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Energy-Efficient Field-Oriented Control for Induction Motors Taking into Account Core Losses

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Abstract—In the need to improve the energy efficiency on an induction motor, the control strategy constitutes an essential element by adapting the flux, according to the operating conditions, to reach the desired goal. The purpose of this paper is to present an energy-efficient field-oriented control structure for a squirrel-cage induction motor (IM), with improved energy efficiency while taking into consideration the effect of the core losses. Optimal flux is computed in off-line calculations based on an improved dynamic model of the IM including core losses. The optimal values are stored in a torque-speed table used to provide the flux reference of the control structure. Simulation results validate the proposed optimized field-oriented control (FOC) showing the improved energy efficiency and the reduction in power losses. Results are also experimentally validated on a 5.5kW IM test bench.

I. INTRODUCTION

The energy efficiency improvement of electrical systems is the main goal of several recent studies. Indeed, the European Climate & Energy package, has set itself a 20% energy savings target by 2020, and motor standards IE2 and IE3 were established to classify high and premium efficiency motors, setting a goal for all produced motors to be compliant with IE3 by 2017. Furthermore, the project targets were increased for 2030 to ensure continuous improvement.

Therefore, several control structures aiming to improve the energy efficiency of the IM are discussed in literature. These methods adapt the flux in the motor according to the operating conditions to reach the best efficiency point. The proposed techniques [1] differ however in the way of reaching the objective.

In a first approach, the Search Control (SC) is an optimization technique that tracks the lowest possible power of the motor by continuously measuring the input power, comparing it to its previous state, and varying the flux accordingly [2]-[3]. By doing so, the system converges to the best efficiency point, yet an average delay of 15 to 20 seconds is introduced to reach the optimal operating point. In addition, oscillations around the optimal flux value are observed when the control reaches the steady state. Therefore, some other versions of the basic SC are

established to improve its performance. For instance, artificial intelligence is used in several works [4]-[6] to enhance the search process through training a fuzzy logic controller, to reach the optimal operating point with reduced delays. Results show that the efficiency increases at reduced flux values while operating at low load torque.

Another optimization approach is the loss minimization control (LMC) [7]-[8], which computes the flux value corresponding to the minimum losses. Thus, the global losses derivative function is computed, and its zero gives the required optimal flux. Some works proposed enhancements to improve the performance in transient phases [9], and others proposed hybrid controllers using SC and LMC [10]-[11] to join the advantages of both structures. Results show that the LMC optimization algorithm increases the efficiency especially in the cases of reduced load torques. However, core losses are either neglected, or estimated using an approximate model, to simplify the calculations, thus, the obtained value of optimal flux is not always the most accurate possible.

Moreover, the best efficiency point tracking can be done through the Maximum Torque Per Ampere (MTPA) algorithm [12]-[13], which is also known as Minimum Current Per Torque (MCPT). It is based on curves computed to ensure the minimal value of current per torque, then the corresponding flux is applied to the motor. Some works [14] combine the MTPA strategy and the intelligent SC in a hybrid controller to join the advantages of both structures. Simulation and experimental results show efficiency increase and losses decrease using the MTPA. However, the approach can lack accuracy because of the approximate estimation of core losses or their neglectation, especially since these losses are known to increase when copper losses decrease with higher level of flux needed to obtain currents reduction.

Eventually, the effect of core losses is either omitted or taken into consideration through an approximate approach, in the proposed improvement methods. In this paper, an improved method of tracking the best efficiency point is applied to the indirect field-oriented control. It is based on a dynamic model of the induction motor including variable core losses. Optimal

flux values corresponding to the best efficiency are computed and stored in a torque-speed table used to optimize the control structure.

In section II, the optimization strategy is presented, based on the improved dynamic model of the IM which is used to compute the optimal rotor flux table. The latter is included in the control structure in section III, and simulation results are presented showing efficiency improvement and losses reduction. Experimental results are shown in section IV to validate the predicted improvement and the feasibility of the optimized control. Finally, conclusions are drawn.

II. OPTIMIZATION STRATEGY

A. Improved dynamic model of the IM

The classic dynamic model of the squirrel-cage induction motor is based on electrical, flux and mechanical equations, modeling the performances of the motor in different operating states and conditions. This model takes into account the effect of the copper and mechanical losses, but neglects the effect of the core losses to simplify the calculations. However, an accurate optimization study must consider the effect of the main losses. Thus, an improved IM model taking into account core losses through an equivalent resistor was developed and detailed in [15]. In the following, a brief summary describes the methodology used as well as the model obtained.

Indeed, core losses P_c vary with the magnetic field and the voltage frequency, according to the Bertotti model [16]-[17] as presented in (1). B_{max} and B_k represent respectively the maximal amplitude and the k th harmonic amplitude of the magnetic field, f the voltage frequency, and K_H , K_E and K_{ex} the core losses model coefficients representing respectively the Hysteresis effect, the Eddy Currents effect, and the excess core losses.

$$P_c(t) = K_H B_{max}^2(t) f(t) + K_E f^2(t) \sum_k k^2 B_k^2(t) + K_{ex} f^{1.5}(t) \sum_k k^{1.5} B_k^{1.5}(t) \quad (1)$$

For the rest of the study, the following parameters need to be known:

- R_s resistance of a stator phase winding
- R_r rotor resistance
- L_s self-inductance of a stator phase winding
- L_r rotor self-inductance
- M_{sr} stator-rotor mutual inductance
- σ motor dispersion coefficient $\sigma = 1 - \frac{M_{sr}^2}{L_s L_r}$

Thus, using the computed losses, and the motor parameters, the core losses equivalent resistor R_c is computed as in (2) to be used in the dynamic model of the IM. v_{sx} represent the stator voltages and i_{sx} the stator currents, with $x = \alpha, \beta$ the stationary reference frame axes.

$$R_c(t) = \frac{1}{P_c(t)} \left[\left(v_{s\alpha}(t) - R_s i_{s\alpha}(t) \right)^2 + \left(v_{s\beta}(t) - R_s i_{s\beta}(t) \right)^2 \right] \quad (2)$$

The equivalent resistor is included in the dynamic model of the IM in a parallel branch [18] as presented in Fig. 1. Thus, the obtained currents shown in (3) are used in the flux equations of the model, which are written as in (4)-(7). Φ represents the flux variable and s and r the stator and rotor subscripts. It should be noted that the voltage and mechanical equations of the classic model are kept unchanged.

$$\begin{cases} i_{2s\alpha}(t) = i_{s\alpha}(t) - \frac{1}{R_c(t)} \frac{d\Phi_{s\alpha}(t)}{dt} \\ i_{2s\beta}(t) = i_{s\beta}(t) - \frac{1}{R_c(t)} \frac{d\Phi_{s\beta}(t)}{dt} \end{cases} \quad (3)$$

$$\Phi_{s\alpha}(t) = L_s i_{s\alpha}(t) - \frac{L_s}{R_c(t)} \frac{d\Phi_{s\alpha}(t)}{dt} + M_{sr} i_{r\alpha}(t) \quad (4)$$

$$\Phi_{s\beta}(t) = L_s i_{s\beta}(t) - \frac{L_s}{R_c(t)} \frac{d\Phi_{s\beta}(t)}{dt} + M_{sr} i_{r\beta}(t) \quad (5)$$

$$\Phi_{r\alpha}(t) = L_r i_{r\alpha}(t) + M_{sr} i_{s\alpha}(t) - \frac{M_{sr}}{R_c(t)} \frac{d\Phi_{s\alpha}(t)}{dt} \quad (6)$$

$$\Phi_{r\beta}(t) = L_r i_{r\beta}(t) + M_{sr} i_{s\beta}(t) - \frac{M_{sr}}{R_c(t)} \frac{d\Phi_{s\beta}(t)}{dt} \quad (7)$$

Consequently, the obtained model includes the effect of core losses varying with the magnetic field and voltage frequency. Simulation and experimental results performed in [15] validate the improved dynamic model which shall be used in the rest of the study for optimal flux calculations.

B. Optimal flux

An accurate knowledge of the motor optimal flux in steady state, is a preliminary step to reach the best energy efficiency operating point. Therefore, the improved model of the IM is used to compute energy efficiency accurately for a given operating point in terms of flux, speed and torque.

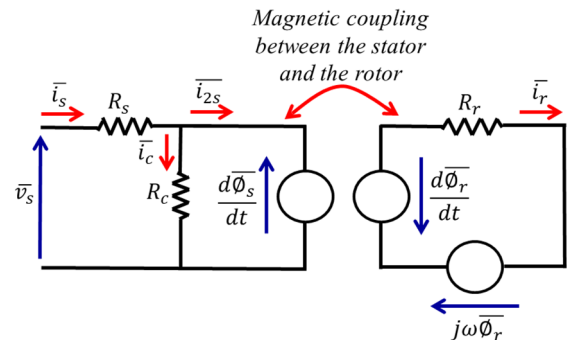


Fig. 1. Improved dynamic model representation including core losses.

In a second stage, the optimal flux values are computed for a series of operating points in the torque-speed plane, so that they could be used to optimize the control structures by imposing the suitable flux reference for each operating point. Thus, a calculation file is built to compute the optimal flux for each possible operating torque-speed point, by systematically scanning the possible flux values and storing the value that corresponds to the best computed efficiency. Then, the optimal flux values are stored in a torque-speed table.

This process should be done for each motor, since the optimal flux values are subject to magnetic circuit characteristics differences. In this study, rotor optimal flux values are computed for a 5.5kW IE2 Leroy-Somer IM, and a sample of the obtained look-up table is presented in TABLE I in per unit values. Results are also presented in Fig. 2 in the torque-speed plane for a clearer image of the optimal flux isocurves.

The obtained results show that the flux is optimized for low loads as for instance for values less than 0.65p.u. at base speed, and 0.33p.u. at 0.1p.u. speed. Above these values, the flux is optimal at 1p.u. Thus, it can be concluded that the efficiency optimization process only affects the cases of operation at low torque loads, since above the values shown in the results, the best efficiency is reached at rated flux, which is the case of the classic control strategy.

It should be noted that optimal stator flux values can be required in other cases according to the control structure. The obtained results are then similar to the rotor flux ones which is normal since the slight difference is due to the flux leakage.

III. OPTIMIZED FIELD-ORIENTED CONTROL

A. Optimal control structure

Control systems are the main structures which affect the motor performance to reach the required operating conditions. Several types of control systems are developed in literature, they differ in the control logic used or in the controlled variable. The optimization process can be therefore applied on the existing controls through the references, as it is the case of the proposed efficiency optimization using the optimal flux.

TABLE I
OPTIMAL FLUX TABLE IN P.U.

$T_L \backslash \Omega$	0.2	0.4	0.6	0.8	1
0.1	0.51	0.48	0.46	0.43	0.43
0.2	0.73	0.67	0.62	0.62	0.56
0.3	0.86	0.81	0.76	0.7	0.67
0.4	1	0.95	0.89	0.84	0.78
0.5	1	1	0.97	0.92	0.86
0.6	1	1	1	1	0.95
0.8	1	1	1	1	1
1	1	1	1	1	1

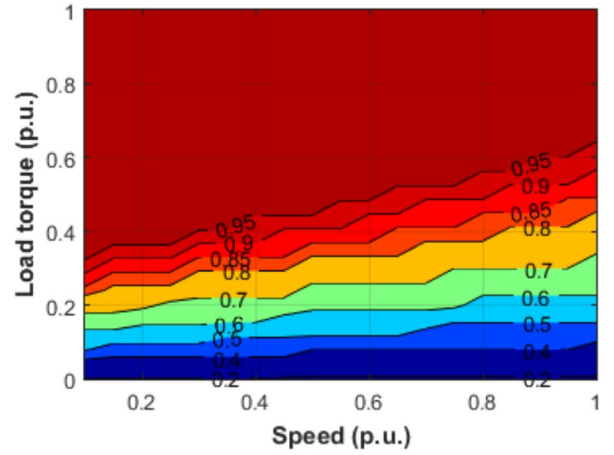


Fig. 2. Optimal flux isocurves.

Indeed, a similar study detailed in [19] was performed on the classic scalar control, using the computed stator flux optimal values for control flux reference.

The studied control structure in this section is the classic indirect FOC based on the rotor flux vector orientation according to the d -axis of the rotating reference frame. This type of control aims to obtain the optimal possible torque through this orientation, and to obtain a separately controllable system where the flux and torque can be regulated by different control variables. These goals can be reached through the model of this control structure [20] written in the $d-q$ rotating reference frame, and obtained from the dynamic model of the IM.

The rotor flux vector should be oriented with the d -axis according to this control structure [21], which corresponds to $\overline{\Phi}_r = \Phi_{rd}$, thus $\Phi_{rq} = 0$. Hence, in order to simplify the flux controller calculation, the rotor flux is represented by a rotor magnetizing current noted i_{mr} as in (8).

$$\Phi_{rd} = M_{sr} i_{mr} \quad (8)$$

Consequently, the control model is obtained in (9)-(13), where $T_r = L_r/R_r$ is the rotor time constant, ω_{dq} the angular speed of the $d-q$ rotating reference frame, and ω the electrical speed of the rotor.

$$v_{sd} = R_s i_{sd} + \sigma L_s \frac{di_{sd}}{dt} + (1 - \sigma) L_s \frac{di_{mr}}{dt} - \sigma L_s \omega_{dq} i_{sq} \quad (9)$$

$$v_{sq} = R_s i_{sq} + \sigma L_s \frac{di_{sq}}{dt} + (1 - \sigma) L_s \omega_{dq} i_{mr} + \sigma L_s \omega_{dq} i_{sd} \quad (10)$$

$$i_{mr} + T_r \frac{di_{mr}}{dt} = i_{sd} \quad (11)$$

$$\omega_{dq} = \omega + \frac{1}{T_r} \frac{i_{sq}}{i_{mr}} \quad (12)$$

$$T_{em} = \frac{p M_{sr}^2}{L_r} i_{mr} i_{sq} \quad (13)$$

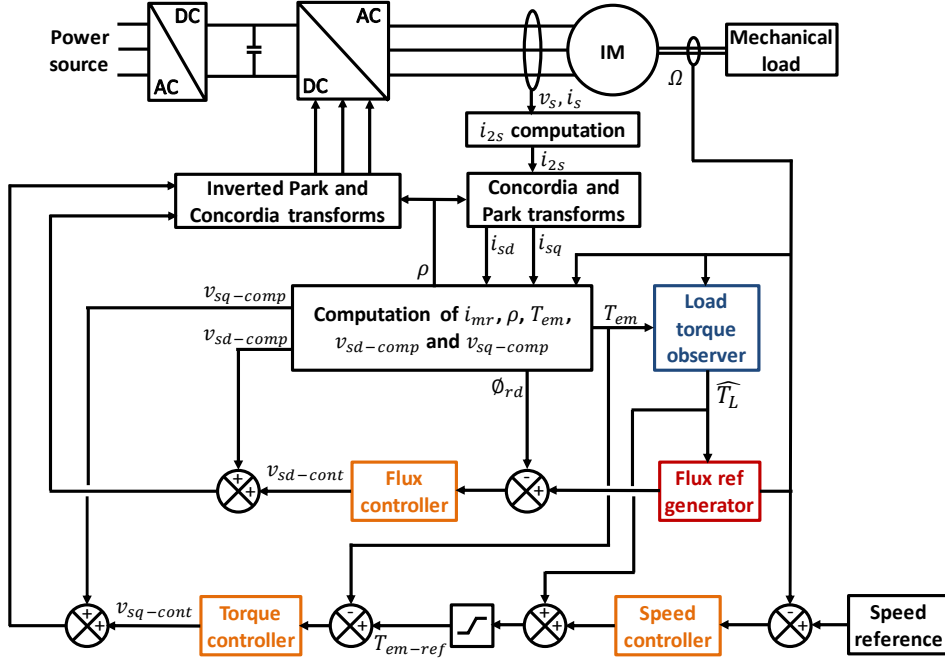


Fig. 3. Optimized field-oriented control structure.

The Park transform is performed using the ρ angle which is estimated by integrating the angular speed of the frame ω_{dq} . The overall control structure is summarized in Fig. 3. The d -axis stator current i_{sd} is the variable affecting the flux variation, and the electromagnetic torque is controlled by i_{sq} .

Furthermore, the control structure delivers to the inverter the computed voltage references v_{sd} and v_{sq} in (9) and (10) containing both i_{sd} and i_{sq} variables. Thus, these voltage equations are divided into a compensation factor $v_{sd,q-comp}$ and a controlling voltage $v_{sd,q-cont}$. The latter are used to compute the PI flux and torque controllers.

The proposed energy efficiency optimization of the FOC is based on the optimal rotor flux look-up table presented in section II, used to define the flux reference. It is introduced in the control system through the flux reference generator. It needs the actual speed and load torque values to continuously generate the rotor flux reference. These values are obtained through the speed sensor, and a Luenberger torque observer as shown in Fig. 3.

It is important to note that the described control structure is based on the classic dynamic model of the IM which does not include the effect of core losses. Thus, in order not to change the model equations, a compromise is made to introduce the effect of core losses. Indeed, since the voltage drop inside the stator resistor is not significant, the schematic representation of the IM in Fig. 1 can be transformed as in Fig. 4 to simplify the calculations. By doing so, the input currents become as in (14).

$$\bar{i}_{2s} = \bar{i}_s - \frac{\bar{v}_s}{R_c} \quad (14)$$

B. Simulation Results

At this point, the improved dynamic model of the IM presented in section II is simulated for the IE2 5.5kW studied motor with the optimized FOC detailed in this section.

The simulation is run with base speed reference, and 0.15p.u. torque load. The following results are presented in the steady-state zone, knowing that the IM is fed with rated flux at start-up. The optimization is then launched at time $t=3s$.

As a first result, the rotor flux variations obtained with the classic FOC presented in Fig. 5-a show that the control strategy is well verified, with the d -axis rotor flux equal to the rated reference value, and the q -axis flux equal to zero throughout the operation. Moreover, the optimization process shows the flux reduction corresponding to the operating torque-speed point.

Furthermore, the mechanical variables shown in Fig. 5-b are proven to stay unchanged despite the flux variation, which guarantees the required operating conditions to the load, with a slight disturbance at the beginning of the optimization process.

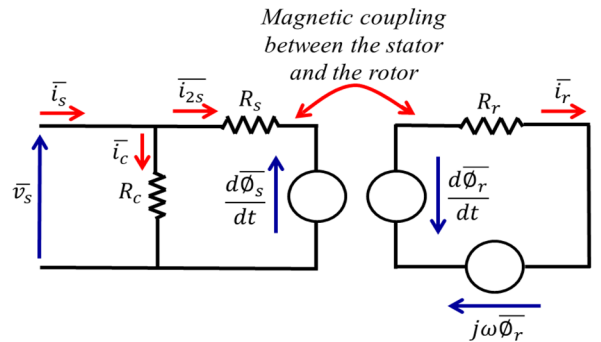


Fig. 4. Approximate IM schematic representation.

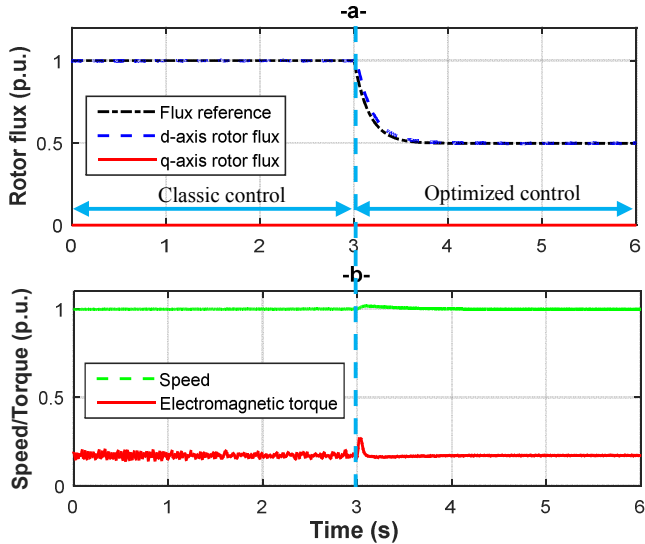


Fig. 5. Operating conditions. **a-** rotor flux, **b-** speed and torque.

The goal of this study remains in the energy efficiency optimization which is presented in Fig. 6 showing the decrease of the input power and the losses when varying the rotor flux. Indeed, core losses are the image of the flux which explains their decrease, and copper losses are affected by the currents which also decrease in that case with the flux reduction to reach the necessary current for the low load. However, cases of higher load torque are not similar, and losses reductions are not always that significant, since an excessive flux decrease is accompanied by currents increase.

Consequently, as a result of input power decrease while keeping on the mechanical variables unchanged for the load requirements, the energy efficiency of the system is proved to increase as shown in Fig. 6-d. An efficiency improvement of 8% is obtained with a satisfactory error of 0.1% compared to the theoretically computed value.

Finally, the simulation of the proposed FOC optimization process has proven to increase the energy efficiency of the studied motor. Thus, to prove the validity of this approach, experimental test results are presented in section IV.

IV. EXPERIMENTAL VALIDATION

The simulated optimized FOC is tested on an experimental test bench constituted of the studied 5.5kW IM, fed by an inverter and controlled by a dSpace structure, using suitable electrical and mechanical sensors to implement the control strategy.

Hence, tests are performed and presented in this section, to validate the optimized FOC proposed technique. Indeed, tests were carried at several operating points on the motor by applying the classic FOC using rated flux reference, then launching the optimization which adapts the flux to the operating conditions. Power and efficiency results for 0.5p.u. speed and 0.25p.u. torque operating point are shown in Fig. 7. Steady-state is established at the beginning with the classic FOC, then optimization is launched at $t=3s$.

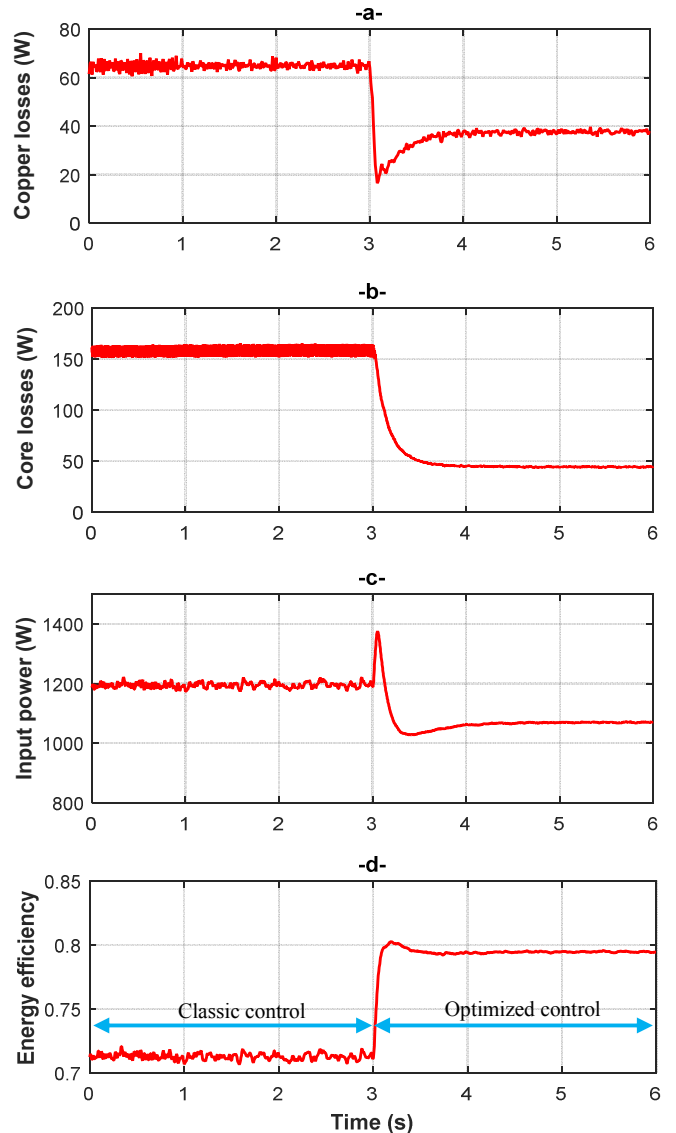


Fig. 6. Input power and losses. **a-** copper losses, **b-** core losses, **c-** input power, **d-** energy efficiency.

The effect of the optimization process is shown in the decrease of the input power by 19.4% and the increase of the energy efficiency by 5% with satisfactory errors between the simulation and the tests of 1.7% for the input power and 1% error for energy efficiency. These tests, also carried for several other operating points, validate the proposed optimized FOC.

V. CONCLUSION

The work presented in this paper proves the effectiveness of the proposed optimization technique for field-oriented controlled IM, improving the energy efficiency and reducing the losses and input power.

The best efficiency point is tracked for a range of operating points of the motor, based on an improved dynamic model of the IM which includes core losses. Then, the corresponding optimal rotor flux values are stored in a look-up table, to be applied to the control scheme as flux reference. Simulation

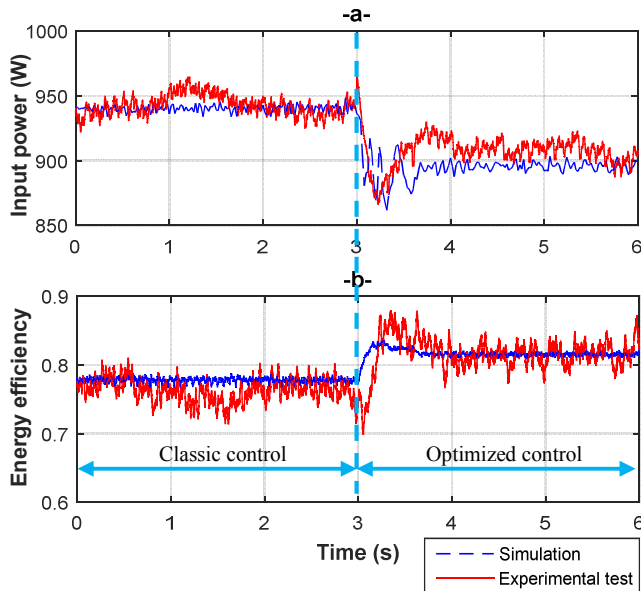


Fig. 7. Simulated and experimental optimized FOC results – 0.5p.u. speed, 0.25p.u. torque. a- input power, b- energy efficiency.

results confirm the increase in energy efficiency of the motor, as well as the decrease of input power and losses. Experimental tests are also carried, validating the proposed approach.

In future works, further tests will be conducted in order to validate the performances of the proposed technique especially for its use in industrial applications, and compare it to state-of-art methods.

VI. APPENDIX: MOTOR CHARACTERISTICS

The characteristics of the 5.5kW Leroy Somer squirrel-cage induction motor used for the experiments are:

$$\begin{aligned}
 U_n &= 400V & L_s &= 163mH \\
 I_n &= 11.9A & L_r &= 163mH \\
 N_n &= 1500Rpm & M_{sr} &= 157mH \\
 T_n &= 36.1N.m & J &= 0.0157 kg.m^2 \\
 p &= 2 & f_v &= 0.002928kg.m^2.s^{-1} \\
 R_s &= 0.86\Omega & T_0 &= 0.2471N.m \\
 R_r &= 0.83\Omega & &
 \end{aligned}$$

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