Optimal Estimation of the Parameters and Losses of Induction Motors Working in Full-Wave

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***Abstract*—Induction machines are the preferred solution in numerous sectors, including industrial, transportation, etc. Accurate estimation of motor parameters and losses is crucial for both efficient operation and precise torque control required by many applications. Numerous techniques have been developed for this purpose. Traditional tests involve no-load and blocked rotor testing procedures. However, they require laboratory facilities with high-precision instrumentation and equipment and might not be feasible in more industrial environments. To overcome these limitations, this paper proposes a method for online parameters and losses estimations for inverter-fed induction motors. The use of the inverter offers interesting possibilities, not only regarding the precise control of the operating point of the machine (torque and speed), but also to exploit the voltage harmonics injected by the inverter for different modulation modes (PWM, SHE, PWM, etc) to enhance the identification algorithms. A two-stage optimization algorithm has been developed and employed to accurately estimate the parameter and losses of the machine. Experimental results obtained from performing tests at different load conditions are provided, demonstrating the validity of the proposed approach.**

***Index Terms*—Induction machine, optimization, losses estimation, parameters estimation, full wave.**

I. Introduction

Three-phase induction motors (IM) are the main energy consumer in electrical systems in global terms [1]. The combination of induction motors and power electronic converters has become essential for high-performance adjustable speed drives and servodrives. Increasing their efficiency can therefore result in significant energy savings. Accurate parameter estimation will be critical for this purpose. Furthermore, many applications (e.g. traction) require accurate torque control, precise knowledge of machine parameter being also required for this purpose. Techniques for both online and offline parameter estimation have been extensively studied in the literature [2]. The traditional offline method consisting of no-load tests and locked-rotor tests is defined by the IEEE standard 112 [3]. The offline testing procedure can be implemented upon the initial enabling of the controller to determine the motor parameters. These offline methods establish fixed parameter values [4], [5]. However, to account for variations in motor parameters due to factors such as aging or temperature fluctuations, online estimation methods present a more suitable alternative [6]–[12]. These methods often require specific conditions during commissioning or involve significantly more complex mathematical processing of measurement data [13]. A specific parameter estimation technique can be applied to the inverter-fed IMs [14]. Other methods have been proposed in [15] where standard tests were performed feeding the induction machine with an inverter. The results confirm the validity of this method and open an important window for obtaining induction motor characterization at frequencies other than the usual 50 Hz. From this application there was no harmonic analysis that could give additional information about the parameters.

Following the presented research context, this paper proposes a new method for online parameter estimation of IMs analyzing the high-frequency voltage harmonics injected by the inverter. In particular, Full-Wave modulation is implemented to increase the harmonic components. The parameter estimation is performed employing an optimization algorithm that minimizes the error between the estimated and measured stator currents and the total power balance for the different harmonic orders analyzed. A two-stage optimization approach is adopted, comprising Particle Swarm Optimization (PSO) and Interior Point (IP) algorithm. This approach determines machine parameters with enhanced accuracy. In addition, a complete evaluation of the losses is reported, validated with a subdivision of the losses by their sources.

Experimental validation is achieved by conducting measurements at various steady-state operating conditions and verifying the proposed ability of the method to accurately estimate torque and losses. The results will be compared with the parameters and losses defined by IEEE standards [3] for further validation.

II. Machine model

Different IM models can be found in the literature, each with its pros and cons, depending on the application requirements.

Type of method	Any operating condition	Harmonic content analysis	Stator resistance measurement	Need of inverter
IEEE standards [3]	No	No	No	No
Offline methods [4], [5], [15], [16]	No	No	No	Yes
Online methods [6]–[14]	Yes	No	Suggested	Yes
Proposed method	Yes	Yes	No	Yes

TABLE I: Parameter estimation methods comparison

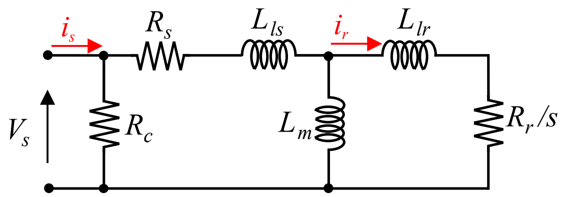
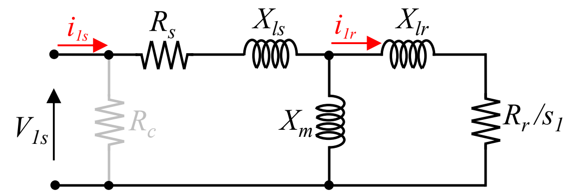
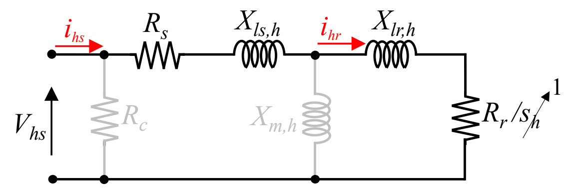


Fig. 1: Single-phase simplified equivalent circuit.



(a) *Equivalent circuit for the fundamental harmonic.*



(b) *Equivalent circuit for higher order harmonics.*

Fig. 2: Equivalent circuit for the fundamental and high-order harmonics analysis of an IM.

Among them, one of the most popular is the per-phase equivalent circuit [17]. It is worth noting that this model is, in principle, suitable for transient analysis. However, in this work, we restrict our attention to steady-state analysis under periodic excitation. A key characteristic of the analysis proposed is that the stator voltage V_s does not consist of a single frequency component; instead, it may include multiple harmonic components.

The model is easy to apply and can estimate core losses. However, its accuracy is directly related to the reliability of the estimation of the parameters of the equivalent circuit. The required parameters are:

- Stator resistance, R_s, that represents the Joule losses of the stator windings.
- Stator leakage inductance, L_{ls}, representative of the flux produced by the stator that does not couple the rotor windings.
- Magnetizing inductance, L_m, which includes all the mutual flux that flows from the stator to the rotor windings through the air gap of the machine.
- Core resistance, R_c, represents the core losses.
- Rotor leakage inductance, L_{lr}, represents all the flux lines that are excluded from the mutual flux, but remain linked in the rotor windings.
- Rotor resistance, R_r, that is divided by s, the slip of the machine. This term is the sum of two terms: R_r that refers to Joule rotor losses and $R_r\frac{1-s}{s}$ that represents the mechanical load of the machine.

In the classical representation of the per-phase equivalent circuit, core losses are accounted for by the equivalent resistance R_c in parallel with the magnetizing branch because it refers to the flux flowing in the iron core. However, a simplified model, as shown in Fig. 1, can be considered without significantly affecting the overall accuracy of the modeling approach [18].

In applications where the IM is powered by an inverter supply, high-order harmonics appear in the supplied voltage and, consequently, in the currents flowing through the machine. The analysis of the equivalent circuit can be simplified depending on whether the fundamental or a high-order harmonic are considered. Considering the fundamental frequency, the equivalent circuit can be solved by assuming that the total leakage inductance is split equally between the rotor and stator. Furthermore, the current flowing through the core resistance branch can be considered to be negligible. The resulting circuit is shown in Fig. 2a.

Following this reasoning, the fundamental component of the stator current can be obtained as:

$$i_{1s}(j\omega_1) = \frac{V_{1s}(j\omega_1)}{\hat{R}_s + j\omega_1\hat{L}_{ls} + \frac{j\omega_1 L_m(\frac{\hat{R}_r}{s_1} + j\omega_1\hat{L}_{ls})}{\frac{\hat{R}_r}{s_1} + j\omega_1(\hat{L}_m + \hat{L}_{ls})}} \tag{1}$$

For high-order harmonics, the value of the magnetizing impedance increases with higher values of the electric speed ω_h. Therefore, a lower negligible current flows in the magnetizing branch. The resulting circuit is shown in Fig. 2b. Thus, the calculation of the high-order component of the stator current becomes:

$$i_{hs}(j\omega_h) = \frac{V_{hs}(j\omega_h)}{\hat{R}_s + 2j\omega_h\hat{L}_{ls} + \hat{R}_r} \tag{2}$$

The formulation of the stator current high-order harmonic component (2) results in a simpler expression with respect to the fundamental one (1). Indeed, fewer parameters are involved. This consideration suggests that analyzing high-order harmonics presents an interesting opportunity for estimating the parameters contained in (2).

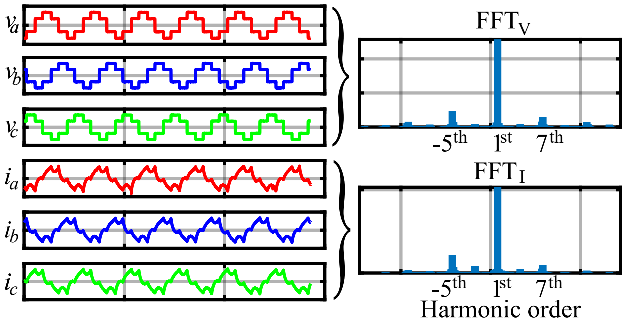


Fig. 3: Example of FFT analysis of V_s and i_s phasors amplitude with FW modulation.

III. Parameter and Losses Estimation

The proposed approach for estimating parameters and losses relies on the separate analysis of the contributions from the fundamental and harmonic components of voltages and currents, considering the simplified equivalent circuits shown in Fig. 2, as discussed in Section II. However, usually a PWM modulation is implemented to supply the IM, leading to negligible current harmonics. To properly exploit (2), use of synchronous modulation methods can be advantageous as they inject a large amount of voltage harmonics at relatively low frequencies [19]. Use of Full Wave (FW) modulation is specially appealing for this purpose, it will be used hereafter. Harmonics of the order of $7^{th}, 13^{th}$... appear in the currents. In the following description of the proposed procedure, superscript "ˆ" represents an estimated quantity.

To estimate the machine parameters, an optimization problem is formulated to minimize the cost function (3), where $\hat{i}_s$ and $i_{s,\text{meas}}$ are the estimated and measured stator currents, respectively.

$$CF_i = |\hat{i}_{hs} - i_{hs,\text{meas}}| \tag{3}$$

This minimization is done for the fundamental (1) and for relevant harmonics (2) in the case of FW modulation.

Signals are measured in the time domain; to perform such minimization (3), they have to be elaborated in the frequency domain. Therefore, the Fast Fourier Transform (FFT) (4) is employed for the harmonic spectrum analysis of the phase input currents, as shown in Fig. 3.

$$i_k = \sum^{N-1} i_n \cdot e^{-j\cdot 2\pi \cdot \frac{k}{N} \cdot n} \tag{4}$$

The same reasoning can be applied to analyze the behavior of the input voltages in the frequency domain. However, voltages are often not measured directly; instead, the procedure can be applied using reconstructed voltages from the imposed duty cycles [20], [21].

A two-stage optimization approach is employed. PSO is used to obtain an initial guess (x_0) of the parameter estimate without prior assumptions. Taking as a starting point the PSO output, an IP algorithm is exploited to find the final solution. This choice is justified by the fact that the IP algorithm results in being superior in the accuracy of resolution of the optimization problem defined. However, it also demonstrates a high sensitivity to the initial guess.

The core resistance R_c was neglected in the current estimation (1), (2), so it cannot be retrieved in this process. However, R_c can be found from the losses analysis. Losses to be estimated include:

- Stator Joule losses
$$\hat{P}_{jl,s} = 3 \cdot \hat{R}_s \cdot {i_s}^2 \tag{5}$$
- Rotor Joule losses
$$\hat{P}_{jl,r} = 3 \cdot \hat{R}_r \cdot {i_r}^2 \tag{6}$$
- Core losses
$$\hat{P}_c = 3 \cdot \frac{V_s^2}{\hat{R}_c} \tag{7}$$
- Mechanical losses
$$\hat{P}_{m_{loss}} = B(\omega_m) \cdot \omega_m^2 \tag{8}$$

The calculation of stator and rotor Joule losses $\hat{P}_{jl}$ can be directly derived from the estimation of the machine electric parameters $\hat{R}_s, \hat{R}_r$ (5) (6). The mechanical losses $\hat{P}_{m_{loss}}$ are dependent on the mechanical speed ω_m and a friction coefficient B, which is in turn dependent on the speed. The trend of such coefficient is found experimentally by performing several no-load tests at different speeds. Voltage commands for the IM are applied in an open-loop fashion. However, by appropriately selecting the electrical frequency f_e and modulation index m_i, the operating point of the machine can be precisely controlled. Different electrical frequencies are imposed, and for each controlled point. Assumed that the mechanical speed ω_m is known the slip is retrieved as (9) where $\omega = 2 \cdot \pi \cdot f_e$ is the electric speed.

$$s = \frac{\omega - \omega_m}{\omega} \tag{9}$$

Neglecting the core losses, torque can estimated as (10).

$$\begin{aligned}\hat{T} = \frac{\hat{P}_{m,loss}}{\omega_m} = \frac{3 \cdot p}{\omega} \cdot R_r \cdot \frac{1-s}{s} \cdot i_r^2 = \\ \frac{3 \cdot p}{\omega} \cdot \frac{V^2}{\frac{R_s^2 + (2 \cdot X_{ls})^2}{R_r} \cdot s + 2 \cdot R_s + \frac{R_r}{s}}\end{aligned} \tag{10}$$

Straightforwardly from (8) and (10) the friction coefficient can be retrieved as:

$$B(\omega_m) = \frac{\hat{P}_{m_{loss}}}{\omega_m^2} = \frac{\hat{T}}{\omega_m} \tag{11}$$

Using a curve-fitting tool with the values of B at different speeds, the trend of B is derived.

Core losses $\hat{P}_c$ are now included and retrieved from the core resistance and the phase voltage amplitude (7). Different approaches can be developed to model the core resistance. The one proposed consists of modeling the core resistance R_c

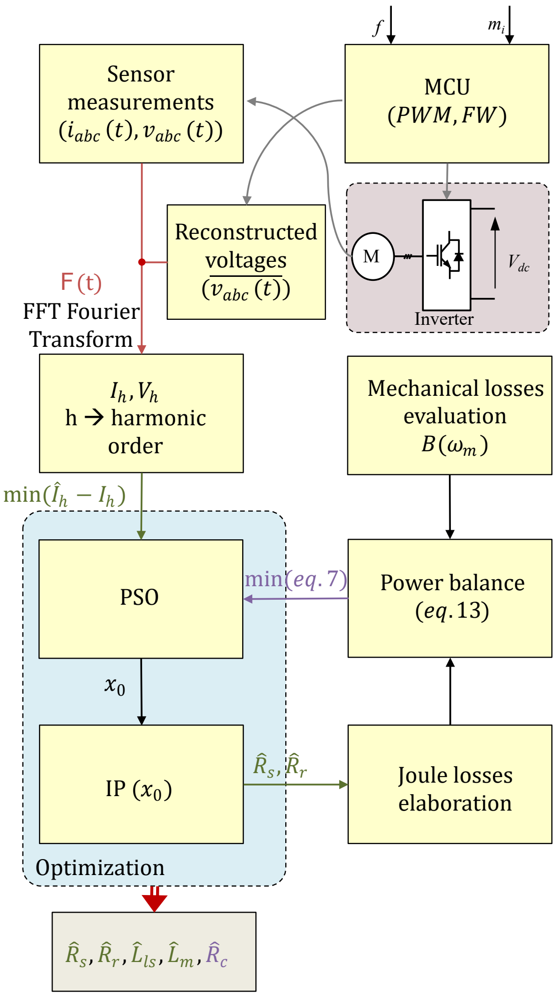


Fig. 4: Flow chart of the proposed procedure.

as a function of only the electrical frequency, respecting the following relationship.

$$\hat{R}_c(f) = A \cdot f^3 + B \cdot f^2 + C \cdot f \tag{12}$$

To derive the core resistance coefficients for both motors A, B, C, a new cost function that has to be minimized is defined. this new cost function consist of the system power balance equation (13).

$$CF_P = \hat{P}_{in} - \hat{P}_{jls} - \hat{P}_{jlr} - \hat{P}_c - \hat{P}_{m_{loss}} \tag{13}$$

The same two-stage optimization approach previously described is used.

The complete flow chart of the proposed procedure is shown in Fig. 4. The estimation of equivalent circuit parameters and machine losses is strongly connected, as the determination of $\hat{R}_c$ depends on the estimation of losses, which is, in turn, influenced by the accuracy of the estimation of $\hat{R}_s$ and $\hat{R}_r$ (see Fig. 4).

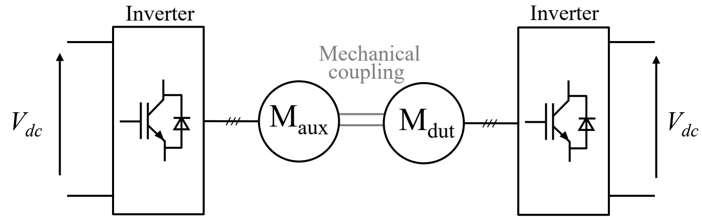


Fig. 5: Back-to-back configuration scheme.

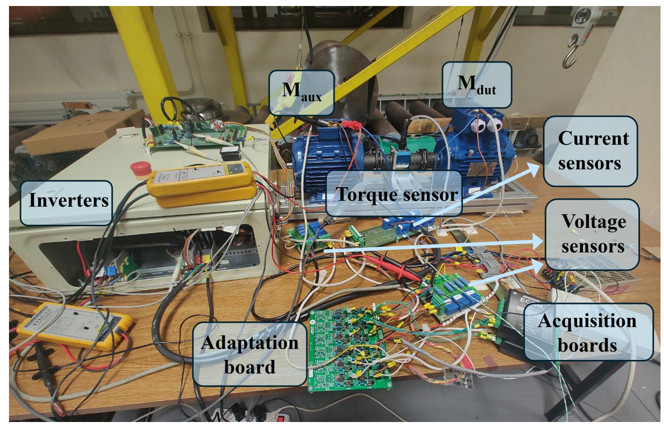


Fig. 6: Test bench.

IV. Experimental Results

The proposed approach is validated experimentally, exploiting a back-to-back configuration with two different IMs, as depicted in Fig. 5. It is highlighted that the proposed method can simultaneously estimate the parameters of both motors.

The test bench used for validation of the proposed method comprises two mechanically coupled 1.1 kW IMs with a peak stator current of 4.7 A and a rated stator voltage of 230 V (see Fig. 6). The two machines are referred to as the Device Under Test (DUT) and the Auxiliary (AUX).

Each motor was fed by a three-phase inverter, sharing the dc-link. For each test, the parameters of both machines can be retrieved. Voltage and current measurements are obtained using LEM sensors (LA55-P, LV25-P) and an acquisition board (ECONseries DT9816), while speed is measured with a tachometer and torque with a torque meter. Voltage commands to both motors are applied in an open-loop fashion, imposing the electrical frequency f_e and modulation index (m_i). Still the operating point of the test bench (torque, speed and flux level) can be precisely controlled by proper selection of f_e and (m_i). The tests were carried out under different operating conditions, varying:

- Electrical frequency f_e
- Mechanical speed ω_m
- Dc-link voltage
- Temperature ($T_1 = 20°C$, $T_2 = 65°C$)
- Modulation method, including PWM and FW

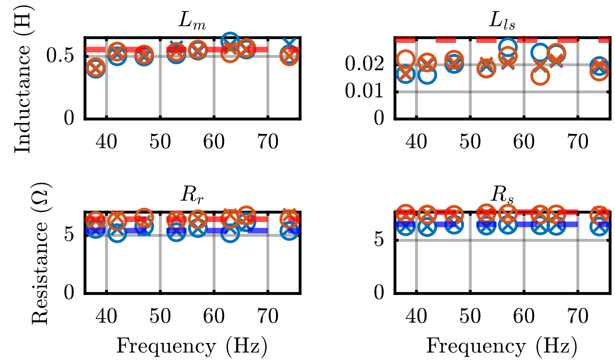
From the optimization procedure of (3), the stator $\hat{R}_s$ and rotor $\hat{R}_r$ resistances, the magnetizing inductance $\hat{L}_m$ and the leakage inductance $\hat{L}_{ls}$ are retrieved. The results are

TABLE II: Standard deviation of the parameters estimated.

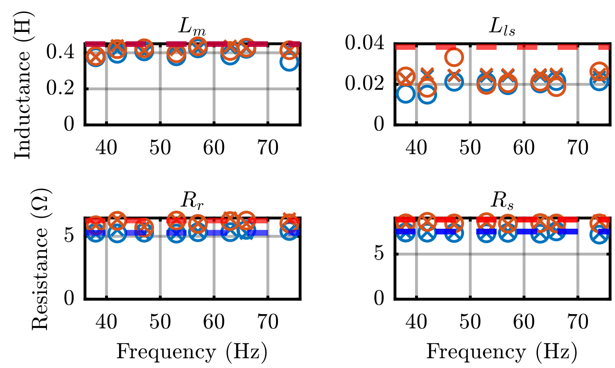
STD	DUT		AUX	
	PWM	FW	PWM	FW
$L_m(\%)$	11.23	11.45	8.56	6.50
$L_{ls}(\%)$	28.89	7.43	36.73	3.07
$R_s(\%)$	2.98	2.84	2.75	2.65
$R_r(\%)$	8.58	7.48	5.94	5.64

TABLE III: Coefficients of the mechanical friction and core resitances

	DUT at T_1	DUT at T_2	AUX at T_1	AUX at T_2
a	0.0117	0.0092	0.0117	0.0092
b	-0.0008	-0.0008	-0.0008	-0.0008
c	0.0913	0.0721	0.0913	0.0721
d	-0.0088	-0.0081	-0.0088	-0.0081
A	-0.0003	-0.0007	-0.0005	-0.0008
B	-0.0089	-0.0086	-0.0067	-0.0047
C	35.8385	45.2107	27.4369	32.2581



(a) *DUT*



(b) *AUX*

Fig. 7: Estimated parameters using the proposed method and IEEE Std 112 for two temperatures ($T_1 = 20°C$ and $T_2 = 65°C$). Color codes: ○ PWM, × FW, – IEEE standard, at T_1; ○ PWM, × FW, – IEEE Std 112, at T_2.

shown in Fig. 7. It is highlighted that the optimization of the harmonic content (2) is performed only when FW modulation is employed. The results obtained using the PWM modulation rely only on the analysis of the fundamental component (1).

To validate the proposed procedure, the parameters of the equivalent circuit have also been computed, following the IEEE Std 112 [3], which serves as a benchmark. Compared with IEEE standard values [3], the results obtained with the proposed method show consistent estimates across conditions, except for L_{ls}. Indeed, the IEEE procedure, limited to sinusoidal supply, cannot account for harmonics, while PWM introduces low-amplitude values of higher-order harmonics only. Therefore, FW analysis, which captures high-order harmonics, has been proven crucial for consistent L_{ls} estimation, as highlighted by the Standard Deviation (STD) of the results reported in TABLE II.

The accuracy of the estimated parameters can be verified by examining the power balance of the overall system (13).

First, the behavior of the mechanical losses for different temperatures has to be retrieved. As shown in Fig. 8a, the relationship between mechanical speed and friction coefficient derived from the methodology described in Section III is of the form of an exponential function, expressed as follows.

$$B(\omega_m) = a \cdot e^{(b \cdot \omega_m)} + c \cdot e^{(d \cdot \omega_m)} \tag{14}$$

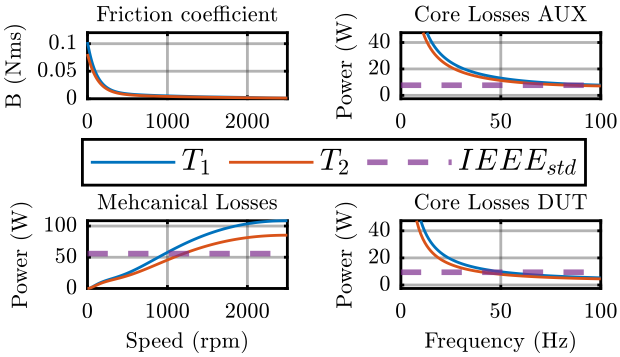
Then, the core resistances can be estimated following the previously described two-stage optimization process to minimize the overall system power balance (13). This way, the core losses are estimated as a function of both the electrical frequency f_e and the temperature, as shown in Fig. 8a. The coefficient derived from such optimization process are reported in Table III.

Finally, the total power balance (13) can be computed. The result of this operation should ideally be zero, meaning a perfect estimation of the losses and, consequently, of the parameters of the two machines. Therefore, the difference obtained by the power balance (13) is used as a comparison parameter to verify the accuracy of the proposed estimation procedure. The power balance error is shown in Fig. 8b. For both PWM and FW modulation results, the overall power error is negligible. However, it is evident that the parameters estimated by analyzing the higher-order harmonics yield a smaller power balance error. These results attest the significant contribution given by the analysis of the harmonic with the simplified circuit (2), shown in Fig. 2b.

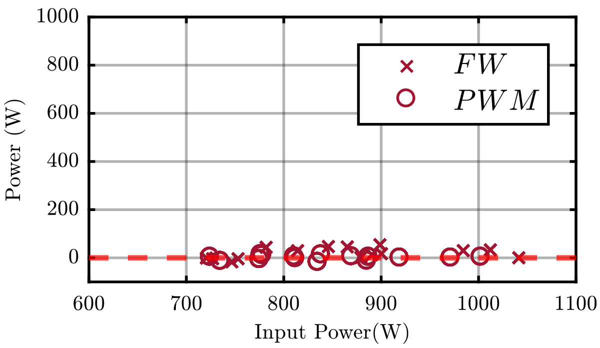
Additionally, from the estimated losses, the torque can be calculated as:

$$\hat{T} = \frac{\hat{P}_m}{\omega_m} = \frac{\hat{P}_{in} - \hat{P}_{jls} - \hat{P}_{jlr} - \hat{P}_c - \hat{P}_{m_{loss}}}{\omega_m} \tag{15}$$

where the mechanical losses $\hat{P}_{m_{loss}}$ have to be considered only for the machine that is working as a motor, because it is the only one compensating for them. The estimated torque can be compared with the measured one to further validate the proposed approach. As can be seen from Fig. 9, the proposed method achieves good accuracy in torque estimation as well.



(a) *Mechanical and core losses for the two motors*



(b) *Power balance error*

Fig. 8: Losses estimation: experimental results.

In Fig. 9 are also reported the values of the electromagnetic torque T_e obtained from:

$$T_e = \frac{3}{2} \cdot p \cdot (\lambda_\alpha \cdot i_\beta - \lambda_\beta \cdot i_\alpha) \tag{16}$$

where λ_α and λ_β are the stator fluxes in the stationary $\alpha\beta$ coordinates derived from the integration of the voltages $v_{\alpha\beta}$.

This formulation is typically used to estimate the torque in control applications. However, as can be seen in Fig. 9, (16) yields a torque error significantly greater than the one obtained with (15). In conclusion, it is highlighted that the proposed approach, which exploits (15) for torque calculation, can also efficiently pursue torque estimation, even better than the classical formulation (16).

V. Conclusion

This paper presents a novel method for the online estimation of IM parameters and losses exploiting the analysis of voltage harmonics injected by the inverter. A two-stage optimization algorithm that combines the PSO and IP methods is used to improve the accuracy of the estimation. FW modulation has been demonstrated to be advantageous to have a consistent estimation of the leakage inductance, thanks to the greater harmonic content. Furthermore, an improved accuracy in losses and torque estimation is demonstrated. Additionally,

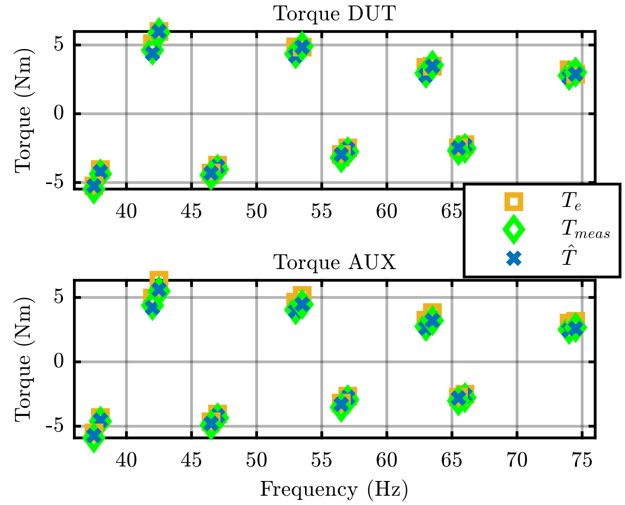


Fig. 9: Torque comparison: experimental results.

losses analysis has been carried out, taking into account the dependencies on speed, electrical frequency, and temperature. The estimated losses are subdivided by their contribution and source. This detailed evaluation distinguishes the proposed method from other methods in the existing literature for its completeness, accuracy, and ease of implementation in different contexts. The negligible total power balance and torque error, as well as consistency with IEEE Std 112, confirm the accuracy and feasibility of the proposed method.

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