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Equivalence Between the Rotor Flux-oriented Controlled Asynchronous Motor and the Separately Excited DC Motor: Modeling, Simulation and Experimental Validation

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ABSTRACT

The problem posed in this article is to make the electromechanical characteristics of the three-phase induction motor behave similarly to those of a separately excited DC motor, thereby enabling its use in applications where DC motors have traditionally demonstrated superior performance, such as electric railway traction.

For it ,

A. We transformed the three-axis system " abc " into a two-axis system " dq " in quadrature using the orthogonal transformation.

We have also made the rotor winding of the motor stationary although the rotor is in motion by using the rotation transformation (commutation transformation). The rotor winding has thus become pseudo stationary (falsely stationary) with respect to the rotor. This rotor winding becomes stationary but their axes rotate with the rotor, it is like in the DC motor.

The two transformations (orthogonal and commutative) led us to the change of variables.

B. We created the decoupling between flux and torque, ie we obtained a mathematical model of the three-phase asynchronous motor such that a direct current " i_d " regulates the flux and an orthogonal current " i_q " defines the torque as in the DC motor.

This is made possible thanks to Park's transformation.

C. We managed to independently control the term of the flux and that of the current to impose an electromagnetic torque by using the oriented flux command which consists in orienting the reference " dq " so as to cancel the component in flux quadrature ($\psi_{qs} = 0$ or $\psi_{qr} = 0$). Oriented flux control is done by suitably choosing the angle " θ_s " of rotation of Park so that the flux " ψ_s " or " ψ_r " is entirely carried on the direct axis " d ". Flux-oriented control is made possible thanks to advances in micro-electronics.

The goal to be achieved with flux-oriented control is therefore to obtain an "inverter-asynchronous motor" system which, by its characteristics, resembles that of the DC motor, but with the advantage of not using the commutator.

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KEYWORDS: *Behavioral equivalence, rotor field-oriented Control, asynchronous motor, current motor DC with separate excitation, modeling, simulation, experimental validation.*

1. INTRODUCTION

1.1. Context and Problem

Electric motors are now the central element of modern electromechanical power conversion systems. They are widely used in industrial applications, electric vehicles, railway networks, the mining industry, and automated manufacturing processes. Among the various available technologies, the three-phase induction motor has become dominant due to its robustness, simplicity of construction, relatively low cost, excellent energy efficiency, and low maintenance [1]. Advances in power electronics, static converters, and digital signal processors (DSPs) have significantly improved its dynamic performance through the development of modern vector control strategies [2].

Despite these advantages, the asynchronous motor naturally exhibits highly nonlinear behavior. The electromagnetic variables are coupled, and the rotor flux depends on the relative position between the rotor and the stator. This coupling makes independent control of electromagnetic torque and magnetic flux difficult, unlike the separately excited DC motor, whose structure allows for natural decoupling between these two quantities. This property explains why the DC motor has long been preferred in applications requiring rapid and precise control of torque and speed, particularly in electric traction systems.

The main drawback of the DC motor, however, lies in the presence of the commutator and brushes. These components cause additional losses, wear, electrical arcing, and require frequent maintenance, while also limiting high-speed performance and the machine's maximum power output. For these reasons, current research aims to achieve, with an asynchronous motor powered by an electronic converter, dynamic behavior similar to that of the DC motor, while retaining the mechanical and economic advantages of the asynchronous machine.

1.2. State of the art

Since the seminal work of Hasse, Blaschke, Park, Krause, Bose, and Hautier, Rotor Flux Oriented Control (RFOC) has become one of the reference methods for controlling induction motors [3]. This approach consists of applying the Park transformation to convert the three-phase system **abc** into a rotating frame **dq,** thus decoupling the components responsible for the electromagnetic flux and torque.

In recent years, much research has focused on improving the performance of this control strategy. Recent work has focused in particular on robust vector control, sensorless methods, adaptive techniques, predictive approaches (Model Predictive Control, MPC), and direct torque control (DTC) [4]. These studies show that vector control remains the most widely used strategy in applications requiring excellent speed accuracy, low torque ripple, and good transient performance.

In parallel, several recent studies have investigated the dynamic modeling of asynchronous motors, the identification of their electrical and thermal parameters, and their integration into railway traction systems and electric vehicles. Advances in simulation software, particularly MATLAB/Simulink, now make it possible to develop models that are increasingly representative of the actual behavior of electrical machines and to experimentally validate their performance.

However, most published work focuses primarily on improving the performance of control algorithms. Few studies explicitly analyze, from a behavioral perspective, how the asynchronous motor can be considered equivalent to a separately excited DC motor thanks to the flux-torque decoupling achieved through vector control. This gap is the main motivation for the present work.

1.3. Article objective

The objective pursued in this work is not only to apply the Park transformation. It is to show that after this transformation and the appropriate orientation of the rotor flux, the asynchronous motor acquires a dynamic behavior analogous to that of a separately excited DC motor, characterized by independent control of the magnetic flux and electromagnetic torque.

This behavioral interpretation is the originality of this study. While most works use the Park transformation as a simple mathematical tool to simplify motor equations, we show that it also allows us to establish a functional correspondence between the variables of the asynchronous motor and those of the DC motor.

1.4. Contribution of this article

This article proposes a behavioral analysis of the three-phase asynchronous motor controlled by rotor flux -oriented control in order to show that the "inverter-asynchronous motor" system can exhibit electromechanical characteristics analogous to those of a separately excited DC motor.

The scientific contribution of this study rests on four main points:

- the establishment of a mathematical model allowing to highlight the decoupling between the magnetic flux and the electromagnetic torque thanks to the Park transformation;
- the theoretical demonstration of the independence of the flux with respect to the angular position of the rotor in the rotating frame **dq;**
- validation of the behavior obtained by numerical simulation under MATLAB/Simulink from an

asynchronous motor intended for railway traction;

- the comparison of simulation results with experimental tests carried out on laboratory electrical machines.

The study thus highlights that rotor flux -oriented control allows the asynchronous motor to reproduce the main dynamic characteristics of the DC motor while eliminating the constraints related to the mechanical commutator.

1.5. Article organization

The remainder of the article is organized as follows. Section 2 presents the development of the mathematical model of the asynchronous motor in the rotating frame **dq,** as well as the principle of flux-torque decoupling. Section 3 presents the numerical simulation results, their experimental validation, and a discussion of the performance obtained. Finally, Section 4 presents the main conclusions and future research directions.

2. MATHEMATICAL MODELING OF THE ASYNCHRONOUS MOTOR AND BEHAVIORAL EQUIVALENCE WITH THE DC MOTOR

2.1. Principle of modeling

The dynamic behavior of the three-phase asynchronous motor is generally described in the natural frame **abc,** in which the electrical equations are strongly coupled and depend explicitly on the angular position of the rotor [5]. This representation faithfully reproduces the physical operation of the machine, but it remains poorly suited to the design of control laws due to the coupling between the electrical and mechanical variables.

To simplify this modeling, the literature proposes the successive use of the Clarke transformation, then the Park transformation. The Clarke transformation allows the three-phase system **abc to be replaced** by an orthogonal two-phase system **αβ,** while the Park transformation performs a rotation of this frame in order to obtain the rotating system **dq** synchronized with the flux chosen as a reference [6].

In this new reference frame, electrical quantities become quasi-stationary in steady state, which considerably simplifies the motor equations and facilitates the development of modern vector control strategies. This representation now forms the basis of Rotor Flux Oriented Control (RFOC), Direct Torque Control (DTC), and predictive methods (MPC).

2.2. Development of the mathematical model of asynchronous motors

Regarding the development of the mathematical model of asynchronous motors, we exploited the Park transformation and the Hasse and Blaschke oriented rotor flux control.

2.2.1. Park Transformation

Let us consider the classical three-phase model of the asynchronous motor in the abc frame (Figure 1) [6].

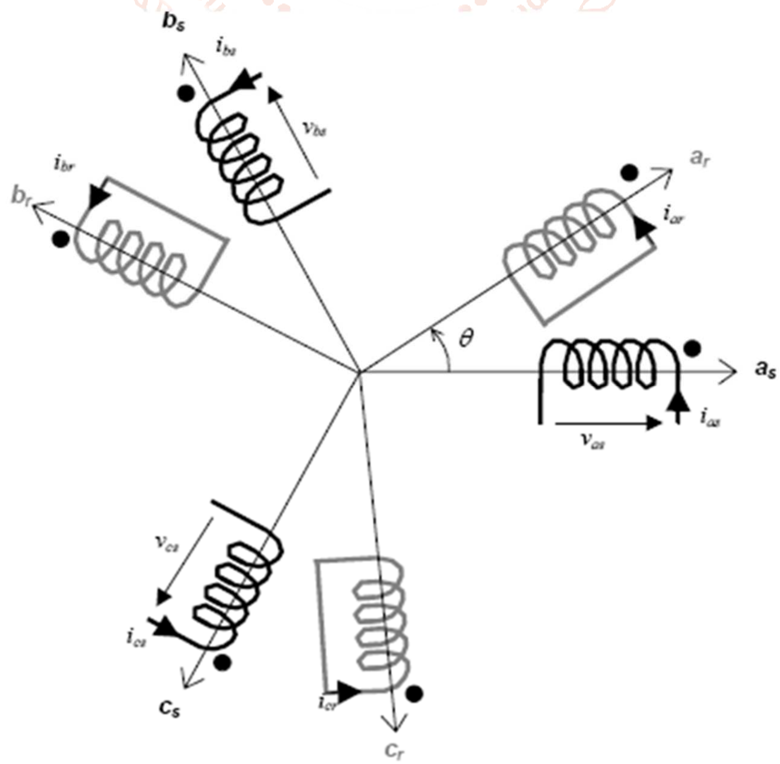


Fig. 2.1. Representation of the stator and rotor windings [6]

Or

- ***θ:*** electric angle between the magnetic axis " a_s " *of the first* stator winding and the magnetic axis " a_r " of the first rotor winding;
- a_s, b_s, c_s: magnetic axes of stator windings;
- a_r, b_r, c_r: magnetic axes of rotor windings.

stator and rotor fluxes are expressed in matrix form as:

$$\begin{bmatrix}\psi_{as}\\ \psi_{bs}\\ \psi_{cs}\\ \psi_{ar}\\ \psi_{br}\\ \psi_{cr}\end{bmatrix}=\begin{bmatrix}L_{as} & M_s & M_s & M_1 & M_3 & M_2\\ M_s & L_{as} & M_s & M_2 & M_1 & M_3\\ M_s & M_s & L_{as} & M_3 & M_2 & M_1\\ M_1 & M_2 & M_3 & L_{ar} & M_r & M_r\\ M_3 & M_1 & M_2 & M_r & L_{ar} & M_r\\ M_2 & M_3 & M_1 & M_r & M_r & L_{ar}\end{bmatrix}\begin{bmatrix}i_{as}\\ i_{bs}\\ i_{cs}\\ i_{ar}\\ i_{br}\\ i_{cr}\end{bmatrix} \quad [7]\ (2.1)$$

with $M_1 = M_{sr}\cos\theta$; $M_2 = M_{sr}\cos\left(\theta-\frac{2\pi}{3}\right)$ and $M_3 = M_{sr}\cos\left(\theta+\frac{2\pi}{3}\right)$

where the inductance matrix depends on the electrical position of the rotor.

This dependency introduces a coupling between the electrical and mechanical equations and constitutes one of the main difficulties in controlling the asynchronous motor.

Applying Park's transformation eliminates this angular dependence by projecting the electrical variables into a rotating frame synchronized with the rotor flux.

The Park transformation matrix is given by:

$$[A]=\frac{2}{3}\begin{bmatrix}\cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right)\\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right)\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{bmatrix} \quad \text{And} \quad [A]^{-1}=\begin{bmatrix}\cos\theta & -\sin\theta & 1\\ \cos\left(\theta-\frac{2\theta}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) & 1\\ \cos\left(\theta+\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) & 1\end{bmatrix} \quad [8]$$

After applying the Park transform to the magnetic flux formula

$[\psi_{dqos}]=[A_s].[\psi_{abcs}]$ And $[\psi_{dqor}]=[A_r].[\psi_{abcr}]$ The equations for the flows become:

a). $$\begin{cases}\psi_{ds}=M.i_{dr}+L_{cys}.i_{ds}\\ \psi_{qs}=M.i_{qr}+L_{cys}.i_{qs}\end{cases} \quad (2.2)$$

b). $$\begin{cases}\psi_{dr}=M.i_{ds}+L_{cyr}.i_{dr}\\ \psi_{qr}=M.i_{qs}+L_{cyr}.i_{qr}\end{cases} \quad (2.3)$$

with $L_{cys}=L_{as}-M_s$: cyclic self-inductance of the stator;

$L_{cyr}=L_{ar}-M_r$: cyclic self-inductance of the rotor;

$M=\frac{3}{2}M_{rs}$: cyclic mutual inductance between stator and rotor;

Two fundamental consequences are immediately apparent.

First, the coefficients dependent on the electric angle disappear completely.

Secondly, the direct (**d**) and quadrature (**q**) components become independent, which is the necessary condition for flux-torque decoupling.

This property represents the theoretical basis of all modern vector controls.

2.2.2. Decoupling of flux and torque

The electromagnetic torque of the asynchronous motor can be obtained from the electromagnetic power developed.

$$P_e = v_{as}.i_{as} + v_{bs}.i_{bs} + v_{cs}.i_{cs} + v_{ar}.i_{ar} + v_{br}.i_{br} + v_{cr}.i_{cr}$$ [9] (2.4)

with

$$\begin{cases} v_{as} = R_s i_{as} + \frac{d\psi_{as}}{dt} \\ v_{bs} = R_s i_{bs} + \frac{d\psi_{bs}}{dt} \\ v_{cs} = R_s i_{cs} + \frac{d\psi_{cs}}{dt} \end{cases} \text{And} \begin{cases} v_{ar} = R_r i_{ar} + \frac{d\psi_{ar}}{dt} \\ v_{br} = R_r i_{br} + \frac{d\psi_{br}}{dt} \\ v_{cr} = R_r i_{cr} + \frac{d\psi_{cr}}{dt} \end{cases}$$ [5]

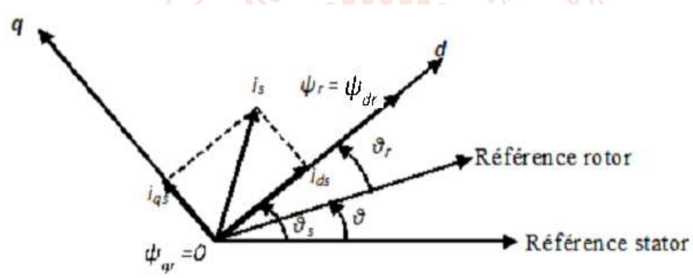
After applying the Park transform to these formulas, we obtain:

$$C_{ém} = \frac{3}{2} p \frac{M}{L_{cyr}} (\psi_{dr}.i_{qs} - \psi_{qr}.i_{ds})$$ (2.5)

The expression for the pair still retains a certain coupling between the variables in the **dq frame** ,

To obtain a structure analogous to that of the DC motor, the principle of oriented rotor flux control is applied. The rotating frame of reference is chosen such that the quadrature component of the rotor flux is zero (Figure 3) [10]:

$$\psi_{qr} = 0 \Rightarrow \psi_{dr} = \psi_r$$



Rotor flux oriented on the axis "d" (source: Blaschke) [10]

By substituting and in the mathematical model of the asynchronous motor in the " *dq* " frame, we obtain:

$$\psi_{qr} = 0 \qquad \psi_{dr} = \psi_r$$

$$\frac{d\psi_r}{dt} = -\left(\frac{R_r}{L_{cyr}}\right).\psi_r + \left(\frac{M.R_r}{L_{cyr}}\right).i_{ds}$$ (2.6)

$$C_{ém} = \frac{3}{2} p \frac{M}{L_{cyr}} (\psi_r.i_{qs})$$ [11] (2.7)

$$(\omega_s - \omega) = \frac{M.R_r}{\psi_r.L_{cyr}} i_{qs}$$ (2.8)

with $M = \frac{3}{2} M_{sr}$ And $L_{cyr} = L_{ar} - M_r$

Upon examination of relations (2.6) and (2.7), we observe that:

- the component " i_{ds} " exclusively controls the rotor flux " ψ_r »;
- the component " i_{qs} " exclusively controls the electromagnetic torque.

This results in two practically independent variables, exactly as in a separately excited DC motor where the excitation current determines the flux while the armature current determines the torque. This behavioral analogy constitutes the essential result of this study.

2.2.3. Physical interpretation

The Park transformation does not, of course, alter the mechanical structure or the electromagnetic configuration of the motor. The motor remains an asynchronous machine powered by a three-phase inverter.

However, from a control perspective, the dynamic behavior becomes practically identical to that of a DC machine. Thus,

- The couple can be imposed instantly;
- the speed can be regulated with excellent precision;
- The interactions between flux and torque are greatly reduced.

rotor flux-oriented control is now widely used in high-power industrial drives, electric vehicles, and modern railway traction systems.

Table 2.1: Comparison between the transformed asynchronous motor and the direct current motor.

Transformed asynchronous motor	DC motor
• Magnetic flux equation for the transformed asynchronous motor: $\frac{d\psi_r}{dt} = -\left(\frac{R_r}{L_{cyr}}\right).\psi_r + \left(\frac{M.R_r}{L_{cyr}}\right).i_{ds}$ with $M = \frac{3}{2}M_{sr}$ And $L_{cyr} = L_{ar} - M_r$ • Torque equation for the transformed asynchronous motor: $C_{ém} = \frac{3}{2}p.\frac{M}{L_{cyr}}(\psi_r.i_{qs})$ • Rotation speed of the converted asynchronous motor: $(\omega_s - \omega) = \frac{M.R_r}{\psi_r.L_{cyr}}i_{qs}$	• Magnetic flux equation for the DC motor $\psi_e = L_e.i_e$ • Torque equation for the DC motor: $C_{ém} = \frac{p}{a}.\frac{N}{2\pi}\psi_e.i_i$ • DC motor rotation speed: $\omega = \frac{\pi.a}{30\ N}\frac{E}{\psi_e}$

We can now independently control the magnetic flux and torque of the asynchronous motor.

3. RESULTS, INTERPRETATION, EXPERIMENTAL VALIDATION AND GENERAL DISCUSSION

3.1. Block diagram of the simulation

Regarding the numerical simulation, we used the diagram in Figure 4 with the three-phase asynchronous motor whose characteristics are as follows:

- motor type: three-phase squirrel cage asynchronous motor;
- nominal voltage: 3*1000 V;
- rated current: 175 A;
- nominal power factor: 0.87;
- Nominal useful power: 221 kW;
- frequency: 50 Hz;
- nominal speed: 1440 rpm;
- number of even poles: p = 2;
- coefficient of friction: f = 0.08 Nms.
- stator resistance per phase:
- R_s = 0.01485 Ω;
- rotor resistance referred to the stator per phase: $R_r^{'}$ = 0.009295 Ω;
- stator leakage inductance per phase: L_s = 0.3027 mH;
- rotor leakage inductance referred to the stator per phase: $L_r^{'}$ = 0.3027 mH;
- mutual (magnetizing) inductance stator-rotor: M = 10.46 mH;
- moment of inertia of rotating masses: J = 3.1 $kg.m^{2}$;

To carry out this simulation, we translated the mathematical model into blocks, each of which is associated with a specific MATLAB function [12].

The program, designed under the Matlab-Simulink environment, groups together all the variables and events describing the course of the process [13].

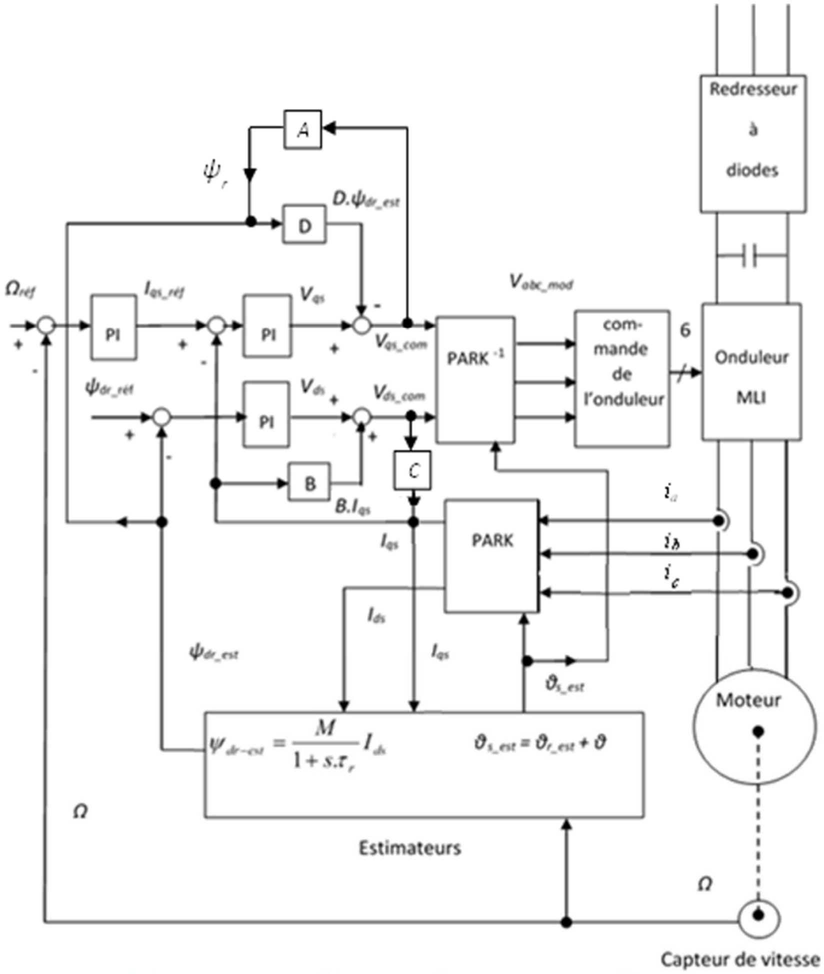


Fig. 3.1: Functional diagram of a rotor flux -oriented control [14]

3.2. rotor flux- oriented control model

The numerical simulations were performed using MATLAB/Simulink based on the mathematical model developed in the previous section. The electrical and mechanical parameters correspond to those of a 221 kW three-phase asynchronous railway traction motor.

The main objective of this simulation is to verify that the Park transformation associated with rotor flux - oriented control effectively achieves dynamic behavior similar to that of a separately excited DC motor. Three representative scenarios were studied to evaluate the system's performance under different operating conditions:

- zero-speed operation under constant load;
- variation of the resisting torque at an imposed speed;
- speed variation under constant resistive torque.

These tests allow for the simultaneous evaluation of speed regulation, torque tracking, and flux-torque decoupling performance.

3.3. Simulation results

3.3.1. Zero-speed operation under constant load

Figure 3.2 shows the system response for a reference speed of 0 rpm and a constant resistive torque of 1200 N·m.

Legend in blue: curves of reference quantities (setpoints);

In red: curve of measured quantities.

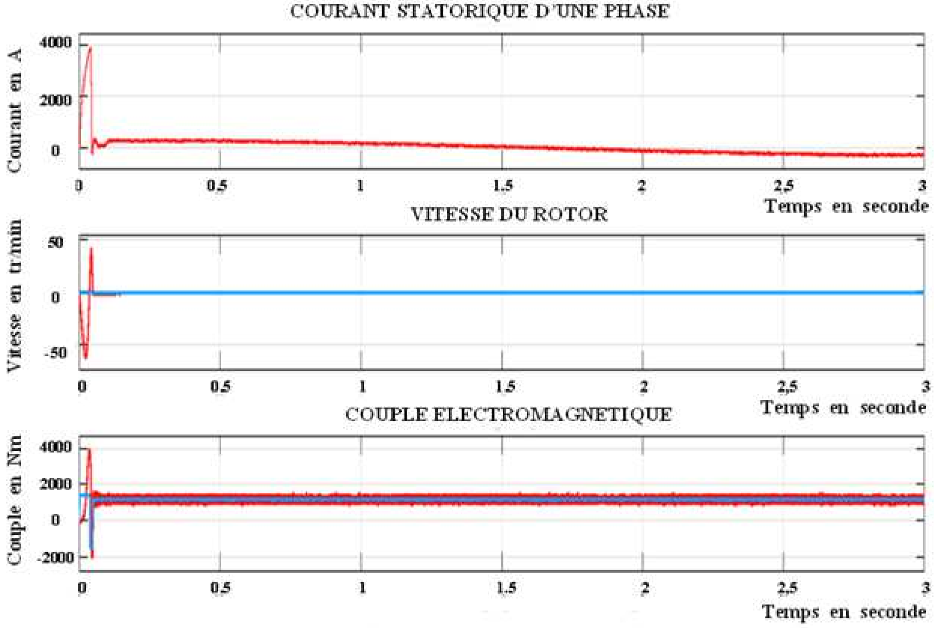


Fig. 3.2: Zero rotational speed and constant load of 1200 Nm

The results show that the motor instantly develops a significant electromagnetic torque while the speed remains zero. This observation is a remarkable property of rotor flux -oriented control.

In a conventional asynchronous motor directly supplied by the grid, the torque available at very low speeds remains severely limited by slip and the coupling between flux and current. In contrast, thanks to the decoupling achieved in the **dq frame, the direct current maintains a practically constant** rotor flux, while the quadrature current exclusively controls the torque. The resulting behavior then becomes comparable to that of a separately excited DC motor, capable of delivering its maximum torque immediately upon startup. This result is of particular interest for railway traction applications, electric vehicles, industrial conveyors, and lifting systems where high torque is required from the moment of inception.

3.3.2. Variation of resisting torque at constant speed

Figure 3.3 illustrates the behavior of the motor when the resistive torque varies gradually while the reference speed remains constant.

Legend in blue: curves of reference quantities (setpoints);

In red: curve of measured quantities

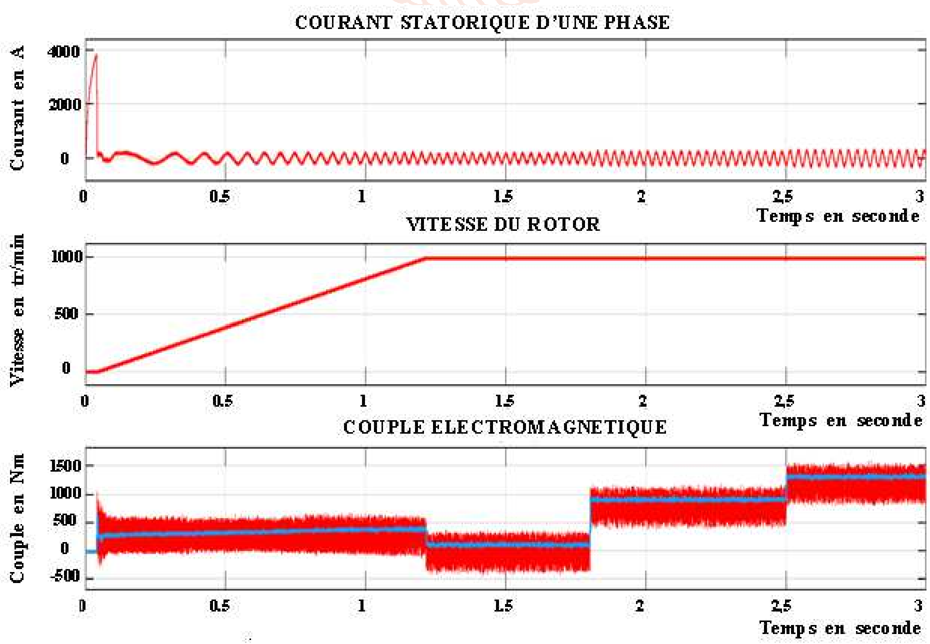


Fig. 3.3: Variable resistive torque at a constant speed of 1000 rpm

The results show that the speed remains virtually unchanged despite significant load variations. This stability reflects the effectiveness of the speed control loop.

An increase in load torque automatically causes an increase in the current " iqs ", while the component " ids ", responsible for the rotor flux, remains practically constant. This independence between the two components constitutes experimental proof of the decoupling achieved by the vector control. The system thus exhibits excellent robustness against external mechanical disturbances. The small deviations observed during transient regimes are mainly due to the electrical and mechanical time constants of the motor, as well as the dynamics of the controller.

3.3.3. Variation of resisting torque at constant speed

Figure 3.4 shows the results obtained when the reference speed varies while the resisting torque remains constant.

Legend in blue: curves of reference quantities (setpoints);

In red: curve of measured quantities

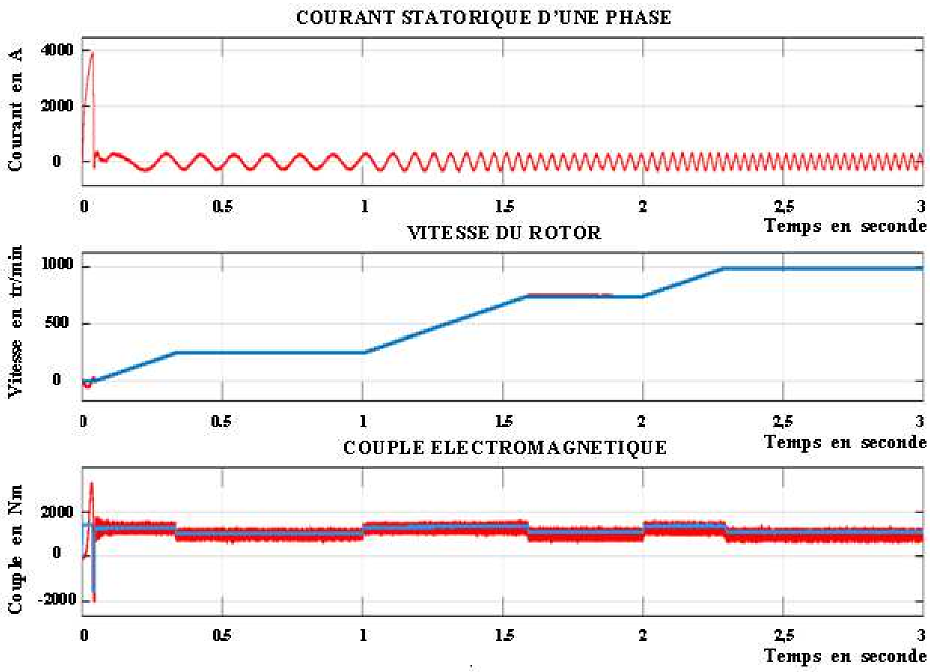


Fig. 3.4: Variable speed with constant resistive torque of 1000 Nm

The motor quickly follows each new speed command without significant oscillation or overshoot. This response confirms that the system dynamics are primarily governed by the speed loop, while the rotor flux remains practically constant. Maintaining a constant flux helps preserve high efficiency and limit electrical losses during speed changes. The observed performance is very close to that typically obtained with a separately excited DC motor.

3.4. Comparison with recent work

The performance obtained in this study is consistent with recently published results concerning the vector control of induction motors. Several authors have shown that rotor flux- oriented control makes it possible to obtain:

- an effective decoupling between the flow and the torque;
- excellent speed regulation accuracy;
- a rapid, dynamic response;
- a reduction in torque oscillations;
- improved performance at low speeds.

Our results confirm these observations.

However, unlike most studies in the literature, this work is not limited to evaluating control performance. It also highlights, from a physical and behavioral perspective, the functional correspondence between the RFOC-controlled asynchronous motor and the separately excited DC motor. This interpretation constitutes the main scientific contribution of this study.

3.5. Experimental validation

To verify the representativeness of the numerical model, the simulation results were compared with tests carried out in the electrical machines laboratory. The experimental tests focused on:
- the speed control of a DC motor;
- load testing of a three-phase asynchronous motor;
- the speed control of the asynchronous motor powered by a frequency converter.

The materials that were used are:
- CETEL 2DC1MG 220V/5.7A 3000rpm DC motor Excitation 220V;
- CETEL 2AC1M 220V/380V 4.3A/2.5A 1kW, 3000rpm three-phase squirrel cage asynchronous motor;
- the ALTIVAR ATV25 U15 frequency converter;
- the three-phase alternating current source 220V/380V 50Hz;
- the PHYWE 220V 10A variable DC voltage source;
- the mechanical load consisting of eddy current brake 2DC 10B 220V 1kW 3000rpm No. 16D;
- the T2DC1/3V3 excitation rheostat;
- the T2DC1/2/3D2 starting rheostat, 2A 20 ohms;
- three Polyca 789 ammeters No. A1, A2, A3;
- two Polyca 790 voltmeters N°V3, V4;
- the three-phase wattmeter Polyca 778 N°W4;
- the CETEL ET 551 tachometer;
- two DEUMO frequency meters No. 173099 and SACI 220V.

Here are the results of validating our simulation:

Table 3.1; DC Motor Speed Adjustment

Supply voltage [V]	Excitation current [A]	Engine speed [rpm]	Armature current [A]
220	0.1	4300	0.88
220	0.2	3250	0.8
220	0.3	2850	0.75

Table 3.2: Load test of the three-phase delta-connected asynchronous motor

Voltage across the terminals of motor [V]	Operating current [A]	Torque resistance [Nm]	Power consumption [W]	Rotation speed [rpm]	Slip
220	2.8	0.1	225	2950	0.0167
220	3.5	1.7	810	2900	0.0333
220	4.3	2.55	1260	2840	0.0533

Table 3.3; Speed control of the three-phase asynchronous motor powered by the frequency converter (ALTIVAR ATV25 U15).

$U_{e\,ATV}$ [V]	$f_{e\,ATV}$ [Hz]	$I_{e\,ATV}$ [HAS]	$U_{DC\,ATV}$ [V]	US_{ATV} [V]	$f_{s\,ATV}$ [Hz]	C_r [Nm]	Is_{ATV} [HAS]	n_r [rpm]
220	50	0.9	330	220	51	0.1	2.8	3000
220	50	4.8	330	220	53.5	1.7	3.5	3000
220	50	5.8	330	220	55	2.55	4.3	3000

Legend :
- $U_{e\,ATV}$: phase-to-phase voltage at the ALTIVAR input;
- $I_{e\,ATV}$: line current at the input of the ALTIVAR;
- $f_{e\,ATV}$: frequency at the input of the ALTIVAR;
- U_{DC}: DC voltage of the intermediate circuit of ALTIVAR;
- $U_{s\,ATV}$: phase-to-phase voltage at the ALTIVAR output;
- $f_{s\,ATV}$: frequency at the output of the ALTIVAR;
- $I_{s\,ATV}$: line current at the output of the ALTIVAR;
- C_r: resisting torque of the load driven by the motor;
- n_r: rotor rotation speed.

The measurements show excellent qualitative agreement with the results obtained from the numerical simulation. In both approaches, the speed remains practically constant despite load variations, while the torque can be controlled independently of the flow.

The differences observed between simulation and experimentation remain small and are mainly explained by:
- actual mechanical losses;
- thermal variations of stator resistances;
- the inaccuracies of the electrical parameters;
- measurement uncertainties;
- magnetic phenomena not taken into account in the simplified model.

These discrepancies remain consistent with the assumptions made during the modeling.

rotor flux-oriented control effectively gives the asynchronous motor a dynamic behavior comparable to that of a separately excited DC machine

3.6. General discussion

The results obtained show that the behavior of the asynchronous motor depends more on the control strategy than on its electromechanical structure.

Thanks to the flux-torque decoupling obtained by the Park transformation and the orientation of the rotor flux, the machine acquires the main dynamic properties sought in DC drives.

This behavioral equivalence opens up important prospects for the gradual replacement of DC motors in high-power applications.

The expected benefits include:
- the removal of the collector and brushes;
- the reduction of maintenance operations;
- improving reliability;
- the increase in specific power;
- the reduction of the overall operating cost.

These results confirm the value of vector control as a preferred solution for modern railway traction systems and high-performance industrial drives.

4. CONCLUSION

The aim of this article was to study, from a behavioral point of view, the possibility of giving the three-phase asynchronous motor electromechanical characteristics similar to those of a separately excited DC motor through rotor flux oriented control (RFOC).

To achieve this objective, we started with the classical model of the three-phase asynchronous motor expressed in the natural frame **abc.** The successive application of the Park transformation and the orientation of the rotor flux allowed us to obtain a representation in the rotating frame **dq,** characterized by the decoupling of the components responsible for the magnetic flux and the electromagnetic torque. This representation considerably simplifies the control of the machine and forms the basis of modern vector control strategies.

Theoretical developments have shown that, assuming correct rotor flux orientation, the direct component of the current exclusively controls the flux, while the quadrature component controls the electromagnetic torque. This property replicates the operating principle of the separately excited DC motor, in which the excitation and armature currents can be independently regulated.

The results of numerical simulations performed using MATLAB/Simulink clearly demonstrate this behavioral equivalence. The RFOC-controlled asynchronous motor develops high torque from startup, maintains excellent speed stability despite load variations, and exhibits a rapid dynamic response to setpoint changes. Experimental tests conducted on electrical machine test benches qualitatively confirm the simulation results, thus demonstrating the validity of the proposed model.

rotor flux-oriented control, which has been extensively studied in the literature, but also in demonstrating that it establishes a **behavioral equivalence** between three-phase induction motors and separately excited DC motors. This approach offers a complementary physical interpretation of classical vector control models and highlights that the dynamic performance of a drive depends more on the control strategy than on the intrinsic structure of the electric machine.

From an industrial perspective, the results obtained confirm that the RFOC-controlled asynchronous motor is a particularly attractive alternative to the DC motor in applications requiring precise torque and speed control, notably in railway traction systems, electric vehicles, high-power industrial drives, and equipment with demanding dynamic requirements. By eliminating the commutator and brushes, this solution improves reliability, reduces maintenance, and increases the service life of electric drives.

This study, however, has certain limitations. The developed model relies on several simplifying assumptions, including the linearity of the magnetic circuit, constant electrical parameters, and an ideal orientation of the rotor flux. Magnetic saturation effects, thermal variations in resistances, phenomena related to inverter harmonics, measurement imperfections, and parametric uncertainties were not explicitly considered. Furthermore, the experimental validation was performed on a moderate-power laboratory machine, which does not allow for a complete reproduction of the operating conditions encountered in high-power railway traction systems.

These limitations open up several avenues for research. Future work will focus on developing a multiphysics model coupling the electromagnetic, mechanical, energy, and thermal phenomena of the induction motor, in order to improve the accuracy of simulations under severe operating conditions. A thorough comparison between different advanced control strategies, including direct torque control (DTC), predictive control (MPC), robust control, and adaptive approaches, will also allow for an evaluation of the respective advantages and limitations of each in railway traction applications. Finally, the integration of artificial intelligence techniques for online parameter identification and automatic optimization of control laws represents a promising prospect for future intelligent electric drive systems.

rotor flux-oriented control is not only a high-performance control technique, but also a theoretical framework for explaining the behavioral equivalence between three-phase induction motors and separately excited DC motors. The results thus contribute to a better understanding of the control mechanisms of induction machines and open new perspectives for their use in modern high-power electromechanical conversion systems.

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