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Research paper

Improving efficiency through the optimization of energy losses in an induction machine for electric vehicle propulsion

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ABSTRACT

Research into industrial electricity consumption reveals that electric motors are the main actuators accounting for overall consumption expenditure. This underlines the importance of minimizing and optimizing the consumption of these electric motors, to the benefit of industry and, above all, contributing to environmental preservation. We present a strategy for improving efficiency by optimizing energy losses in an induction machine for electric vehicle propulsion. This involves incorporating a speed controller and a flux reference trajectory generator. The proposed control strategy dynamically adjusts the flux reference in real-time, intending to minimize the currents consumed by the machine and subsequently reduce losses, such as Joule losses due to currents and iron losses due to flux. The performance of the proposed control strategy is explicitly analyzed, as is its superiority to other strategies with fixed flow references. The effectiveness of the proposed controls has been verified by simulations and experimentally on a three-phase asynchronous motor. As an application, the optimal control of an asynchronous motor, fed by an inverter, is proposed for the propulsion of electric vehicles. The reduction in current demand on the machine controlled by optimal control means lower current consumption by the vehicle's batteries.

1. INTRODUCTION

Electricity accounts for 30% of the world's energy consumption. Electric motors consume around 56% of the electrical energy produced in industrialized countries. In addition, the induction motor (IM) accounts for 96% of the consumption of all these motors, which means that it consumes around 54% of the electrical energy produced in industrialized countries (Abrahamasen et al., 1998), so we thought it would be interesting to extend our approach to this type of electrical machine.

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Many countries have steadily improved their energy efficiency in the industrial sector, and this development has been supported by substantial resources, which have increased sharply in recent years, devoted to minimizing and making the most of heat losses. To achieve this, a great deal of effort is currently being devoted to advanced process modeling and control, in particular through the management and optimization of electrical machine control techniques. As a result, we need to focus on technological approaches and algorithms for reducing the energy consumption of electrical machines. In addition to control tools, work on motors is also a priority (the dimensioning aspect is outside the scope of this study), and our work will focus on the development of controls that meet energy optimization criteria.

Most of the electric motors used in industry are oversized, and many of them are subject to time-varying loads. This means in current practice, they work generally far from their nominal capacity, therefore far from their optimal performance, and consumption electricity consumption is excessive by reporting real needs indicated by (Juan, 2008). From this finding, it is clear that the study of optimizing the control of induction machines is indispensable for improving the efficiency of the industrial drive system and, consequently, improving the whole chain of production, transmission, and distribution of electrical energy.

Electrical energy losses in electrical machines are the subject of much research. Losses are much greater during acceleration mode (when the machine must be supplied with mechanical and magnetic energy). Controlling and identifying the amount of electrical energy lost in electrical machines enables us to determine the efficiency of the system, hence the solutions proposed to improve it.

For high-power drives, motors and converters are built to order. Choosing the type of converter to combine with the motor, the dimensions of the two, and the type of control system all become complex issues. Consequently, in electric drives, the power converter plays a key role in terms of performance and reliability. A wide variety of converter-motor combinations and structural solutions have been developed to improve conversion efficiency.

Most previous work on electric machine controls has approached these controls by considering a constant reference flux and assuming that the machine's magnetic characteristic is linear (A. El Fadili et al., 2010), We note that many electric drives work outside the nominal operating point, as the desired torque changes as a function of speed or position indicated by (Ramirez, 1998). However, the variation in magnetic flux over time induces heat release in the magnetic circuit, the origin of which is mainly attributable to iron losses and which adversely affects the efficiency of the structure. These losses are often amplified when static converters are used to power electrical machines, due to the high harmonic content associated with the supply quantities. Excess stored energy can be reduced by appropriately adjusting the flux level in the rotor. We can therefore consider other operating modes aimed at improving the machine's efficiency, bringing it closer to that of the synchronous machine (Boukhelifa, 2007).

The transition to electric mobility requires particular attention to optimizing propulsion systems to maximize energy efficiency and extend the range of electric vehicles (Zhu, et al., 2017; Xu, et al., 2016; Chen, et al., 2019). This article examines optimization techniques aimed at reducing energy losses in induction machines used in electric vehicles. With a focus on several key areas, such as optimal vector control, this study explores the latest strategies for minimizing energy losses. By integrating these approaches, significant gains in the energy efficiency of electric vehicles can be achieved, thus contributing to a more sustainable and environmentally friendly mobility.

2. OPTIMAL ENERGY CONTROL OF AN INDUCTION MOTOR

In the control of an induction machine, there is an additional degree of freedom, namely the selection of the machine's flux (optimum flux). The aim is to deduce the best flux references to apply to the machine to minimize losses in the IM (Tazerat et al., 2015). In the field of variable-speed electric motors, the power supply network, converter, motor, and control system form an indissociable unit, the purpose of which is to convert electrical energy taken from a network into mechanical energy as illustrated in Fig 1.

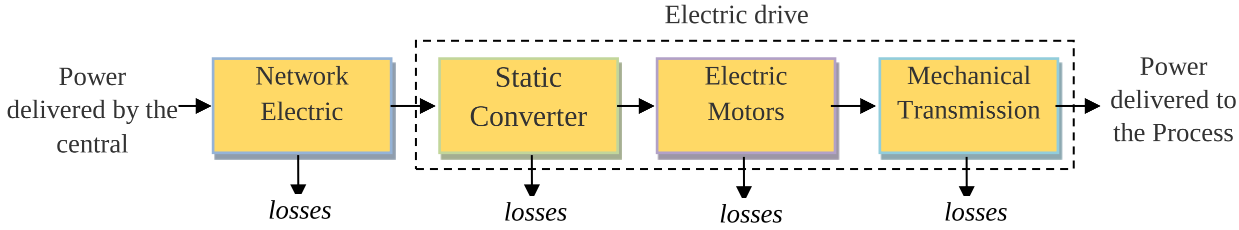

Fig 1. Flow of power through an electric motor drive

The principle of reducing losses by adapting the flux level is explained in Figure 2, (Kazmierkowski et al., 2002): it shows the flux and current vectors of a motor at low load and flux: nominal, medium, and low. The torque developed is the same in all three cases, represented by the hatched area, and is proportional to flux and rotor current Ψ_r Ir.

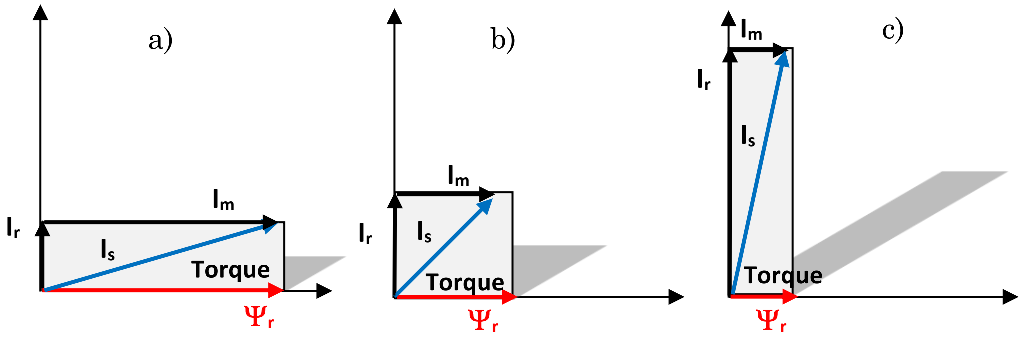

Fig 2. Torque production at low load with different flux levels:
(a) nominal flux; (b) medium flux; (c) low flux

At rated flux (Fig. (2. a)), the stator current is high, while the rotor current is low. In this case, stator iron and joule losses are high, while rotor joule losses are low. In Figure (2.b), rotor flux is reduced to 50% of its nominal value, while rotor current is doubled. This reduces iron losses but increases rotor joule losses. Magnetizing current is more than halved because the core is no longer saturated, so stator joule losses are also low. Overall, motor losses in figure (2.b) are lower than in figure (2.a). If rotor flux is further reduced, in Figure (2.c) iron losses are further reduced, but rotor and stator joule losses increase again, so total motor losses will also increase. Induction machine control techniques for variable-speed drives are well-covered in the literature. Vector control and direct torque control seem to be very practical and competitive methods, giving better dynamic (low transient) torque and flux responses. However, virtually all these strategies assume a constant rotor flux reference, i.e. independent of machine states, and are based on nominal point operation. In this case, the flux level is maintained at its nominal value. However, at low load, constant flux operation generates high iron losses; consequently, to maintain system efficiency, it is necessary to reduce the flux value at steady state (Kim et al., 1984; Kisko et al., 1983; Kirschen et al., 1985). It is possible to reduce the excess stored energy, by appropriately adjusting the rotor flux, so we can consider other modes of flux operation that aim to improve the machine's efficiency and bring it closer to that of the synchronous machine. Power factor and efficiency can be improved by making motor flux an increasing function of load (Gao, H., et al 2018; Wang, S., et al 2019)

2.1 Approach based on the search for the optimal value of the flow

This optimization method consists of minimizing the sum of losses noted in the steady state as it is shown in Figure 3 while imposing the necessary torque defined by the speed corrector (Kazmierkowski et al., 2002).

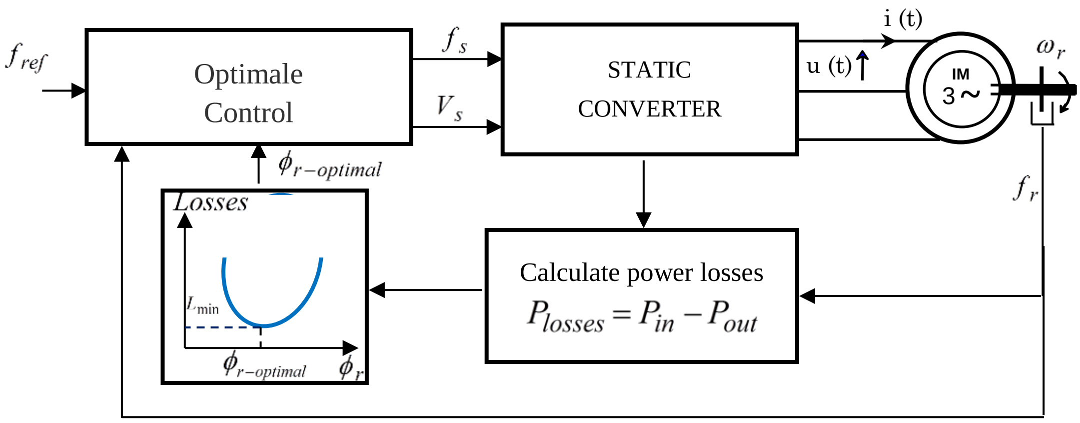

Fig 3. Diagram of the control strategy based on the search for the optimal flow

In steady-state, these losses (used as the criterion to be minimized) can be written as a function of the rotor flux ϕ_r and the electromagnetic torque T_e such as:

$$L_{loss} = \frac{(R_s + R_{fs})}{M^2}.\phi_r^2 + [\frac{R_s + \frac{R_r}{(1+\sigma_r)^2} + \frac{\sigma_r.R_{fs}}{(1+\sigma_r)}}{[p.(1-\sigma).(1+\sigma_s)]^2}].T_e^2.\phi_r^{-2} \tag{1}$$

Where: $\sigma_s = \frac{L_s - M}{M}$, $\sigma_r = \frac{L_r - M}{M}$ and $\sigma = 1 - \frac{M^2}{L_s.L_r}$.

The expression of the sum of losses as a function of flux and torque is given by equation (2)

$$L_{losses} = A.\phi_r^2 + \frac{B.T_e{}^2}{\phi_r^2} \tag{2}$$

The optimum rotor flux r ensuring minimum losses is obtained by solving equation (3):

$$\frac{\delta(L_{losses})}{\delta(\phi_r)} = 0 \tag{3}$$

Hence, we obtain

$$\phi_r^* = K_{opt}.\sqrt{|T_e|} \tag{4}$$

2.2 Power factor optimization

This technique is based on the fact that at the optimal operating point of the machine, several quantities can be measured and controlled quite easily, for example, the power factor (Bennoui, 2009). Since the value of the power factor is easy to determine, controlling this variable becomes an efficient and economical technique to ensure an optimal operating point as shown in the figure Fig 4.

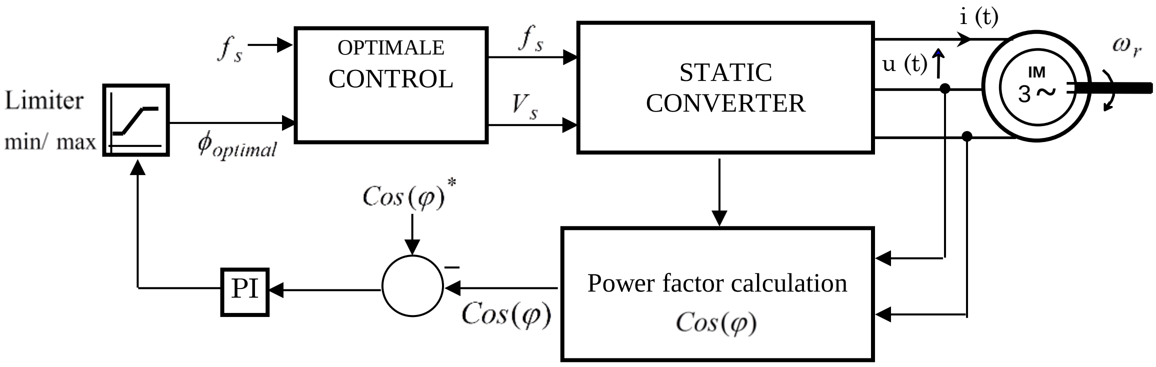

Fig 4. Diagram of optimal control strategy based on power factor

In the (d,q) reference frame, the power factor is defined by equation 5:

$$\cos\varphi = \frac{i_{ds}.V_{ds} + i_{qs}.V_{qs}}{\sqrt{V_{ds}^2 + V_{qs}^2}\sqrt{.i_{ds}^2 + i_{qs}^2}} \tag{5}$$

The power factor in the reference frame is given by :

$$\cos\varphi = \frac{i_{ds\alpha}}{i_s} \tag{6}$$

Assuming that the dynamics of establishing the flow are fast enough, the optimization algorithm can be formulated by :

$$i_m \cong i_{dsréf} = K_{EOF} \cdot \left| i_{qsréf} \right| \tag{7}$$

2.3 Optimal direct torque control

The principle of this control is the combination of the advantages of two control strategies, one of which is control by loss minimization in a Minimum Loss Model Controller (LMC) and the other is direct torque control of a DTC. The difference between the proposed DTC method and conventional DTC (Benbouhenni et al., 2019; Boukhalfa et al., 2022; Berabez et al., 2023) lies in the use of the optimal stator flux block obtained from the optimal rotor flux value as shown in Figure 5.

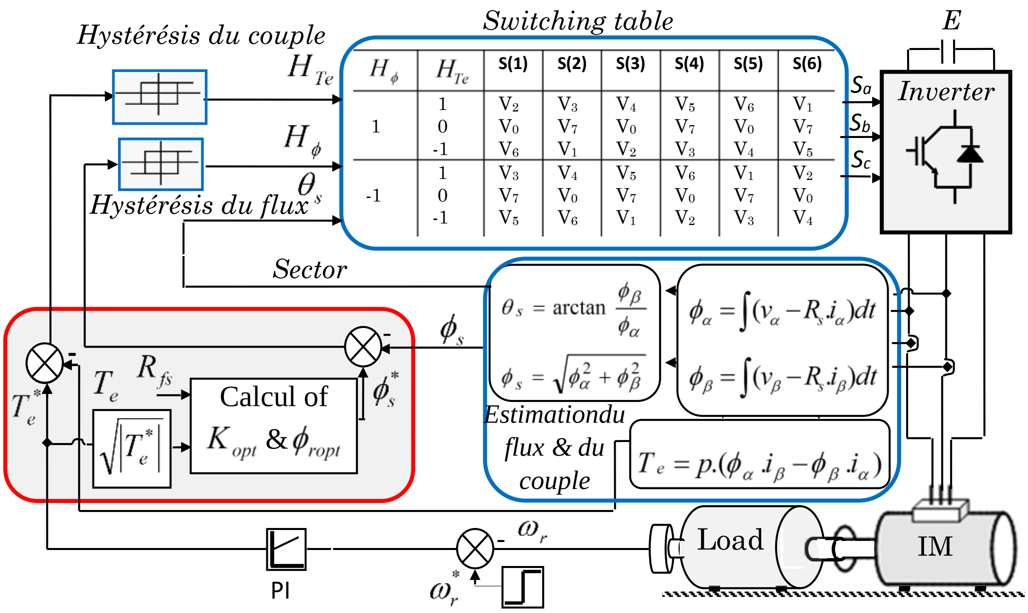

Fig 5. Optimal DTC block diagram with speed controller

From the model of the machine expressed in a reference frame linked to the stator, the stator flux vector is estimated from the following relationship:

$$\vec{\phi}_s(t) = \int_0^t (\vec{V}_s(t) - R_s\, \vec{i}_s(t))dt \tag{8}$$

The magnitude of the stator flux can then be estimated by:

$$\phi_s = \sqrt{\phi_{s\alpha}{}^2 + \phi_{s\beta}{}^2} \tag{9}$$

Where: $V_{s\alpha}$, $V_{s\beta}$, $i_{s\alpha}$ and $i_{s\beta}$ are stator voltages and currents along α and β stator axes respectively.

The phase angle of the stator flux can be calculated by:

$$\theta_s = \tan^{-1}\frac{\phi_{s\beta}}{\phi_{s\alpha}} \tag{10}$$

and the electromagnetic torque can be estimated by:

$$T_e = \frac{3}{2}.p.(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}) \tag{11}$$

Assuming that none of the motor parameters affects the rotor flux, we can yield $\phi_{r\text{-}opt}$, under a constant load torque, by setting the derivative of equation (2) to zero:

$$\frac{\partial L_{loss}}{\partial \phi_r} = 0 \tag{12}$$

Subject to:

$$\phi_{r\,\min} \le \phi_r \le \phi_{rated} \tag{13}$$

Thus, the relationship that minimizes the criterion L_{loss} can be obtained by:

$$\phi_{r-opt} = K_{opt} \cdot \sqrt{\left|T_{e-ref}\right|} \tag{14}$$

Where:

$$K_{opt} = \sqrt{\frac{M}{P.(1-\sigma).(1+\sigma_s)}} \sqrt{\frac{R_s + \dfrac{R_r}{(1+\sigma_r)^2} + \dfrac{\sigma_r R_{fs}}{(1+\sigma_r)}}{R_s + R_{fs}}} \tag{15}$$

Once the optimal rotor flux is calculated using equation (14), the optimal stator flux $\phi_{s\text{-}opt}$ can be deduced as:

$$\phi_{s-opt} = \phi_s^* = \frac{L_s}{M} \sqrt{\left(\phi_{r-opt}\right)^2 + \left(\frac{2}{3}\frac{\sigma.L_r}{P}\right)^2 \left(\frac{T_{e-ref}}{\phi_{r-opt}}\right)^2} \tag{14}$$

In the proposed approach, the reference flux will be set to this optimal value.

3. DIAGRAM OF THE PROPOSED CONTROL FOR AN ELECTRIC VEHICLE

To demonstrate the performance of the proposed approach, simulation work has been carried out. A simplified schematic diagram of the proposed Optimal DTC strategy, based on the loss minimization strategy, is shown in Figure 6. An electric car is powered by an electric motor supplied by batteries of varying sizes, depending on the manufacturer and the vehicle's power output. This battery is often coupled to an energy recovery module that recovers energy during braking and deceleration, thereby increasing the vehicle's range.

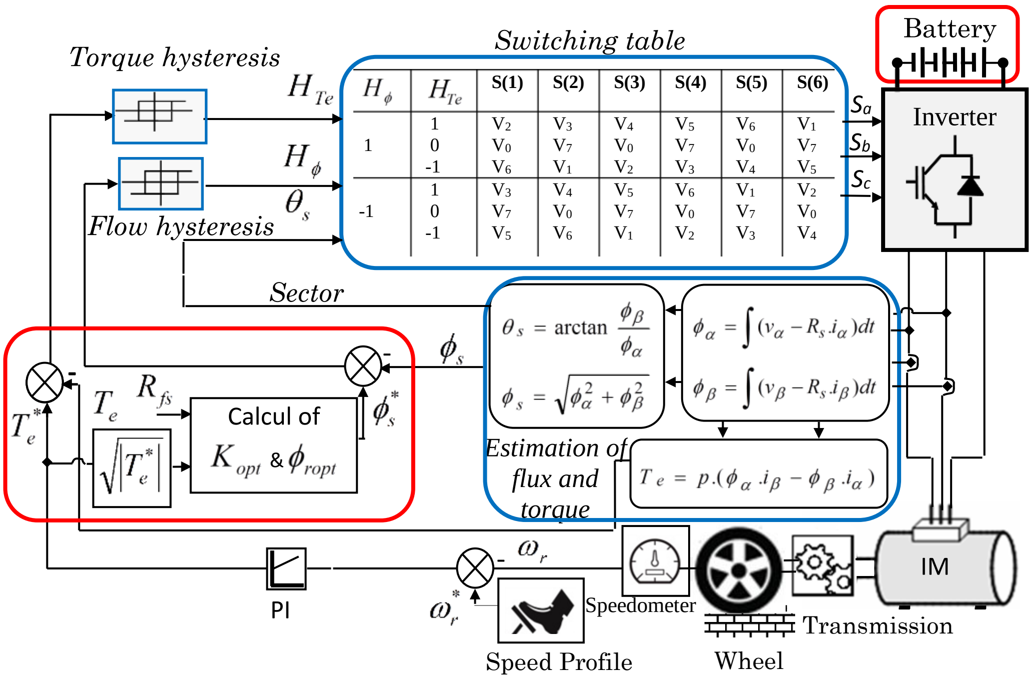

Fig 6. Schematic diagram of the optimal DTC of an asynchronous motor powered by an inverter for the propulsion of an electric vehicle

4. PRESENTATION OF THE EXPERIMENTAL TEST BENCH

The tests were carried out on a test bench Figure 7 consisting of (1) a Three-phase asynchronous machine (2) a Three-phase inverter, (3) a DC power supply (+15V and -15V) (4) Current and voltage sensors, (5) dSPACE 1104 interfacing box (6) Computer equipped with specific software, (7) Oscilloscope.

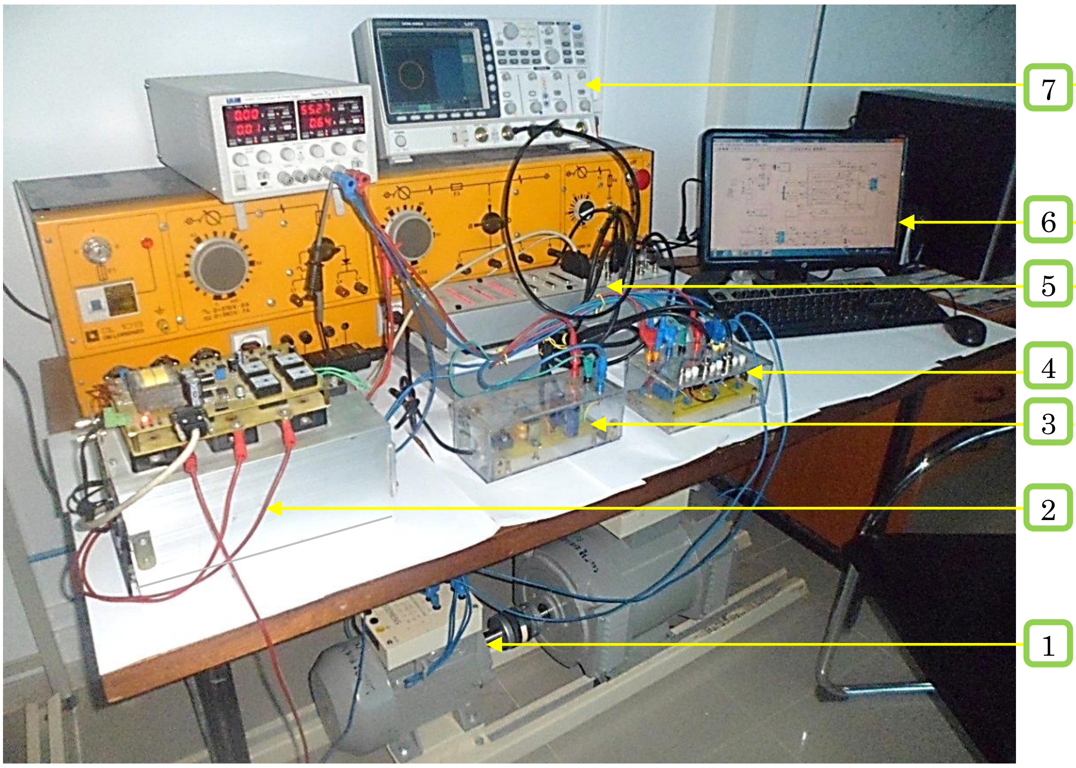

Fig 7. Experimental test bench

4.1 Experimental results of optimal direct torque control strategy

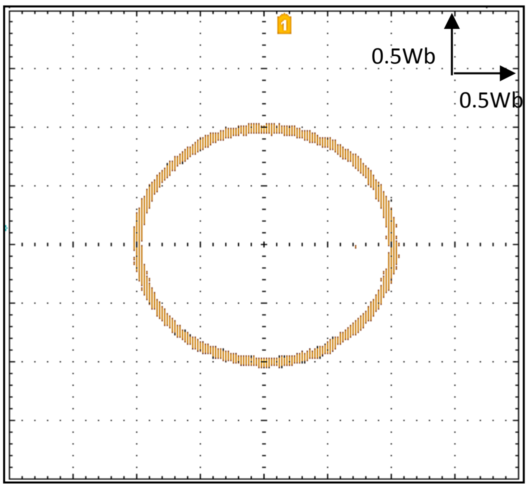

Fig 8. Circular stator flux with classical DTC

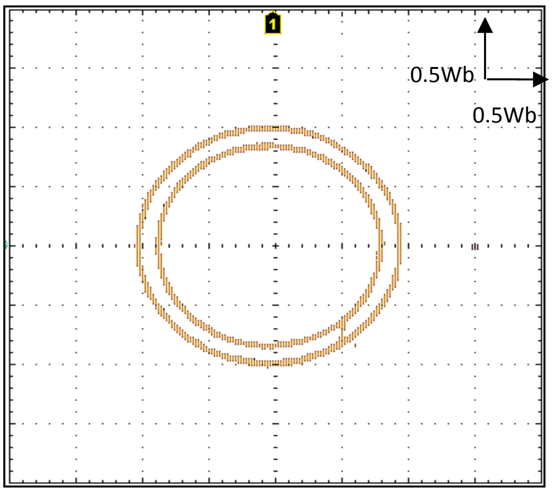

Fig 9. Circular stator flux with optimal DTC

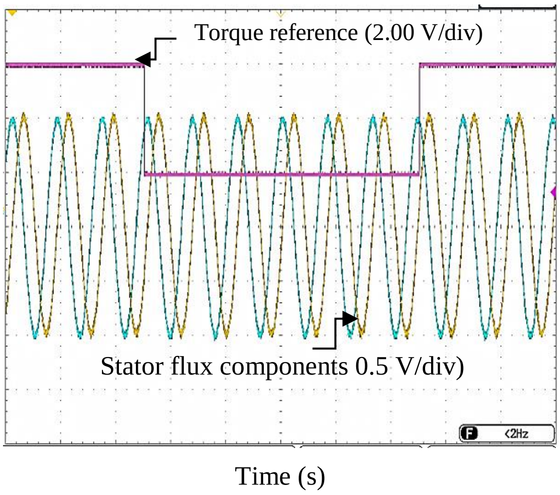

Fig. 10: Stator flux variation with DTC as a function of load

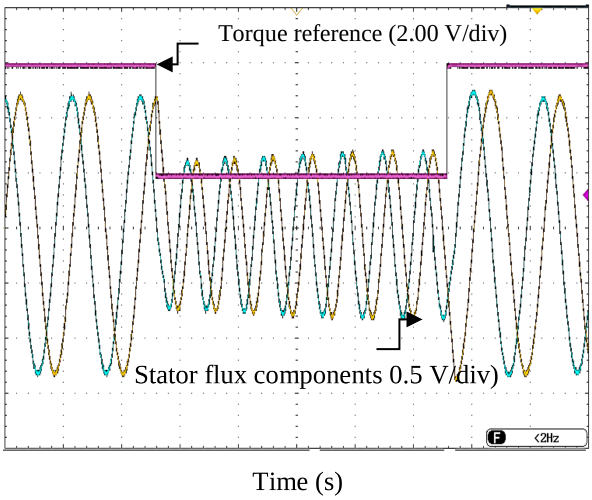

Fig 11. Stator flux variation with Optimal DTC as a function of load

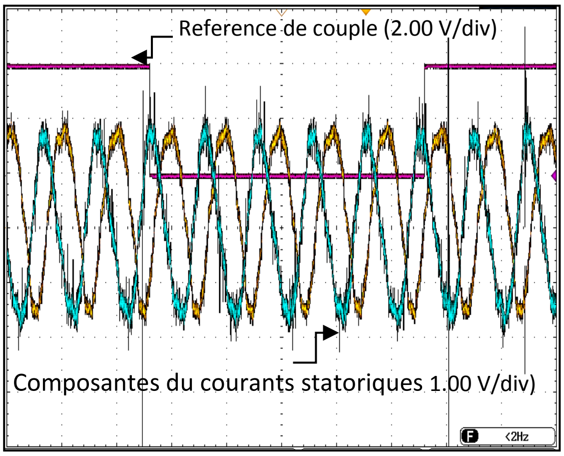

Fig 12. Variation of stator current with classical DTC depending on load

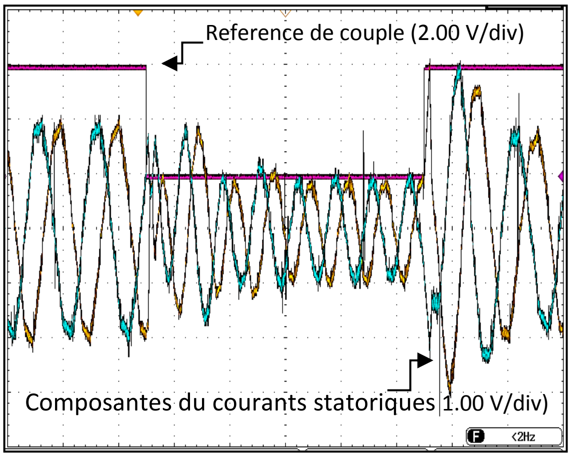

Fig 13. Variation of stator current with Optimal DTC as a function of load.

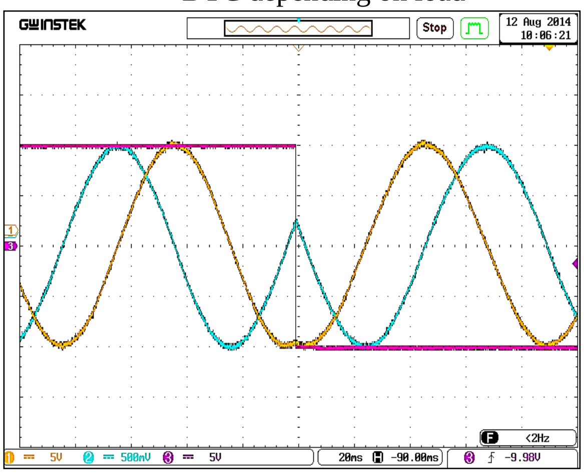

Fig 14. Stator flux accompanied by a torque reversal with Optimal DTC

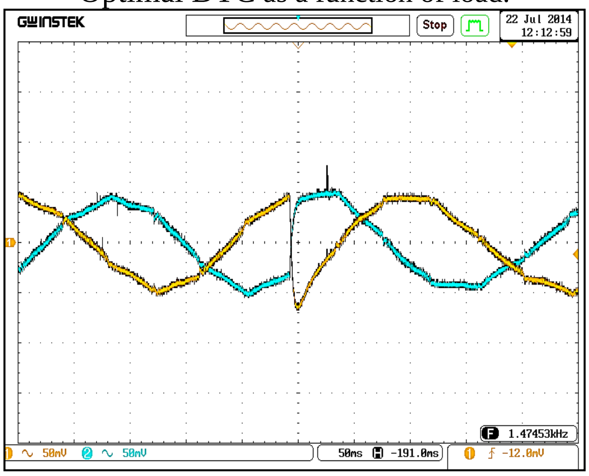

Fig 15. Stator current accompanied by a torque inversion with Optimal DTC

Capturing the control signal from the inverter switches for Optimal DTC control while showing the dead time by varying the oscilloscope time base, as shown in the following figures:

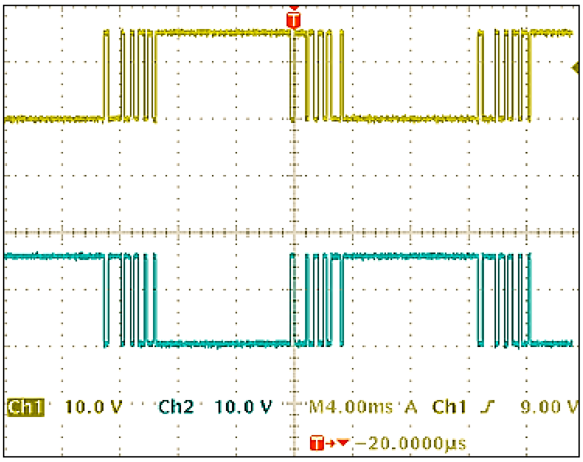

Fig 16. Control signals of two IGBTs of the same arm of the inverter with Optimal DTC

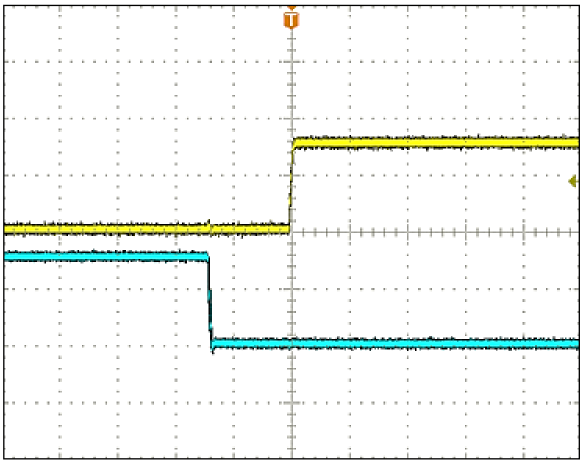

Fig 17. Dead time of two IGBTs of the same arm of the inverter with Optimal DTC

4.2 Interpretation of results

It can be seen from figures (8) to (17) that using the Optimal DTC application brings advantages in terms of controlling the stator and rotor fluxes, which vary according to load. This is to minimize iron losses in the machine, through the idea of minimizing the maximum value of induction and therefore minimizing flux (see figure (11)). Thus, we can see the reduction in currents consumed by the machine following the application of the Optimal DTC strategy (figure (13)) compared with the DTC strategy. A high current in the machine leads to an increase in Joule losses, while a high voltage results in an increase in iron losses.

CONCLUSION

The primary aim of this article was to introduce a novel optimal control strategy for an asynchronous machine, specifically focusing on direct torque control with energy loss minimization. Our proposed control strategy aims to ensure precise tracking of the torque reference trajectory by utilizing flux as a degree of freedom to minimize energy consumption in the asynchronous machine. Our practical contribution involved active involvement in setting up a test bench and conducting various phases of data acquisition (instrumentation), which facilitated the validation of our strategy.

One of the key applications targeted by this optimized direct torque control (ODTC) strategy is electric vehicles, which have been the subject of extensive research in recent years. This focus has been on leveraging asynchronous machine technology while maintaining exceptionally high dynamic performance.

In this study, we successfully optimized the direct torque control (DTC) of an asynchronous machine by minimizing overall losses. Additionally, we implemented a real-time vector control strategy using a dSPACE1104 card for an electric vehicle application. The simulation results and experimental tests yielded satisfactory outcomes, affirming the viability of combining DTC control with loss minimization strategies while preserving dynamic response.

Furthermore, we enhanced the efficiency of the drive system by optimizing flux, serving as a reference value for classical DTC techniques during steady-state conditions. This optimization was achieved through the design of an optimal flux determination block integrated into the classical direct torque control system.

Moreover, in instances where speed control mode is required instead of torque control, a speed regulator becomes necessary to generate the reference electromagnetic torque value. By amalgamating these techniques, the optimized direct torque control (ODTC) can be effectively deployed in electric vehicle propulsion systems to maximize efficiency, extend battery lifespan, and mitigate discharge, particularly during acceleration and deceleration phases.

ACKNOWLEDGEMENTS

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APPENDIX

Table 4. Parameters of the induction machine

Parameter	Value
Rated power	37 kW
Speed	1420 rpm
Voltage	230V
Stator current	I_s= 64 A
Stator resistance	R_s= 0.0851 Ω
Rotor resistance	R_r = 0.0658 Ω
Stator inductance	L_s= 0.0314 H
Rotor inductance	L_r= 0.0291 H
Mutual inductance	M= 0.0291 H
Number of pole pairs	P= 2

Table 5. Parameters of the EV and the traction system

Parameter	Value
Vehicle Mass	1540 Kg
Vehicle frontal area	1.8 m^2
Tire rolling resistance coeffi	0.015
Aerodynamic drag coefficient	0.25
Stokes coefficient	0.22
Air density	0.23 Kg/m^2
Wheel radius.	0.3 m
Transmission ratio.	2

NOMENCLATURE

V_s	Stator voltage vector
$V_{s\alpha}$	Componentstator voltage along α axis,V
$V_{s\beta}$	Componentstator voltage along β axis,V
$i_{s\alpha}$	Componentstator current along α axis, A
$i_{s\beta}$	Componentstator current along β axis, A
R_s	Stator resistance, Ω
L	Inductance, mH
T_e	Electromagnetic torque, Nm
p	Pair-pole number of the induction machine

Greek symbols

α	Nomination for axis
β	Nomination for axis
ϕ	Stator flux, Wb
θ_s	Angular position of flux, deg
ω_{ref}	Reference rotor mechanical speed, rad/s
ω_r	Rotor mechanical speed, rad/s

Abbreviations

AC	Alternating Current
DC	Direct Current
IM	Induction Machine
DTC	Direct Torque Control
EV	Electric Vehicle
IM	Induction Motors

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