

Supplementary Material

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

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1 Materials and Methods

1.1 Implementation of the system

This section provides the main technical specifications of the electric drive system.

Table 1: Technical specifications of the electric drive and measurement setup.

Group	Technical specification	Value
VFD	Model	FR-D720S-014SC-EC
	Rated input voltage, single phase	200–240 V AC
	Rated motor capacity, normal duty	0.2 kW
	Output frequency range	0.2–400 Hz
IM	Rated power	130 W
	Rated voltage, Y/ Δ	380/220 V
	Rated current, Y/ Δ	0.38/0.66 A
	Rated speed	2900 rpm
Alternator	Nominal output voltage	14 V
	Rated output current	95 A
Battery	Nominal voltage	12 V
	Capacity	62 Ah
Rheostat	Resistance	7.5 Ω
	Current rating	10 A
Shunt resistor	Resistance	0.1 Ω
	Power rating	3 W
	Tolerance	$\pm 1\%$
Voltage divider	Resistors	$R_1 = 2.2 \text{ M}\Omega$, $R_2 = 1 \text{ M}\Omega$, $R_3 = 1 \text{ k}\Omega$
Isolated amplifier	Device	TI AMC1300
	Input range, peak	$\pm 250 \text{ mV}$
	Gain	8.2
NI USB-6009	Analog input channels, SE/DIFF	8/4
	Maximum analog input sample rate	48 kS/s aggregate
	Analog input range	$\pm 10 \text{ V SE}$, up to $\pm 20 \text{ V DIFF}$
	Interface	USB, bus powered

1.2 Signal Processing

Each measured channel $x(t)$ was represented by its fundamental component at the commanded frequency f_0 . Given the samples $\{(t_n, x[n])\}_{n=0}^{N-1}$ and $\omega_0 = 2\pi f_0$, the mean value was removed as

$$\bar{x} = \frac{1}{N} \sum_{n=0}^{N-1} x[n], \quad x_0[n] = x[n] - \bar{x}. \quad (1)$$

The fundamental component was then obtained by solving the least-squares problem

$$(a, b) = \arg \min_{a, b} \sum_{n=0}^{N-1} (x_0[n] - a \cos(\omega_0 t_n) - b \sin(\omega_0 t_n))^2. \quad (2)$$

Using the coefficients obtained from Eq. (2), the reconstructed waveform is expressed as

$$\hat{x}[n] = a \cos(\omega_0 t_n) + b \sin(\omega_0 t_n) + \bar{x}. \quad (3)$$

The corresponding complex peak phasor is defined as

$$X_{\text{peak}} = a - jb, \quad (4)$$

where j is the imaginary unit. The extracted phasor represents the fundamental component, while $\hat{x}[n]$ enables time-domain validation against the measured waveform.

1.3 Electrical Parameter Estimation

Locked rotor: R'_r and L_σ . Under locked rotor, the impedance of each phase is approximated by the series branch

$$Z_{\text{LR}}(\omega_0) \approx (R_s + R'_r) + j\omega_0 L_\sigma, \quad (5)$$

where R'_r is the rotor resistance referred to the stator and L_σ is the total leakage inductance.

$V_{LL,1}$ and $I_{L,1}$ indicates the complex *RMS* phasors of the measured line-to-line voltage and the line current respectively. $V_{\text{ph},1}$ and $I_{\text{ph},1}$ are obtained using the Δ relations. Impedance for each phase is:

$$Z_{\text{ph}} = \frac{V_{\text{ph},1}}{I_{\text{ph},1}}. \quad (6)$$

Separating real and imaginary parts,

$$R_{\text{eq}} = \Re\{Z_{\text{ph}}\}, \quad X_{\text{eq}} = \Im\{Z_{\text{ph}}\}, \quad (7)$$

the rotor resistance (referred in stator) and leakage inductance are defined as follows:

$$R'_r = R_{\text{eq}} - R_s, \quad L_\sigma = \frac{X_{\text{eq}}}{\omega_0}. \quad (8)$$

No-load test: magnetizing inductance L_m . The RMS value of phase voltage and current are:

$$V_{\text{ph},1} = V_{LL,1}, \quad I_{\text{ph},1} = \frac{I_{L,1}}{\sqrt{3}} e^{j\phi}, \quad (9)$$

Using the series stator impedance from DC + locked rotor estimations,

$$Z_s = R_s + j\omega_0 L_\sigma, \quad (10)$$

the internal voltage phasor behind the series drop is

$$E_1 = V_{\text{ph},1} - I_{\text{ph},1} Z_s. \quad (11)$$

The shunt branch admittance is then described as:

$$Y_0 = \frac{I_{ph,1}}{E_1} = G_0 + jB_0. \quad (12)$$

For an inductive magnetizing branch, $B_0 < 0$, and the magnetizing reactance and inductance are obtained as follows:

$$X_m = -\frac{1}{B_0}, \quad L_m = \frac{X_m}{\omega_0} = -\frac{1}{\omega_0 B_0}. \quad (13)$$

1.4 Validation

Using the notation $\dot{\psi} = d\psi/dt$ and the slip frequency $\omega_{sl} = \omega_e - \omega_r$, the voltage equations are

$$v_{ds} = R_s i_{ds} + \dot{\psi}_{ds} - \omega_e \psi_{qs}, \quad (14)$$

$$v_{qs} = R_s i_{qs} + \dot{\psi}_{qs} + \omega_e \psi_{ds}, \quad (15)$$

$$0 = R'_r i_{dr} + \dot{\psi}_{dr} - \omega_{sl} \psi_{qr}, \quad (16)$$

$$0 = R'_r i_{qr} + \dot{\psi}_{qr} + \omega_{sl} \psi_{dr}. \quad (17)$$

The flux linkage relations are

$$\psi_{ds} = L_{ss} i_{ds} + L_m i_{dr}, \quad \psi_{qs} = L_{ss} i_{qs} + L_m i_{qr}, \quad (18)$$

$$\psi_{dr} = L_m i_{ds} + L_{rr} i_{dr}, \quad \psi_{qr} = L_m i_{qs} + L_{rr} i_{qr}, \quad (19)$$

where $L_{ss} = L_{\sigma s} + L_m$ and $L_{rr} = L_{\sigma r} + L_m$ indicate stator and rotor self inductances. The electromagnetic torque is computed as

$$T_e = \frac{3}{2} p (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}), \quad (20)$$

with p the number of pole pairs.

2 Results and Discussion

2.1 Direct current test result

Based on the DC terminal measurement performed immediately after on-load operation, the stator resistance is estimated as $R_s = 60.5 \, \Omega$.

2.2 Locked rotor test results

Table 2 presents the locked rotor parameter estimations.

Table 2: Locked-rotor test results for electrical parameter estimation.

f (Hz)	U (V)	$ I_{L,1} $ (A)	R'_r (Ω/ph)	L_σ (H/ph)
$f = 10 \, \text{Hz}$				
10	30	0.4183	42.429	0.71982
10	40	0.5667	42.447	0.67201
10	50	0.7192	41.740	0.61177
$f = 15 \, \text{Hz}$				
15	30	0.3859	47.029	0.68199
15	40	0.5226	45.962	0.57451
15	50	0.6619	47.653	0.55100

The estimated rotor resistance referred to the stator varies between $R'_r \approx 41.7$ and $47.7 \Omega/\text{ph}$, while the total leakage inductance lies from $L_\sigma \approx 0.55$ to 0.72 H/ph . When the frequency of VFD increases from 10 to 15 Hz, the estimated R'_r increases, which is physically consistent with locked-rotor operation ($s = 1$). The frequency of current signal of the rotor is equal to the frequency of current signal of the stator, which means that higher frequency increases skin effects in the rotor conductors, resulting in a higher rotor resistance. On the other hand, for a fixed frequency, L_σ decreases as the applied voltage (consequently the current) increases, which is consistent with the nonlinear magnetic behavior of leakage flux paths. In particular, partial saturation has reduced the permeability in these regions, leading to a lower leakage inductance at higher current.

For subsequent DT simulations using fixed locked-rotor parameters, the 10 Hz results provide the most representative reference case. The 10 Hz estimates were summarized as the mean $\pm$ standard deviation across the three voltage cases, resulting in $\overline{R'_r} = 42.205 \pm 0.403 \Omega$ and $\overline{L_\sigma} = 0.6679 \pm 0.0541 \text{ H}$.

2.3 No-load test results

The no-load test results summarized in Table 3, which shows the identified magnetizing inductance as mean $\pm$ standard deviation over five repeated runs at each excitation frequency. The stator leakage inductance $L_{\sigma s}$ used in the no-load analysis was taken from the locked-rotor test.

Table 3: No-load test results for magnetizing inductance estimation.

f (Hz)	$ \overline{V_{LL,1}} $ (V)	$ \overline{I_{L,1}} $ (A)	$\overline{L_m} \pm \sigma_{L_m}$ (H)
30	128.2360	0.569822	1.74456 ± 0.00880
35	149.1800	0.577157	1.72330 ± 0.00291
40	169.9820	0.576976	1.72578 ± 0.01102
45	192.9700	0.586292	1.72333 ± 0.00150
50	215.1740	0.586444	1.72850 ± 0.00661

The resulting estimations are consistent across the tested operating points. The standard deviation of L_m is small relative to its mean at each frequency. It indicates that the extraction of the shunt branch from the measured fundamental phasors is robust. This consistency is expected because the VFD was operated with a V/f strategy from the rated point (50 Hz) down to 30 Hz, which maintains approximately constant air-gap flux over the normal operating range. Therefore, L_m remains nearly constant between 30 and 50 Hz, with only modest variations to voltage drops in stator winding and weak saturation effects at 30 Hz. At low current values, the air gap flux is small and the magnetic circuit remains far from saturation. As result, the effective magnetizing inductance L_m tends to be higher.

For the DT model, the no-load estimation provides a practical and physically representative characterization of the magnetizing branch over the full 30–50 Hz range. Unlike the locked-rotor test where high frequency operation is impractical and the series branch resistances are strongly affected by skin effects, the no-load test reflects the intended operating regime of the IM with small slip and controlled flux under V/f . Therefore, L_m values in Table 3 are suitable for direct use in the DT for the corresponding operating regimes, while the locked-rotor estimates of R'_r and L_σ are best used to parameterize the model series impedance branch. They should not be extrapolated to represent high frequency operation.