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Experimental Electrical Parameter Identification and Model Validation of an Induction Motor for Digital Twin Applications

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Abstract

Digital Twins of electric drives require parameter values that are both physically consistent and predictive across operating regimes. This work proposes a methodology for parameter estimation and model validation of an induction motor (IM) as part of an electric drive digital twin framework, validated experimentally. Synchronized measurements of the IM terminal voltage and stator currents are used to estimate the fundamental component at the operating frequency using a least-squares sinusoidal fit. This produces complex phasors and reconstructed waveforms, reducing the influence of Pulse Width Modulation (PWM) harmonics and noise. In addition, electrical parameters are estimated from direct-current (DC), locked-rotor, and no-load tests using the steady-state equivalent circuit. A time-domain synchronous direct-quadrature (dq) model in MATLAB/Simulink is validated on separate time intervals, so that any difference between simulation and measurements is attributed to model mismatch, not to the fact that parameter values vary with the operating point. Validation demonstrates very good agreement: (i) locked-rotor current residuals are extremely small, with normalized root mean square error (NRMSE) of approximately 0.05% and $R^2 = 1$; and (ii) no-load current tracking remains high across 40–50 Hz, with **NRMSE ≈ 3.93 – 4.19%** and **$R^2 \approx 0.998$** . The resulting calibrated model provides a baseline for subsequent online adaptation and condition monitoring applications.

Keywords: Digital Twin, Induction Motor, Electric Drive, Parameter Estimation, Model Validation

1 Introduction

Digital Twin (DT) technology, a key component within Internet of Things (IoT) ecosystem, has emerged as a major paradigm for creating virtual replicas of physical assets. These replicas enable high-fidelity simulation, performance evaluation, machine-learning integration, and multiphysics modeling [1–3]. Recent works report DT rapid reconfiguration of automated systems, standards-based DT frameworks for robotic drilling, and real-time CNC monitoring platforms supporting predictive maintenance at scale. DTs have also been validated for induction motor monitoring and diagnostics, including multiphysics temperature estimation with low error [4] and IIoT-based predictive maintenance integrating low-cost sensing with high-fidelity Finite Element Method (FEM) models [5]. A variety of optimization and observer methods have been proposed to improve parameter estimation and diagnostics in induction motor (IM) drives. These include nonlinear optimization using manufacturer data with saturation effects and motor validation [6], Particle Swarm Optimization (PSO) based multi-objective offline identification of equivalent-circuit parameters across operating ranges [7], and online estimation via conventional versus adaptive Extended Kalman Filter (EKF), where adaptive schemes improve robustness by updating noise statistics in real time [8]. Other contributions combine optimization with learning models for parameter estimation under varying conditions [9], use transient data to estimate electrical parameters, losses, load torque, and inertia for accurate prediction and monitoring applications [10], and propose offline identification from a single start-up and coast-down experiment for IMs [11].

This paper presents an offline experimental methodology for electrical parameter estimation and model validation of an induction motor drive within a DT framework. Synchronized voltage and current measurements are processed using a least-squares sinusoidal fit to extract the fundamental component at the commanded frequency. The resulting phasors are used to estimate equivalent-circuit parameters from direct-current, locked-rotor, and no-load tests. The identified parameters are then implemented in a synchronous direct-quadrature (dq) model in MATLAB/Simulink and validated on time intervals different from those used for estimation. This separation allows the validation error to be attributed mainly to model mismatch rather than to parameter tuning at the same operating point.

The main contributions of this work are as follows:

- an experimental workflow for extracting fundamental voltage and current components from measurements recorded on a variable speed induction motor drive;
- estimation of electrical parameters using direct-current, locked-rotor, and no-load tests;
- integration of the identified parameters into a time-domain induction motor model for DT applications;
- validation of the calibrated model under locked-rotor and no-load operating regimes using residual-based performance indicators.

The remainder of this paper is organized as follows. Section 2 describes the experimental setup and the methods employed for measurement, data acquisition, signal processing, parameter estimation, and validation. In addition, Section 3 presents the

electrical parameter estimation results and further discusses the validation performance across operating regimes. Section 4 concludes the paper and outlines future directions.

2 Materials and Methods

2.1 Implementation of the system

The experimental electric drive bench is shown schematically in Fig. 1. Mitsubishi FR-

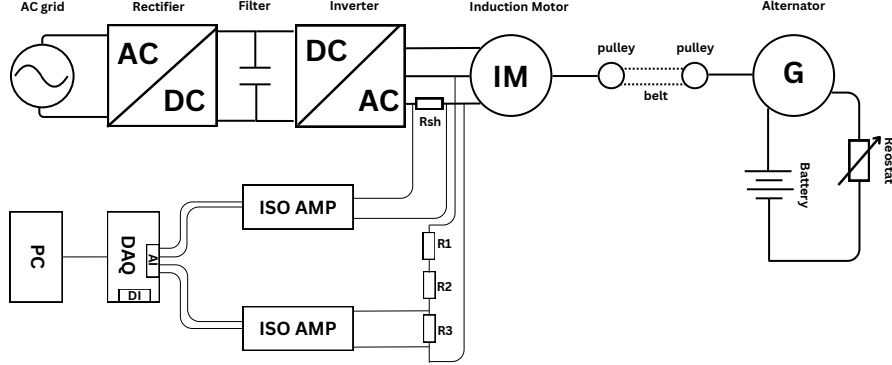


Fig. 1 Schematic of the experimental electric drive test bench and measurement setup

D720S-014SC-EC variable frequency drive (VFD) is supplied from a single-phase AC grid. It generates three phase output and supplies 130 W squirrel-cage IM connected in delta. The motor shaft is mechanically coupled to an alternator via a belt-pulley transmission. The generator output is connected to a battery and rheostat, forming an electrical load for adjustment of the loading conditions during experiments. The selected power and load components are well matched for laboratory identification experiments. The converter rating exceeds the IM nominal rating, while the alternator-battery subsystem provides a load that can be operated at partial capacity within the motor and drive current limit [5, 12–14]. The main technical specifications of the IM electric drive can be found in the Supplementary Material.

2.2 Measurements

This subsystem measures the electrical quantities required for estimation and validation of the IM model. The line current is measured using a shunt resistor placed in series with one phase output of the VFD and motor. Shunt resistors retain waveform fidelity, while avoiding the phase and frequency errors that may occur with current transformers or Hall sensors. This resistor provides a voltage proportional to the line current. The line to line voltage of the motor is measured via a resistive divider (R_1 , R_2 and R_3) that scales the inverter output to a low level signal suitable for instrumentation. Voltage and current signals passed through reinforced isolated amplifier AMC1300 to ensure electrical division between the power and measurement circuit. This isolation

ensures safe operation and limits ground loop current that can reduce measurement accuracy [5, 12–14]. The main technical specifications of the measurement components can be found in the Supplementary Material.

2.3 Data Acquisition

Voltage and current are obtained using an NI USB-6009 DAQ. Two analog input differential channels are used to record the voltage and current outputs from the AMC1300 as shown in Fig. 1. The main technical specifications of NI USB 6009 can be found in the Supplementary Material. The differential analog inputs improves the common mode noise rejection, making the device more insensitive to ground-referenced interference. The DAQ is connected to a PC where MATLAB is installed. A MATLAB script is used to stream and store the acquired channels as synchronized time series data. In the present implementation, a sampling rate of 20 kS/s is selected for each analog channel (voltage and current), which remains within the device sampling capability. The MATLAB code also applies scaling coefficients to convert the recorded voltages into physical units. The acquired signals are further employed for signal processing, parameter estimation, and validation of the developed model [10, 12, 14].

2.4 Signal Processing

In this phase fundamental phasor extraction via least-squares fitting (Supplementary Material) are applied to the voltage and current for electrical parameter estimation under steady-state operation [10, 11].

Fig. 2 shows an example of fundamental phasor extraction at steady state operation for the voltage and current signals at 30 Hz, which is used as the input for electrical parameter estimation described in Section 2.5 [7, 10, 11].

2.5 Electrical Parameter Estimation

Signals obtained from the signal processing step are employed as inputs for estimating electrical parameters [7, 10, 11].

The induction motor was connected in Δ for all three standard laboratory tests. For the AC tests, all quantities were evaluated at the commanded fundamental frequency f_0 with $\omega_0 = 2\pi f_0$, using a steady-state window $[t_s, t_e]$.

For a balanced Δ connection, the phase voltage equals the line-to-line voltage,

$$V_{ph,1} = V_{LL,1}, \quad (1)$$

while the line current and phase current satisfy

$$I_{L,1} = \sqrt{3} I_{ph,1} \angle(-30^\circ) \Rightarrow I_{ph,1} = \frac{I_{L,1}}{\sqrt{3}} \angle(+30^\circ). \quad (2)$$

DC test: stator resistance R_s

A low DC voltage (5 V) was applied directly at the motor terminals immediately after the motor completes a loaded operating regime, in order to keep the estimated R_s as

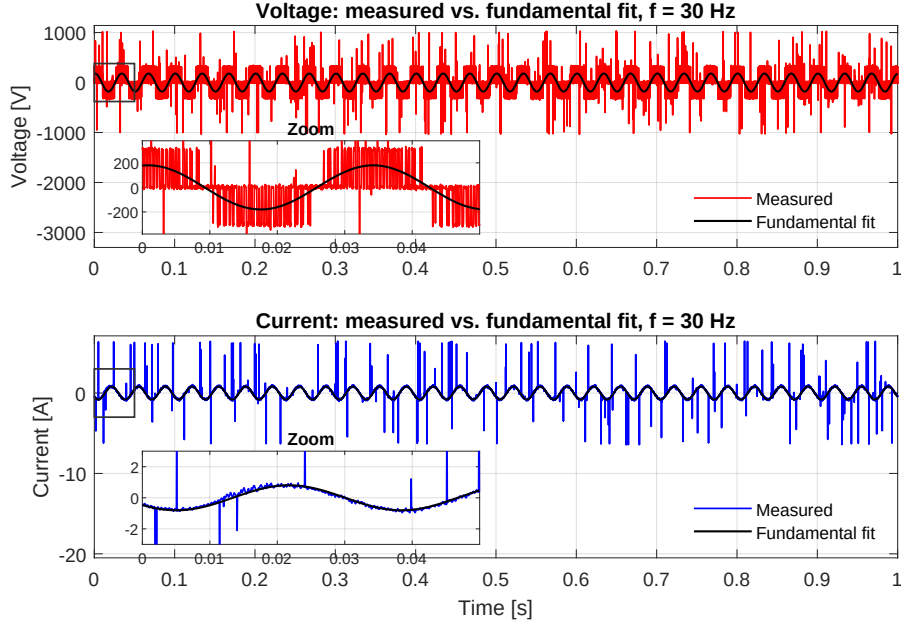


Fig. 2 Measured voltage and current signals and their corresponding fundamental sinusoidal fits

close as possible to its effective value under PWM operation. The resulting current was recorded once it reaches a constant value. This condition guarantees that the initial inductive transient has fully decayed ($di/dt \approx 0$), allowing the measured ratio V_{dc}/I_{dc} to accurately represent the winding resistance R_s [6, 11]. For a Δ connected,

the winding resistance for each phase R_s used in the equivalent circuit is derived as follows:

$$\begin{aligned} R_{eq,dc} &= R_s \parallel 2R_s = \frac{R_s(2R_s)}{R_s + 2R_s} \\ &= \frac{2}{3}R_s \quad \Rightarrow \quad R_s = \frac{3}{2}R_{eq,dc}. \end{aligned} \quad (3)$$

Locked rotor: R'_r and L_σ .

In the locked rotor test, the rotor is mechanically blocked and a reduced voltage AC supply of 30, 40 and 50V is applied at 10 and 15 Hz. Under locked rotor, described mathematically in the Supplementary Material, the rotor resistance and leakage inductance are derived as follows:

$$R'_r = R_{eq} - R_s, \quad L_\sigma = \frac{X_{eq}}{\omega_0}. \quad (4)$$

No-load test: magnetizing inductance L_m .

In the no-load test, the IM runs with negligible mechanical load at frequency f_0 . To estimate L_m , the VFD was operated at 30, 35, 40, 45, and 50 Hz. The magnetizing reactance and inductance, mathematically proved in Supplementary Material, are

obtained as follows:

$$X_m = -\frac{1}{B_0}, \quad L_m = \frac{X_m}{\omega_0} = -\frac{1}{\omega_0 B_0}. \quad (5)$$

2.6 Validation

Validation was performed using the same experimental regimes as in the estimation step (locked-rotor and no-load). The IM model (described in the Supplementary Material) was validated in the MATLAB/Simulink environment using locked-rotor and no-load tests at the same frequency points used for parameter estimation.

In this case, the voltage signal generated during the processing step were the model inputs, while the output was the current signal. Additionally, the estimated current signal was compared with the real current signal generated during the processing step using residual analysis and quantitative performance metrics like RMSE/NRMSE and R^2 . Using same parameters values at different frequencies would make it impossible to show whether deviations are due to operating point dependent parameters or modeling error.

3 Results and Discussion

3.1 Selected Electrical Parameters

Based on the DC terminal measurement performed immediately after on-load operation, the stator resistance is estimated as $R_s = 60.5 \, \Omega$. The full locked-rotor and no-load parameter estimation results are provided in the Supplementary Material. Table 1 summarizes the electrical parameters selected for the calibrated DT model. All selected parameters in Table 1 are used in the calibrated DT model.

Table 1 Selected electrical parameters used in the calibrated induction motor model.

Parameter	Selected value	Source
R_s	60.5 Ω	DC test
R'_r	$42.205 \pm 0.403 \, \Omega$	Locked-rotor test at 10 Hz
L_σ	$0.6679 \pm 0.0541 \, \text{H}$	Locked-rotor test at 10 Hz
L_m	$1.729 \pm 0.009 \, \text{H}$	No-load tests at 30–50 Hz

The 10 Hz locked-rotor results were selected to obtain stable low-frequency estimates with limited skin effect influence. The no-load tests over 30–50 Hz were used to identify L_m because this range corresponds to the intended V/f operating region of the drive, where the motor operates with small slip and nearly constant air-gap flux.

3.2 Model Validation

Following the validation protocol described in Section 2.6, the calibrated IM model was tested using the same experimental regimes considered during parameter estimation, but on different time intervals of the measured data. This separation ensures that the validation error reflects model mismatch rather than parameter tuning at the same operating point.

For the locked-rotor regime, the rotor was mechanically blocked in the model ($\omega_m = 0$), and the series-branch parameters were set using the $f = 10$ Hz locked-rotor estimates of R'_r and L_σ . The simulated stator current closely matches the measured current, with negligible residuals across all three voltage cases (30–50 V). The obtained errors were $\text{RMSE} = 2.05 \times 10^{-4}$ – 3.59×10^{-4} , $\text{NRMSE} \approx 0.05\%$, and $R^2 = 1$.

Fig. 3 shows the locked-rotor validation results. The residual remains small over the full interval, confirming that the estimated series-branch parameters reproduce the short-circuit dynamics accurately at this operating point.

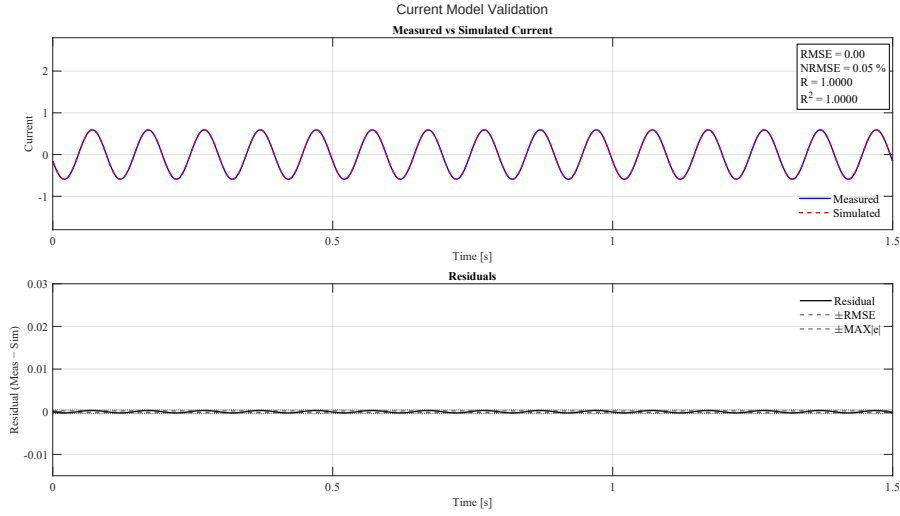


Fig. 3 Locked-rotor validation at $f = 10$ Hz: measured versus simulated stator current and residual signal.

For the no-load regime, the model was driven by the processed voltage waveform and validated at $f_0 \in \{40, 45, 50\}$ Hz using the corresponding L_m values. The results show high agreement over repeated runs, with RMSE on the order of 2×10^{-2} , $\text{NRMSE} \approx 3.93$ – 4.19% , and $R^2 \geq 0.9969$ in all cases.

In the no-load validation, the core-loss resistance R_c was not included because the standard dq IM model implemented in Simulink neglects the iron-loss resistor. Therefore, the shunt branch is represented only by the magnetizing inductance L_m . This modeling choice is intentional because the same dq model structure will be used in future work for online parameter estimation.

Fig. 4 shows the no-load validation at $f = 50$ Hz. The simulated current follows the measured waveform closely, and the residual remains small, indicating accurate current tracking even without modeling R_c .

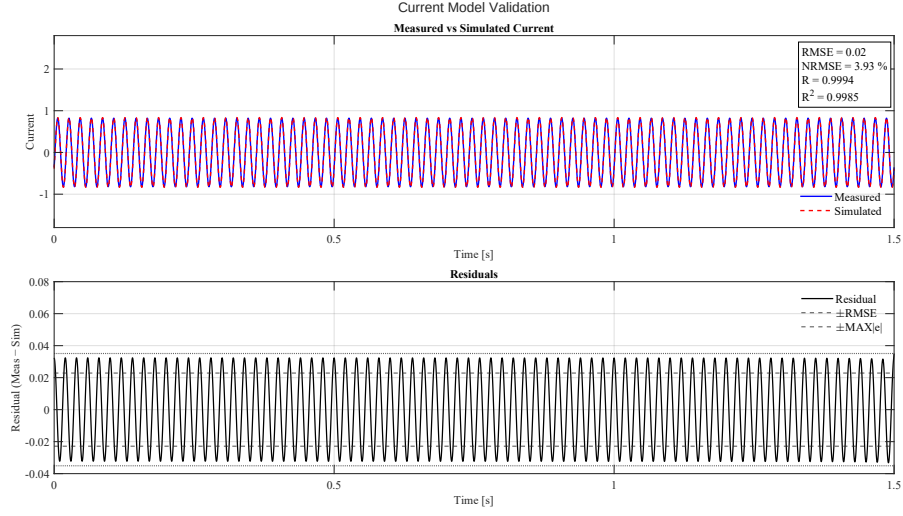


Fig. 4 No-load validation at $f = 50$ Hz: measured versus simulated stator current and residual signal.

In summary, the validation results show that the estimated electrical parameters accurately reproduce the measured stator current under the tested operating conditions. This supports the use of the calibrated electrical subsystem as part of the proposed DT.

4 Conclusion and Future Work

Conclusions. This paper presents an offline identification workflow for an IM DT that cleanly decouples: (i) least-squares phasor extraction of the fundamental component; (ii) electrical parameter estimation from standard DC, locked-rotor, and no-load tests; and (iii) model validation using residual-based performance metrics. Parameter estimation and validation were carried out on separate time intervals, so differences between simulation and measurement can be linked to model mismatch rather than parameter tuning effects. The calibrated dq model reproduces locked-rotor current with high fidelity ($R^2 = 1$) and maintains excellent agreement under no-load conditions ($R^2 \approx 0.998$). Collectively, these results support the estimated electrical parameter sets as a physically consistent baseline for the calibrated DT.

Future work. Future work will extend this offline calibrated digital twin toward online parameter estimation, updating electrical parameters in real time using voltage and current measurements under varying operating conditions. Based on the validated model established here, will be developed an online parameter estimator like EKF.

This estimator will enable monitoring and predictive maintenance in the presence of thermal effects and load variations.

Statements and Declarations

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Competing interests. The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval. Not applicable.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability. The MATLAB/Simulink code used for signal processing, parameter estimation, and model validation is available from the corresponding author upon reasonable request.

Author contributions. Darjon Dharmo contributed to conceptualization, methodology, experimental implementation, data acquisition, signal processing, model validation, result analysis, and manuscript writing. Denis Panxhi contributed to methodology, experimental implementation, validation, and manuscript review. Aida Spahiu contributed to supervision, methodology, interpretation of results, and manuscript review.

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