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Original Scientific Article

TOWARDS DIGITAL TWINNING OF ELECTRICAL MOTORS – SIMULATION MODELS

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Abstract This paper presents a methodological framework for building a digital shadow of an induction motor based on standardised tests and a two-axis (dq) simulation model. The tests were carried out according to IEEE Std 112 and IEC 60034-2-1. The parameters of the equivalent circuit were identified and entered into the model. Validation was performed by comparing the torque–speed and current–speed curves at 180 V and 220 V, while the nominal behaviour at 400 V was estimated using the model and voltage scaling. The model was then calibrated to reduce the discrepancy between the simulation and measurements, and the error was quantified using the root-mean-square error (RMSE) and mean absolute percentage error (MAPE). An automated load-simulation setup that reproduces the torque test is also presented, enabling rapid evaluation of parameter influence. The results show a very good match in the current channel, with larger deviations in the prediction of characteristic torque points, indicating the limitations of linearised parameters and motivating nonlinear model extensions. The approach enables summarised reliable estimates at nominal voltage when direct measurements are not feasible.

Keywords
induction motor, digital shadow, standardised tests, dq model, torque test, automated load simulation, model calibration

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1 Introducton

Digital twins (DT) and digital shadows (DS) for electric drives are active research topics. A digital shadow is a one-way representation of a physical system in a digital environment, whereas a digital twin extends this by establishing a two-way link with forecasting and optimisation capabilities in real time. A DS is, therefore, the first step towards a DT, as it enables systematic data collection and analysis, as well as validation of simulation models prior to industrial deployment. This paper focuses on the DS level for an induction machine (IM), where the simulation model is validated using standardised tests and laboratory measurements.

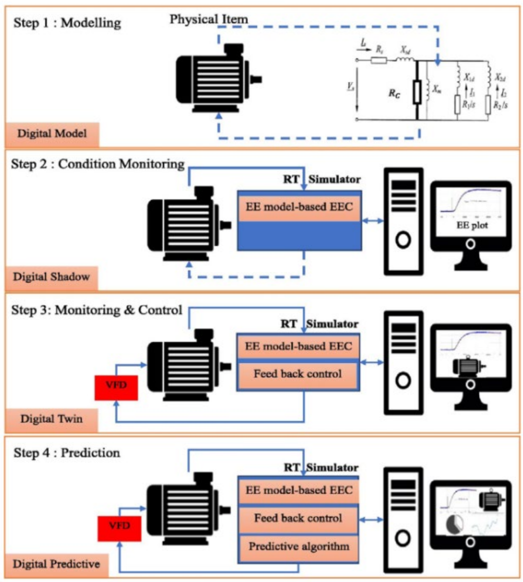

Figure 1: Reference hierarchy for IM DT/DS development.
Source: adapted from [1]**.**

Within this hierarchy, the present work addresses the second level—the digital shadow—bridging the measured data and a simulation model, to obtain trustworthy estimates and to prepare the ground for closed-loop DT functions.

Recent literature emphasises energy efficiency and reliability in electric-machine DS/DT development [1, 2, 3], torque-test methodologies and torque/speed characterisation [4, 5, 6, 7], and both dynamic simulation and in-field speed measurement using low-cost tools [8, 9]. However, few works combine parameter identification from standardised tests with a torque-test-based validation and standard voltage scaling (IEEE 112) (SVS) to nominal voltage within one coherent workflow—this is the gap our paper addresses.

The standardised tests defined in IEEE Std 112 and IEC 60034-2-1 [10, 11] are essential for obtaining motor parameters and validating models. They include DC resistance measurement, no-load test (NLT), locked-rotor test (LRT), load test (LT), optimal-voltage test (OVT) and the torque test (TT). The TT yields torque–speed and current–speed characteristics, and allows extracting key points: starting torque (T_s), maximum torque (T_{max}), and breakdown speed (n_{bd}). These serve as reference markers when comparing simulations against laboratory results. In this work, the standardised tests were carried out in a certified laboratory, and the identified parameters were entered into a dq-frame simulation model implemented in MATLAB/Simulink.

Our validation strategy is two-pronged. First, the laboratory and simulation results are compared at reduced voltages (180 V and 220 V). Second, the nominal behaviour at 400 V was estimated using SVS (simulation-assisted voltage scaling) from the reduced-voltage data and the corresponding simulations. Quantitative agreement is reported using root-mean-square error (RMSE) and mean absolute percentage error (MAPE), providing an objective assessment across the operating ranges. The approach also supports rapid sensitivity studies by reproducing the TT conditions in the simulation.

The remainder of the paper is organised as follows. Section 2 details the methodology, including the standardised testing, the 400 V scaling procedure, the simulation model and the error metrics. Section 3 presents the measurement and simulation results with the associated tables and figures. Section 4 discusses the findings in the context of DS development and the transition towards a full DT. Section 5 concludes with the main contributions and outlines directions for future work.

2 Methodology

Standardised tests were carried out to develop the digital shadow (DS) of the induction motor. The resulting parameters were entered into a dq simulation model. Comparing the simulation and laboratory results at 180 V and 220 V enabled model calibration and extraction of characteristic points (T_s, T_{max}, n_{bd}). Finally, SVS was used to estimate the performance at the nominal 400 V.

2.1 Standardised tests

The following standardised tests (IEEE Std 112) were used to obtain the parameters for the equivalent circuit and to provide reference curves for model validation.

2.2 Scaling to 400 V

An SVS procedure was applied to estimate operation at the nominal 400 V. Measurements at the reduced voltages (180 V, 220 V) were combined with the pointwise ratio of simulated curves at 400 V and at the corresponding reduced voltage, for each speed n (see (1)–(2)).

$$T_{400}(n) = T_{lab,V_1}(n) \cdot \left(\frac{T_{sim,400}(n)}{T_{sim,V_1}(n)} \right) \tag{1}$$

$$I_{400}(n) = I_{lab,V_1}(n) \cdot \left(\frac{I_{sim,400}(n)}{I_{sim,V_1}(n)} \right) \tag{2}$$

Procedure: (1) laboratory curves T(n) and I(n) at 180 V and 220 V are interpolated onto a common speed grid; (2) from the simulation, $T_{sim,400}(n)$, $I_{sim,400}(n)$, $T_{sim,V1}(n)$ and $I_{sim,V1}(n)$ are obtained, with $V_1 \in \{180, 220\}$; (3) the ratio above is computed pointwise over speed and applied to the measured curves. Because the method is multiplicative, the relative errors (MAPE) at 400 V equal to those at the source voltage, while the absolute errors (RMSE) scale with the level of the variables. Parameters are treated as constants (no explicit saturation or skin effect); nonlinearities are assumed to be moderate. Scaling from both source voltages (180→400 and 220→400) was used, and the 400 V reference points (T_s, T_{max}, n_{bd}) were taken as the average of the two estimates.

Table 1: Standardised tests and abbreviations.

Test (abbr.)	Description	Obtained parameters / characteristics
DC test (DC)	Measurement of stator winding resistance using a DC current	Stator resistance R_s
No-load test (NLT)	Motor running without mechanical load at a rated voltage	Magnetising reactance X_m; core-loss resistance R_{fe}; constant losses
Locked-rotor test (LRT)	Rotor locked mechanically; supply at reduced voltage	Rotor resistance R'_2; total leakage reactance $X_1+X'_2$; split into stator and rotor components
Load test (LT)	Motor loaded at a rated voltage and frequency	Efficiency; power factor; limiting operating points
Optimal Voltage Test (OVT)	Adjust supply voltage to an optimal value for the given operating point (without exceeding the allowed limits)	Trade-off among current/losses/torque; not an over-voltage test
Torque test (TT)	Progressive loading up to near-synchronous speeds at 180 V and 220 V	Torque–speed T(n) and current–speed I(n); key points: T_s, T_{max}, n_{bd}

2.3 Simulation model

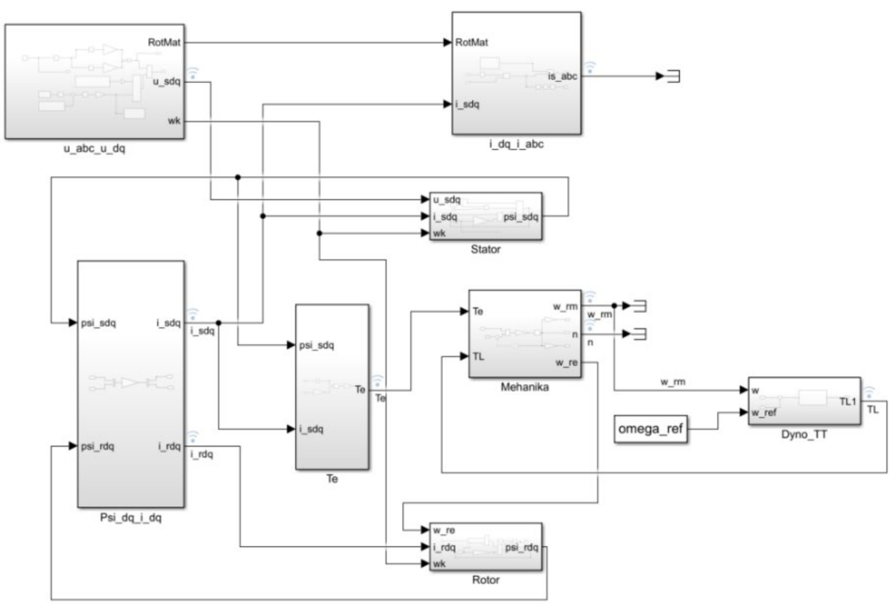

Figure 2: dq-model structure implemented in MATLAB/Simulink.

A dq-frame induction-motor model with constant parameters (R_s, R'_2, X_m, X_1, X'_2) identified from standardised tests was implemented in MATLAB/Simulink. A simple mechanical sub-model of the load is included. The model generates torque–speed and current–speed curves at 180 V, 220 V, and 400 V for direct comparison with the torque test (TT). The parameters are treated as constants with respect to temperature and frequency; nonlinear phenomena (magnetic saturation, skin effect, temperature dependence) are not modelled explicitly. Despite this simplification, empirical parameter tuning provides sufficient agreement for DS validation (see Figure 2). The approach follows the standard dq formulation and modelling practice reported in the literature [2].

2.4 Metrics for quantitative comparison

For quantitative comparison of the laboratory and simulation results we used RMSE (root-mean-square error) and MAPE (mean absolute percentage error) defined in (3)-(4). RMSE emphasises the absolute deviations between paired curves (large deviations weigh more), whereas MAPE expresses the average relative error in percent, enabling comparison across magnitudes and test conditions.

$$\mathrm{RMSE}_X = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (\mathrm{X}_{\mathrm{sim,i}} - \mathrm{X}_{\mathrm{lab,i}})^2} \tag{3}$$

$$\mathrm{MAPE}_X = \frac{100}{N} \cdot \sum_{i=1}^{N} \left| \frac{X_{sim,i} - X_{lab,i}}{X_{lab,i}} \right| \tag{4}$$

3 Results

This section reports the results of the standardised tests (ST) and the torque-test (TT) comparison between the laboratory measurements and the dq simulation model. First, the parameters identified from ST are summarised, followed by the T–n and I–n curves at 180 V and 220 V and 400 V estimates obtained via SVS. For fair comparison, all the data were interpolated onto a common speed grid (n = 0–1500 rpm, step 10 rpm), with a threshold n ≥ 100 rpm to avoid initial transients. Quantitative metrics (RMSE, MAPE) are then presented, and the key TT points (T_s, T_{max}, n_{bd}) are indicated.

3.1 Identified parameters

Identified parameters used in the dq model and in the comparisons are summarised below.

Table 2: Identified parameters of the induction motor from standardised tests.

Parameter	Value	Test method
R_s [Ω]	1.912	DC
R'_2 [Ω]	1.50	LRT
X_m [Ω]	80.0	NLT
$X_1 + X'_2$ [Ω]	8.0	LRT

3.2 Torque test — measurements vs. simulation

The I–n and T–n curves are compared and discussed at 180 V and 220 V, together with the 400 V estimates obtained by SVS. Characteristic points T_s, T_{max}, and n_{bd} are marked on each curve. See Figures 3–4.

Table 3: Key TT points — 180 V (Lab vs. Sim)

Quantity	Lab	Sim	Abs. diff	Rel. diff [%]
T_s [Nm]	4.96	3.91	-1.06	-21.29
T_{max} [Nm]	7.06	9.45	2.38	33.74
n_{bd} [rpm]	1280.00	1200.00	-80.00	-6.25

Table 4: Key TT points — 220 V (Lab vs. Sim)

Quantity	Lab	Sim	Abs. diff	Rel. diff [%]
T_s [Nm]	8.39	5.84	-2.55	-30.44
T_{max} [Nm]	11.64	14.11	2.47	21.26
n_{bd} [rpm]	1250.00	1200.00	-50.00	-4.00

3.3 Quantitative agreement

RMSE and MAPE were computed over the common speed grid (n = 0-1500 rpm, step 10 rpm), with $n \geq 100$ rpm. The following values are reported by voltage level.

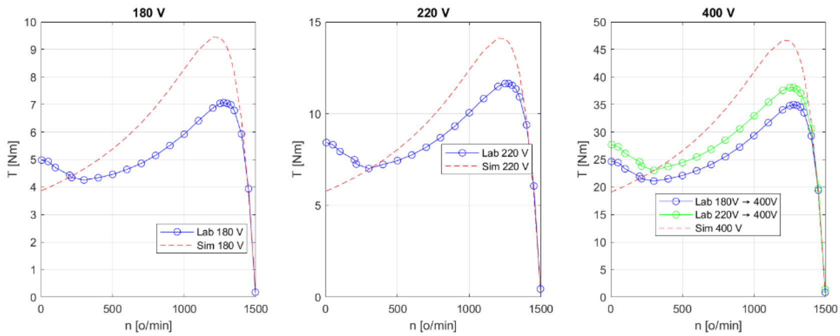

Figure 3: Comparison of T–n curves (180 V, 220 V and 400 V scaled).

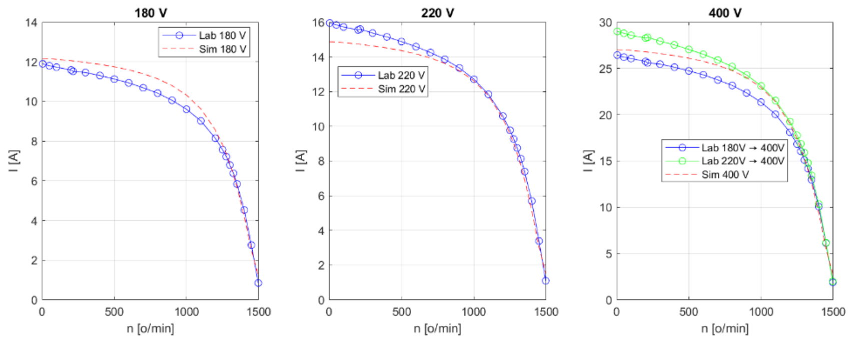

Figure 4: Comparison of I–n curves (180 V, 220 V and 400 V scaled).

Table 5: Error metrics (RMSE, MAPE) by voltage level for the TT comparisons.

Voltage	$RMSE_T$ [Nm]	$MAPE_T$ [%]	$RMSE_I$ [A]	$MAPE_I$ [%]
180 V	1.60	24.79	0.56	5.68
220 V	1.63	14.91	0.47	3.50
400 V (180→400, scaled)	7.89	24.79	1.25	5.68
400 V (220→400, scaled)	5.38	14.91	0.86	3.50

Note on abbreviations: $RMSE_T$ — RMSE for torque [Nm]; $MAPE_T$ — MAPE for torque [%]; $RMSE_I$ — RMSE for current [A]; $MAPE_I$ — MAPE for current [%].

4 Analysis and discussion

Across 180 V and 220 V, the model reproduced I–n more accurately than T–n consistently. The largest deviations occurred in the vicinity of T_s, T_{max}, and n_{bd}, which is consistent with the omission of nonlinear phenomena (magnetic saturation, skin effect) and temperature-dependent parameters. SVS to 400 V yielded physically credible curves in the linear region, but for the DS→DT transition the model should be extended with nonlinear magnetising characteristics X_m=f(i_m) (or f(U)), frequency-dependent rotor resistance R'_2 (skin effect), and a thermal sub-model to track the parameter drift. Integrating real-time telemetry and control closes the loop towards a full DT capable of online optimisation of efficiency, reliability and safety.

5 Conclusion

We presented a methodology for developing a digital shadow (DS) of an induction motor based on standardised tests and comparison of laboratory measurements with a dq simulation model. The measurements were carried out per IEEE Std 112 and IEC 60034-2-1 [10, 11] (DC, NLT, LRT, LT, OVT, TT). The parameters identified from these data were used in the model. Emphasis was placed on the TT at reduced voltages (180 V and 220 V) and on estimating nominal behaviour at 400 V through SVS. We observed good agreement in the current prediction (e.g., $MAPE_I$ ≈ 5.7% at 180 V and 3.5% at 220 V; $RMSE_I$ ≈ 0.56 A and 0.47 A), with larger discrepancies in torque ($MAPE_T$ ≈ 24.8% and 14.9%; $RMSE_T$ ≈ 1.60 Nm and 1.63 Nm). Under scaling to 400 V, the relative errors remained unchanged, whereas the absolute errors increased proportionally to the signal level (e.g., $RMSE_T$ ≈ 7.9 Nm for 180→400 and 5.38 Nm for 220→400). The characteristic TT points corroborated the pattern: T_s was underestimated (≈ −21% to −30%), T_{max} was overestimated (≈ +21% to +34%), and n_{bd} was shifted by about −50 to −80 rpm compared with the measurements. Future work will introduce nonlinear magnetisation, frequency-dependent rotor resistance, and thermal effects, and will integrate telemetry and control towards a DT platform.

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Povzetek v slovenskem jeziku

Proti digitalnemu dvojčku električnih motorjev – simulacijski modeli. Članek predstavlja metodološki okvir za gradnjo digitalnega dvojčka asinhronskega motorja na podlagi standardiziranih preskusov in dvoosnega (dq) simulacijskega modela. Preskusi so bili izvedeni v skladu s standardoma IEEE Std 112 in IEC 60034-2-1. Parametri ekvivalentnega vezja so bili določeni in vneseni v model. Validacija je bila izvedena s primerjavo krivulj navor–hitrost in tok–hitrost pri 180 V in 220 V, medtem ko je bilo nazivno obnašanje pri 400 V ocenjeno z uporabo modela in skaliranja napetosti. Model je bil nato umerjen za zmanjšanje razlike med simulacijo in meritvami, napaka pa je bila kvantificirana z uporabo srednje kvadratne napake (RMSE) in povprečne absolutne odstotne napake (MAPE). Predstavljena je tudi avtomatizirana merilna postavitev za simulacijo obremenitve, ki ponazarja preskus navora in omogoča hitro oceno vpliva parametrov. Rezultati kažejo zelo dobro ujemanje v kanalu toka, pri napovedi značilnih točk navora pa so večja odstopanja, kar nakazuje omejitve lineariziranih parametrov in spodbuja razširitve modela na nelinearne. Pristop omogoča zanesljive povzetke ocen pri nazivni napetosti, kadar neposredne meritve niso izvedljive.