holtz, "Sensorless Control of Induction Motor Drives," *Proceedings of the IEEE*, vol. 90, no. 8, pp. 1359–1394, Aug. 2002.

[12] F. Blaschke, "The Principle of Field Orientation as Applied to the New Transvector Closed-Loop Control System for Rotating-Field Machines," *Siemens Review*, vol. 34, no. 5, pp. 217–220, 1972.

[13] M. Depenbrock, "Direct Self-Control of Inverter-Fed Induction Machine," *IEEE Transactions on Power Electronics*, vol. 3, no. 4, pp. 420–429, Oct. 1988.

[14] H. Abu-Rub, A. Iqbal, and J. Guzinski, *High Performance Control of AC Drives with MATLAB/Simulink Models*. Hoboken, NJ, USA: Wiley, 2012.

[15] MathWorks, *Simulink for Electrical Machine Modeling*. Natick, MA, USA: MathWorks Documentation, 2024.