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Predictive Control for Synchronous Reluctance Machine

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﴿ رَبَّنَا لاَ تُؤَاخِذْنَا إِن نَّسِينَا أَوْ أَخْطَأْنَا رَبَّنَا وَلاَ تَحْمِلْ عَلَيْنَا إِصْرًا كَمَا حَمَلْتَهُ عَلَى الَّذِينَ مِن قَبْلِنَا رَبَّنَا وَلاَ تُحَمِّلْنَا مَا لاَ طَاقَةَ لَنَا بِهِ وَاعْفُ عَنَّا وَاغْفِرْ لَنَا وَارْحَمْنَا أَنتَ مَوْلاَنَا فَانصُرْنَا عَلَى الْقَوْمِ الْكَافِرِينَ﴾ **سورة البقرة : الآية286 .**

" صدق الله العظيم"

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We would like to sincerely thank all those who have helped us to elaborate and carry out this dissertation, as well as to all those who have helped us directly or indirectly to accomplish this work.

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DEDICATION

In the name of God, the Merciful Praise be to Allah Almighty

We dedicate this humble work as respect, appreciation and thanks:

To our dear fathers, mothers and brothers who helped us from near and far.

To everyone who contributed to the development of this humble work and all these are dear to us.

Abstract

Abstract

The Synchronous Reluctance Motor SynRM is a very robust electric actuator and has low moments of inertia, which gives it a dynamic characterized by very low time constants and makes it possible to design speed, torque, or rotor position with very interesting precision and dynamic performance.

The reluctance concept of this motor remains a good candidate because of a number of advantages it has, namely no rotor losses, high overload capacity, stable and constant speed at a given frequency, and high mass torque compared to that of an asynchronous motor and a classical synchronous motor.

Predictive control is an advanced automatic control technique. Its purpose is to control complex industrial systems. It has reached maturity, so much so that it is used enough in the industry, whose various applications have proved very conclusive, in particular in robotic systems, electrical machines, and the monitoring and control of biotechnological processes.

Keywords: Synchronous Reluctance Motor, Predictive control, synchronous machine, asynchronous motor, control.

Résumé:

Le Moteur Synchrone à Réluctance SynRM est un actionneur électrique très robuste et à faibles moments d'inertie, ce qui lui confère une dynamique caractérisée par des constantes de temps très faibles et permet de concevoir vitesse, couple ou position avec une précision et des performances dynamiques très intéressantes.

Le concept Reluctance de ce moteur reste un bon candidat en raison de plusieurs avantages dont il dispose, à savoir absence de pertes rotoriques, capacité de surcharge élevée, vitesse stable et constante à une fréquence donnée, et surtout en raison de son couple massique élevé par rapport à celui du moteur asynchrone et moteur synchrone classique.

Le contrôle prédictif est une technique de contrôle automatique avancée. Son objectif est de contrôler des systèmes industriels complexes. Arrivé à maturité, tant il est assez utilisé dans l'industrie, dont les diverses applications se sont révélées très concluantes, notamment dans les systèmes robotiques, les machines électriques, le suivi et le contrôle des procédés biotechnologiques.

Mots clés: Machine Synchrone a Reluctance Variable, Contrôle prédictif, machine synchrone, moteur asynchrone, contrôle.

الملخص

محرك التردد المتزامن **SynRM** هو مشغل كهربائي قوي للغاية وله لحظات منخفضة من القصور الذاتي، مما يمنحه ديناميكية تتميز بثوابت زمنية منخفضة للغاية ويجعل من الممكن تصميم السرعة أو عزم الدوران أو الموضع بدقة مثيرة للغاية وأداء ديناميكي.

يظل مفهوم ممانعة هذا المحرك مرشحًا جيدًا بسبب عدد من المزايا التي يتمتع بها، وهي عدم وجود خسائر في الدوار، وسعة التحميل الزائد العالية، والسرعة المستقرة والثابتة عند تردد معين، وقبل كل شيء عزم الكتلة العالي مقارنةً بعزم الدوران غير المتزامن محرك متزامن وكلاسيكي.

التحكم التنبئي هو تقنية تحكم تلقائية متقدمة. والغرض منه هو التحكم في الأنظمة الصناعية المعقدة. وصل إلى مرحلة النضج، لذلك يتم استخدامه بشكل كافٍ في الصناعة، والتي أثبتت تطبيقاتها المختلفة أنها حاسمة للغاية، لا سيما في الأنظمة الروبوتية، والآلات الكهربائية، ومراقبة عمليات التكنولوجيا الحيوية والتحكم فيها..

الكلمات المفتاحية: محرك التردد المتزامن SynRM، التحكم التنبئي، الآلة المتزامنة، المحرك غير المتزامن، التحكم.

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Abbreviations

Abbreviations

Isa , Isb, Isc	Stator phase currents of the machine.
Fsa ,Fsb ,Fsc	Flow of the stator phases of the machine.
f	Flux of magnets.
Vsa ,Vsb ,Vsc	Stator phase voltages.
I d s , I q s	Stator currents of direct axis and quadrature.
Te	Electromagnetic torque.
T_L	Load Torque.
f	Coefficient of friction.
Ω	Rotor rotation pulse
Ts	sampling period
R_s	Stator resistance
P	Number of pole pairs.
M	Cyclic inductancemutual stator-rotor
J	Moment of inertia of rotor masses.
Ld , Lq	Direct and quadrature component of inductance in Park's model
Uc	DC voltage at the inlet of the inverter.
D	Direct axis index
Q	Index of the axis in quadrature
ω	Stator voltage pulsation.
τ	Electric time constant.
ABC	Index corresponding to the three phases of the stator
d q	Axis corresponding to the reference frame related to the rotating field
SynRM	Synchronous reluctance motors
MPC	Model Predictive Control
IMC	Internal Model Controler
GPC	Generalized Predictive Control
Kp , Ki	Proportional-integral coefficient

General Introduction

General Introduction

Model Predictive Control (MPC) is an advanced control technique in automation. It is the most suitable technique for controlling complex systems in industrial environments, such as petrochemical, process engineering, and the automotive field, where it has proven its worth. Its ability to jointly address operating specifications and operating constraints in the development of the control law has made it successful. The evolution of computing is also no stranger to success, as the powerful computers developed have allowed automation engineers to achieve their goals with great precision in a record period of time. All these factors have propelled predictive control to occupy a prominent place in academic and industrial circles.

The main idea of predictive control is based on the use of a model of the system to be controlled to predict its output over a certain horizon. The control objectives are specified by a criterion to be minimized and constraints to be imposed on the state, control, and output variables [1, 2, 3]. Therefore, the command to be applied at each sampling moment is obtained by solving an optimization problem with constraints in a time less than the sampling period [4, 5]. The nature of the optimization problem usually depends on the type of model used for prediction since the criterion is usually quadratic and expresses objectives of pursuit and energy minimization [2, 3]. When the model is linear, the analytical solution to the optimization problem exists and is simple to calculate, and the performance will be better since the overall optimum has been reached.

In this dissertation, we will focus on studying the role of predictive control strategy for Synchronous Reluctance Motor. So, Model-based is studied in order to improve the performance of this MPC. Our brief will be organized as follows:

In the first chapter, we will give a brief overview of the development history of this machine. The concept of energy conversion in electromagnetic converters will also be discussed. Subsequently, we will apply this concept to the MSRV, where we will put the machine into equations. We will establish the equation relating the electromagnetic torque to the different electrical, magnetic, and geometric parameters of the machine.

The first chapter provides general information on the synchronous reluctance machine, including comparisons to other machines in the literature, the reluctance concept, and further details.

The second chapter of the research work presents the topic of field-oriented control. Inverters are important in electric motor speed drives as they convert DC power into AC power with variable frequency and amplitude. Moreover, we will present the Inveret model.

Furthermore, the equation and the modeling of the synchronous reluctance motor (SynRM) However, controlling SynRMs is challenging due to their complex, multi-variable nature. Field-oriented control (FOC) was proposed to address this, allowing independent control of magnetic field and torque components. FOC initially faced implementation difficulties but became popular with the advent of microcontrollers and signal processing devices, leading to increased research and applications in the field.

The third chapter presents predictive control, where we are particularly interested in Model Predictive Current Control. We expose the history of this control strategy and its theoretical basis. Subsequently, as a validation of the theory presented, we developed a simulation program under Simulink/Matlab control. Results obtained by simulation make it possible to highlight the performance of the MPC on a Syn RM.

Finally, we conclude our work with a general conclusion and perspectives.

Chapter I

State of the art on Synchronous Reluctance Machine

I.1. Introduction

Conventional alternating current machines (synchronous and asynchronous) are mainly based on the mainly on the interaction of two rotating fields. The relative theory of their study neglects, at least in a first approximation, the effect of gearing.

In the case of variable reluctance machines (VRM), the salience due to the presence of is the very basis of their operation. The design of a Synchronous Reluctance Motor is therefore based on a more thorough theoretical development. The latter, based on the calculation of the magnetic energy in its structure, will allow to determine the parameters and the performances of this machine. This design must be done by magnetic analysis and by the use of numerical methods.

I.2. Electromechanical conversion

I.2.1 General

Electrical energy is a secondary form of energy that has very little direct use. direct use. On the other hand, it is an intermediate form very interesting by its ease of transport, its flexibility and its possibilities of conversion. Among all the possibilities of transformation, the electromechanical form plays a particularly important role. It is necessary to know that 95% of the production of electrical energy results from a mechanical - electrical conversion.

Electromechanical conversion plays an important role in fields as varied as electric traction (public transport, electric and hybrid cars), machines used in packaging machines, food production, microelectronics, ..., or home automation [1].

I.2.2 General properties of electromechanical conversion

The electromechanical conversion as it will be seen in this thesis, has the following common following common characteristics:

- search for a high energy efficiency.
- reversible systems, i.e., capable of converting both electrical energy into mechanical energy into mechanical energy or the opposite.
- reliability and life span.

I.2.3. Characteristics of electromechanical conversion

The study of electromechanical conversion is based on the principle of conservation of energy. This uses an intermediate form of energy, it is the Electromagnetic energy or its homologous form, the magnetic Conergy. The electromechanical force or torque results from three possible forms of interactions:

- the interaction between two currents.

- the interaction between a current and a ferromagnetic circuit.
- the interaction between a magnet and a current or a ferromagnetic circuit.

I.3. General information on Synchronous Reluctance Motor

The Synchronous Reluctance Motor is structurally a synchronous machine with poles without excitation. Its stator is identical to that of ordinary alternating current machines. The electromagnetic torque consists exclusively of the the salient torque. The energy conversion in the machine is done by variation of the inductances of its phase windings due to the rotation of a rotor magnetically dissymmetrical between the direct axes (of minimal reluctance) and in quadrature of maximum reluctance. It is indeed a variable reluctance machine and more precisely a polyphase pure reluctance machine with a smooth stator and a sinusoidal supply. As the machine rotates synchronously with its supply and as it the name "Synchronous Reluctance Motor" has been chosen. The variable reluctance synchronous machine is therefore suitable for high power applications is therefore suitable for high power and high-speed applications, a field largely occupied by the occupied by the asynchronous machine. But the latter presents Joule and iron losses at the rotor in steady state. The synchro-reluctant machine is therefore a real competitor on this point. a real competitor of the asynchronous machine on this point [2].

I.4. Operating principle of synchro-reluctant machine

The stator of the variable reluctance synchronous machine is wound in the same way as that of ordinary synchronous machines. of the ordinary synchronous machines. It is a three-phase winding with p even poles fed by a balanced three-phase system of currents of pulsation ω . The three-phase winding then creates a rotating magneto-motive force (m.m.f.) with an angular velocity $\frac{\omega}{P}$.

Its rotor is protruding: it presents an "asymmetry" between the direct axis and the axis in quadrature axis. The rotor is positioned in relation to the rotating f.m.m. so that the that the reluctance crossed by the magnetic induction flux in the air gap is the smallest that the load it is driving allows. As it rotates, the magnetomotive force thus drives the rotor at the same speed $\frac{\omega}{P}$.

The angle between the maximum of the magnetomotive force and the angle between the maximum of the magnetomotive force and the axis d of the rotor is called "load angle"[1].

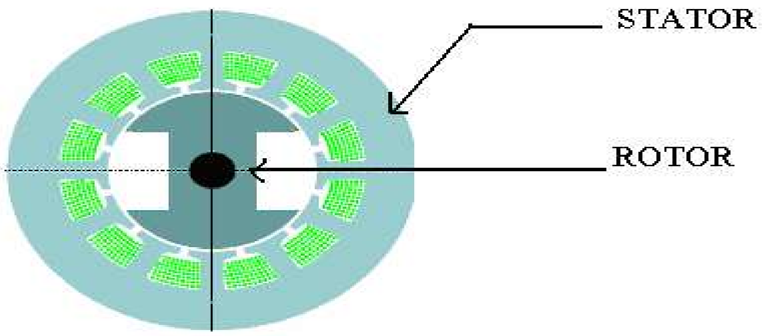


Figure I.1: SynRM stator and rotor.

I.5. The different rotor structures of a Synchronous Reluctance Motor

There are currently five main structures of the synchronous machine rotor with variable reluctance, simple, with flow barriers and axially laminated, magnet assisted and superconducting [3].

I.5.1. Simple rotor

If the starting point in the development of rotor models the latter was under formed by a stack of electromagnetic laminations.

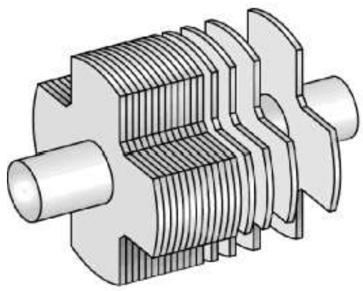


Figure I.2: Single rotor of the MSRV

I.5.2. Rotor with flux barriers

Flux barriers are one of the devices that allow to increase the salinity ratio (L_d /L_q) (up to about 13). The salience ratio is increased mainly by the reduction of the inductance L_q , i.e. by increasing the reluctance q of the path of q in the rotor. The rotor then becomes an assembly of ferromagnetic segments flux and non-magnetic segments. The salience ratio is adjusted by adjusting the relative widths of the segments.

The flux barriers can be made of air (holes in the rotor). A is then necessary to ensure the solidity of the rotor and the reduction of the reduction of the q-axis flux. To preserve the mechanical balance of the rotor, the flux barriers can also be can also be made of non-magnetic steel. A robust assembly technique (explosion welding) is then essential to allow the rotor to operate at high speed [4].

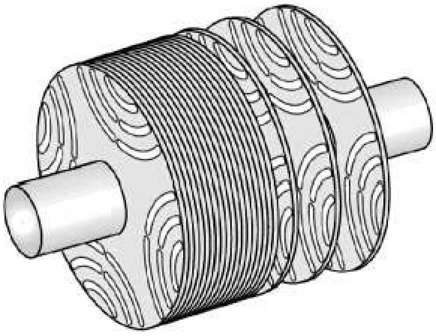


Figure I.3: Rotor with flux barriers

I.5.3. Axially laminated rotor

A second device to increase the salience ratio is the axial lamination of the rotor. non-magnetic sheets. The rotor then behaves like a homogeneous anisotropic material. It is this anisotropy of the rotor material that ensures the asymmetry between the direct axis and the quadrature axis. The gloss ratio is adjusted by adjusting the relative thicknesses of the sheets.

It is possible to reach a gloss ratio of about 20 in two poles and 10 in four poles [2].

Note that this structure is generally used for synchro-reluctant machines with four poles. The assembled sheets are then shaped like hyperbolas as shown in figure (I.4). Because of the high number of assembled elements and the relatively low mechanical mechanical strength, this structure is limited to low speeds (less than 5000 rpm) and low (below 5000 rpm) and low power (below 2kW) but it has higher performances than the first two. higher performance than the first two.

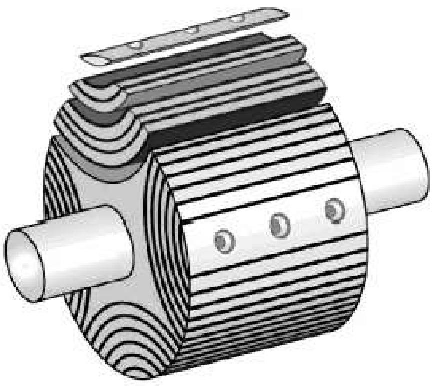


Figure I.4: Rotor axialement laminé

I.5.4. Magnet assistance

In order to further reduce the q-axis flux, permanent magnets can be used housed in the flux barriers. In contrast to an ordinary excitation, the flux created by the magnets opposes the quadrature flux. Most of the torque remains due to the to the salience of the rotor. This technique allows to improve the performance in terms of torque, power factor and efficiency.

But because of the polarity of the magnets, the machine loses its reversibility and the direction of direction of rotation. Of course, the use of magnets increases the cost of the machine [5].

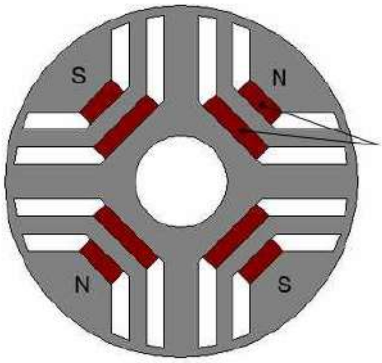


Figure I.5: Magnet assistance of a synchro-reluctant machine.
Four-pole configurations

I.5.5. Use of superconductors as magnetic insulators

The high-temperature superconductor is by far the best device to reduce the q-axis flux. reduce the q-axis flux. It is used as a magnetic insulator. It can be used to It can be used to enclose a solid rotor or instead of flux barriers as shown in figure (1.6)

The introduction of flux barriers made of superconducting material has the advantage of considerably reduce L_q while preserving a high value of L_d.

The magnetic isolation leads to a considerable increase of the and consequently a significant improvement of the power factor. In contrast to magnet assistance, the use of superconductors allows to the reversibility of the machine with respect to the direction of rotation. But it has two major disadvantages: the cost of the superconducting material and the complexity of the structure and implementation [1].

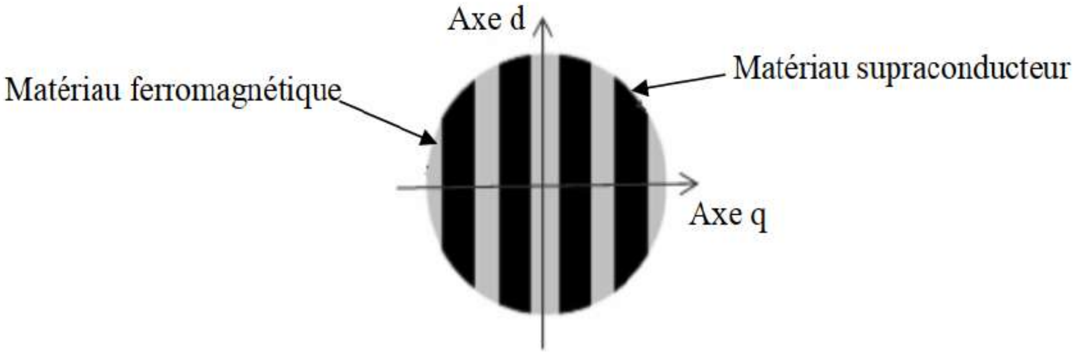


Figure I.6: Rotor of a superconducting variable reluctance machine.

The rotor in this type of motor is made up of several layers, interposing ferromagnetic and high-temperature ferromagnetic layers and layers of superconductor at high critical temperature, this configuration. This configuration allows to have a reluctance difference along the axes d and q axes of the rotor figure (I.6).

The rotor is cooled with nitrogen. The power of the variable reluctance motors realized and tested tested vary between 0.75 and 10 kW. These motors have a power density 4 to 7 times higher than that of non-superconducting variable reluctance motors [4].

I.6. Influence of the parameter (L_d/L_q) on machine performance

An in-depth study of the influence of the ratio (L_d/L_q) on the performance of the variable reluctance synchronous machine.

We will recall the main results of this study.

The expression of the electromagnetic torque developed by this type of machine in steady state is given by the relation.

$$C_e = \frac{3}{2} p(L_d - L_q) I_d I_q \tag{I.1}$$

We have defined in Figure (I.7), the angle θ identifying the position of the current vector stator I_s with respect to the d-axis. In steady state, this vector is fixed.

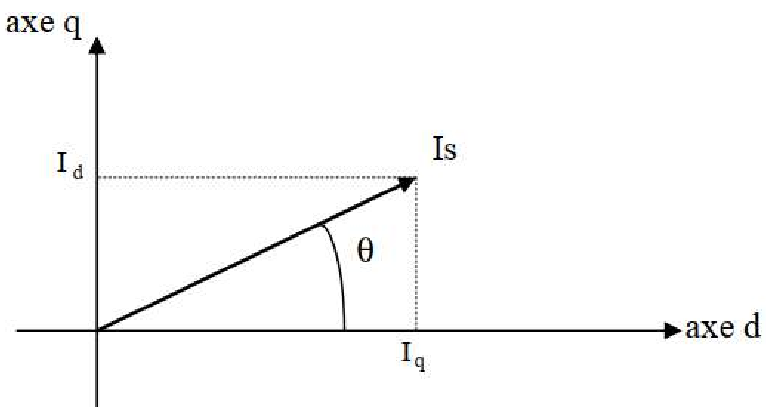


Figure I.7: Position of the stator current in the coordinate system (d-q).

The value of the modulus of the stator current is given by the following relationship

$$I_s = \sqrt{I_d^2 + I_q^2} \tag{I.2}$$

The electromagnetic torque can be expressed as a function of θ and the stator current

$$C_e = \frac{3}{2}p(L_d - L_q)I_s^2 \sin 2\theta \tag{I.3}$$

It is shown from the two previous relations that for a given value of the stator current, the torque is the torque is maximum when $\theta = \pi/4$ which corresponds to impose $I_d = I_q$.

This mode of operation corresponds to a particular control strategy.

By setting $\theta = \pi/4$ in equation (I.3), we obtain equation (I.4). We see appearing in this equation, the salience ratio L_q/L_d.

$$C_e = \frac{3}{2}pL_d I_s^2 \left(1 - \frac{1}{\left(\frac{L_d}{L_q}\right)}\right) \tag{I.4}$$

We can define the power factor of the machine which corresponds to the phase shift between the fundamental of the line current and the corresponding simple voltage. This factor also represents the ratio between the active power and the apparent power absorbed by the machine. It is important that this ratio is as close as possible to 1 to limit the power of the source feeding the machine. By neglecting the losses in the model of the machine, we obtain a simple expression for the power factor [6]:

$$\cos\varphi = \frac{\left(\frac{L_d}{L_q} - 1\right)\sin\theta}{\left(\frac{L_d}{L_q}\right)^2 + \tan^2\theta} \quad \text{(I.5)}$$

The power factor is maximized and depends only on the ratio L_d/L_q for / $\sin(\theta) \approx 1$.

The expression for the power factor is then given by the following relationship:

$$\cos\varphi = \frac{\frac{L_d}{L_q} - 1}{\frac{L_d}{L_q} + 1} \quad \text{(I.6)}$$

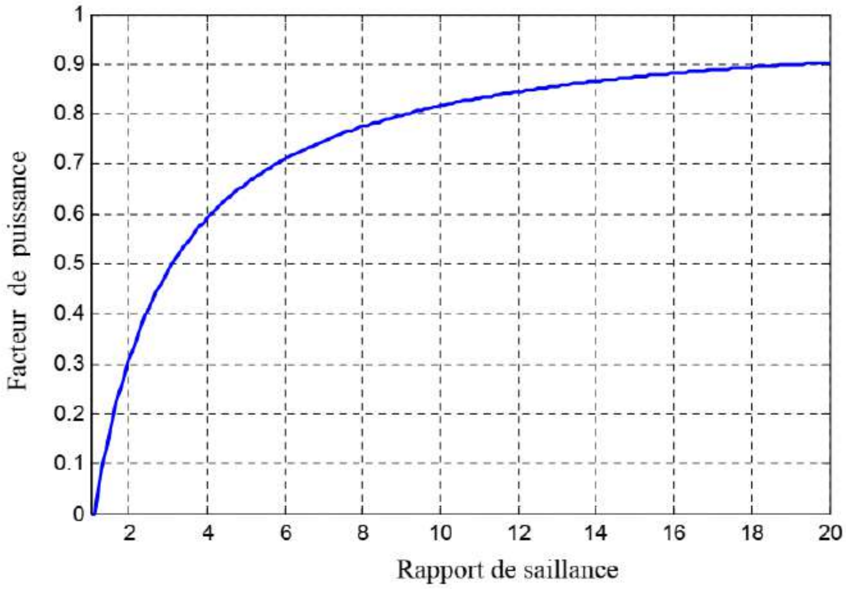


Figure I.8: Power factor as a function of salience ratio.

We have represented on figure (I.8), the variations of the power factor as a function of the salience ratio L_d/L_q. We can observe on this figure that the power factor starts to become interesting for power factor starts to become interesting for salience ratios higher than 6. Taking into account the electrical losses (Joule losses and iron losses) increases this power factor slightly increases this power factor [7].

Equations (I.4) and (I.6) show that in order to optimize machine performance, a rotor structure must be designed such that the inductor L_d has the greatest possible value and the ratio (L_d/L_q) is as large as possible. This is a problem of optimization of an electromagnetic structure with two constraints. The search for an optimal rotor structure can be solved using the finite element method applied to magnetic field calculation.

I.7. Benefits of SynRM

The main motivations that make the MSRV competitive with other machines are:

- ✓ The improvement of the saliency ratio makes the MSRV competitive with the asynchronous machine, especially in terms of power factor and power absorbed power.
- ✓ Small and medium-sized drives can have simpler control by using MSRV compared to using the SynRM compared to the vector control of the asynchronous machine. asynchronous machine.
- ✓ The SynRM has stable operation at low speeds and full load unlike an asynchronous motor. unlike an asynchronous motor which can have problems with overheating. overheating.
- ✓ The SynRM has no magnets which is an advantage over the permanent magnet machine in permanent magnet machine in high temperature applications. Therefore, it does not have demagnetization problems.
- ✓ It is very simple to build and very robust.

I.8.Conclusion

This chapter has allowed us to highlight the principle of energy conversion in the Synchronous Reluctance Motor (SynRM). The different structures proposed seek to the dissymmetry between the direct axis and the quadrature axis, which is at the origin of the reluctance torque. of the reluctance torque. The performance improvement is then to minimize the quadrature inductance while trying to keep the direct inductance as high as possible. as possible. The optimization of the rotor structure of the variable reluctance synchronous machine is still a nowadays, an important research axis. Previous studies have shown that the increase of the salience ratio allows to obtain with this type of machine to obtain with this type of machine, performances comparable to those of the other electric machines.

Chapter II

Inverter-SynRM modeling with rotor field-oriented control

II.1. Introduction

Inverters play an important role in the speed drives of electric motors. The inverter is a static converter that allows alternating current machines to be supplied by a system of sinusoidal voltages with variable frequency and amplitude. Nevertheless, several problems arise, particularly that of the appearance of higher-order harmonics. These harmonics have an undesirable effect on the dynamic behavior of the machine; they interfere with the normal operation of the machine. Indeed, the presence of these harmonics leads to unwanted pulsative couples, as well as additional losses.

The permanent magnet synchronous machine tends to replace the direct current machine. This evolution, motivated by undeniable qualities of robustness and reliability. However, a major problem arises: the model of the permanent magnet synchronous motor corresponds to a multi-variable and strongly coupled system, it is for this reason, a control method called 'flow orientation', was proposed by Blaschke in 1972 [6], it did not however immediately have a great boom because the regulations, At the time, based on analog components, the implementation of the control was then difficult. With the advent of microcontrollers and signal processing devices, it has become possible to carry out such a command at a reasonable cost. This has led to an explosion of research and applications relating to Field oriented control of the permanent magnet synchronous machine.

II.2. Static DC-AC converter :

A static converter is a system for adapting the source of electrical energy to a given receiver. The development of power components in the middle of the century (power electronics) made it possible to develop electrical power converters without rotating machinery. The technology of the components used (semiconductors) is constantly evolving:

- Low cost;
- High switched powers
- Ease of control.

II.2.1. Definition of the inverter :

The inverter is a static converter providing continuous-AC conversion. If we have at the input a direct voltage, thanks to semiconductors, we connect each of the terminals of the receiver a voltage sometimes positive, sometimes negative [7] [8].

By an adequate sequence of control of the semiconductors, it is therefore possible to produce at the output of the inverter an alternating voltage of zero average value. This voltage may comprise one or more alternating slots depending on whether it is an alternating one-slot control or a pulse width modulation control [7].

There are several types of inverters:

- According to the source :
  - Voltage inverters,
  - Current inverters;
- Depending on the number of phases (single-phase, three-phase, etc.),
- Depending on the number of levels (2.3, etc.).

II.2.2.Voltage Inverter Modeling:

The voltage inverter powers the SYNRM can ideally be represented according to Figure (II.1), where Ti and T'i (i = a, b, c) are MOSFET transistors, Si and Si' are the logical commands associated with them such that:

• if Si = 1, the switch Ti is passed and T'i is open,

• if Si = 0, the switch Ti is opened and T'i is passing.

The network-side converter consists of a three-phase diode rectifier and a filter, and the converter on the machine side, and a three-phase voltage inverter.

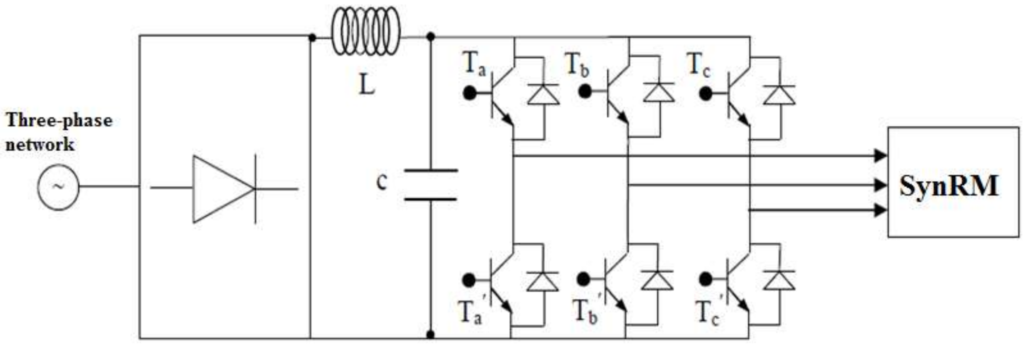


Figure II.1: Diagram of the association synchronous machine-voltage inverter

It is considered the power supply of the inverter is as a perfect source, supposed to consist of two generators of f.e.m. equal to $U_0/2$ connected to each other by a point denoted n_0. The inverter consists of three arms, each arm consists of two transistors

Whose order is complementary. The transistors are shunted by recovery diodes, Each arm of the inverter can be presented by a switch with two positions as shown in Figure (II.2).

The synchronous machine is connected in a star, U_0 is the DC voltage feeding the voltage inverter.

The compound voltages are obtained from the outputs of the inverter [9]:

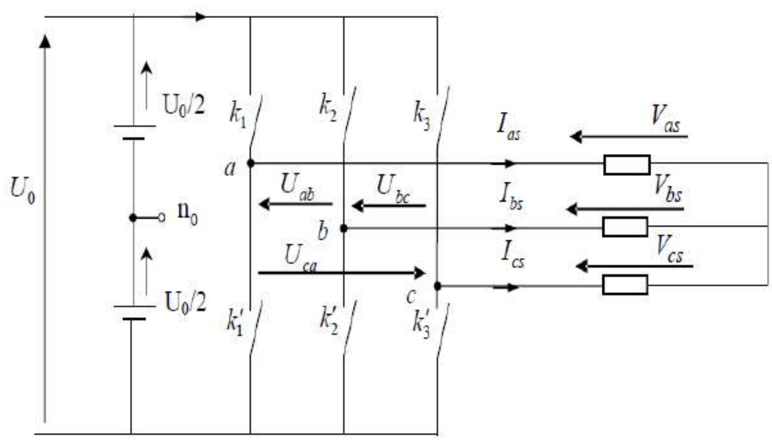


Figure II.2: Equivalent diagram of the inverter

The line voltages delivered by the inverter are:

$$U_{ab} = V_{as} - V_{bs} = U_0(S_a - S_b) \tag{II.1}$$

$$U_{bc} = V_{bs} - V_{cs} = U_0(S_b - S_c) \tag{II.2}$$

$$U_{ca} = V_{cs} - V_{as} = U_0(S_c - S_a) \tag{II.3}$$

The voltages Vas, Vbs and Vcs form a balanced three-phase voltage system then:
From (II.1) and (II.3) :

$$V_{as} = \frac{U_0}{3}(2S_a - S_b - S_c) \tag{II.4}$$

From (II.1) and (II.2) :

$$V_{bs} = \frac{U_0}{3}(2S_b - S_a - S_c) \tag{II.5}$$

From (II.2) and (II.3) :

$$V_{cs} = \frac{U_0}{3}(2S_c - S_a - S_b) \tag{II.6}$$

Therefore:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{1}{3}U_0 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{II.7}$$

In our work, the inverter is controlled by the Pulse Width Modulation (PWM) technique. It consists in imposing on the terminals of the machine voltages, chopped at fixed frequency, evolving according to the voltage references obtained from the current regulators. Using a triangular signal called a carrier, these voltages are modulated in pulse width to determine the switching times and conduction time of each switch of the inverter. At any given moment, one of the two switches on each arm is in conduction and the other is blocked.

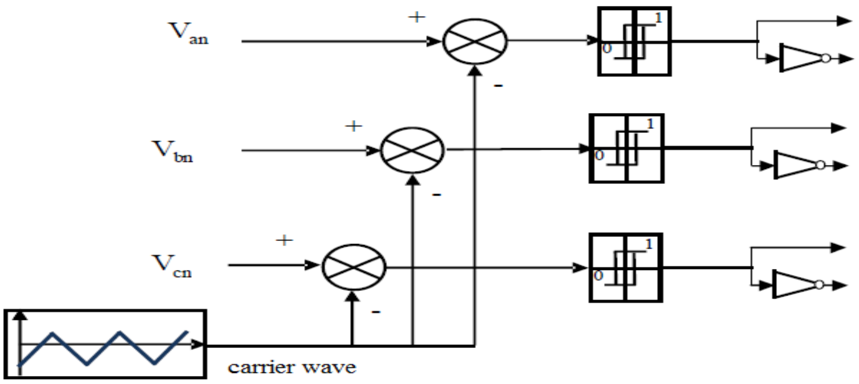


Figure II.3: Schematic diagram of the triangle-sinusoidal technique

II.3. Modeling of the Voltage Inverter- SynRM association :

Voltage inverters, combined with alternating current machines, are nowadays very widely used in industrial drive systems. In the first place, advances in semiconductors have made it possible to produce increasingly efficient static converters. Secondly, the evolution of digital techniques, in particular the ever-increasing use of signal processors (DSP "Digital Signal Processing") [9], now makes it possible to execute complex converter control algorithms in real time.

II.3.1.Models of the double alternating three-phase rectifier:

The rectifier is an "alternating/continuous" converter [10], A conversion of electrical energy makes it possible to have a source of direct current from an alternative source, it is represented by Fig.II.4

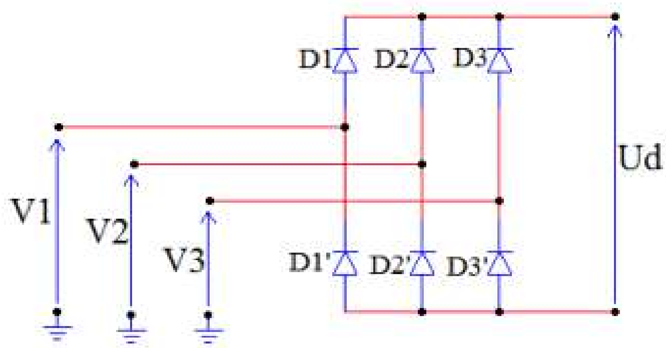


Figure II.4: Representation of the three-phase rectifier double alternating diodes.

This rectifier comprises three diodes(D1, D2, D3)with common catho ensuring the go of the current Id and three diodes (D1', D2', D3')with common anode V2 = Vm $\sin(2\pi ft-\frac{2\pi}{3})$ ensuring the return of the current Id. If we assume that the rectifier is powered by a balanced three-phase network of voltage.

$$V_1 = V_m \sin(2\pi ft) \tag{II.8}$$

$$V_2 = V_m \sin(2\pi ft - \frac{2\pi}{3}) \tag{II.9}$$

$$V_3 = V_m \sin(2\pi ft - \frac{2\pi}{3}) \tag{II.10}$$

The three-phase diode Grayetz bridge powered by a three-phase sinusoidal voltage system. The conduction sequence of diodes is defined as follows:

Di conduit if v i =max (vj); j=1,2,3; i=1.2.3

D'i conduit if v' i =max (vj); j=1,2,3; i=1.2.3

The voltage U_d at the rectifier output is :

$$U_d = V_i - V_i' = \quad \min(V_j) - \max(V_j) \tag{II.11}$$

With :

Di;D'i: Conduction diodes

Vi: Di V'i anode voltage: D'i anode voltage

The average value of the rectified voltage is given by:

$$U_{dmoy} = \frac{3\sqrt{3}}{\pi} V_m \tag{II.12}$$

II.3.2. Filter modeling:

To improve the quality of the DC voltage source, a capacitance C_f is inserted at the input of the inverter, this absorbs the difference between the unidirectional current Id and the run *I*, so it eliminates the sudden variations of U_{dc} during switching, on the other hand, to reduce the ripple of current I and protect the inverter against the critical growth rate of current, is placed in series a smoothing inductor L_f (internal resistance *R*) the whole L-C constitutes a low pass filter 24.

A low-pass filter (LC) is inserted between the rectifier and the voltage inverter to eliminate high frequencies. The representative diagram is given by (FigII.4) [10].

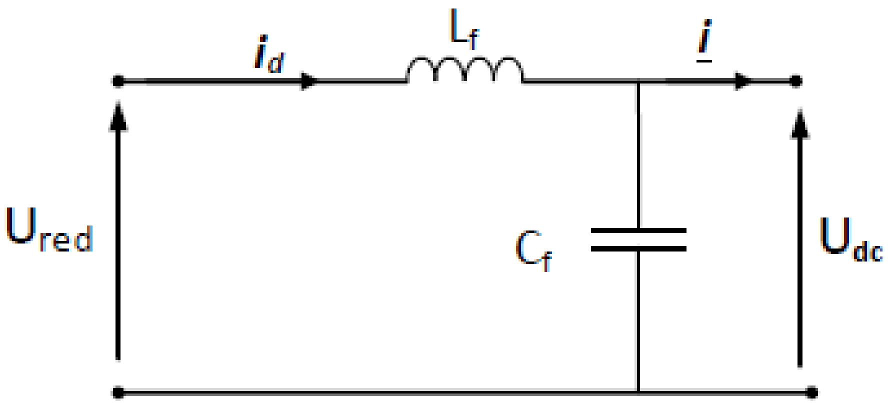


Figure II.5: Representation of a low-pass filter

The filter model is defined by the following system of equations;

$$U_d = L_f \frac{d_i d(t)}{dt} + U(t) \qquad \text{(II.13)}$$

$$\frac{U(t)}{dt} = \left(\frac{1}{c_f}(id(t) - i(t))\right) \qquad \text{(II.14)}$$

The previous two equations, we give the transfer function F(s) of the filter in the form:

$$f(s) = \frac{U(s)}{U_d(s)} = \frac{1}{1 + \left(\sqrt{L_f c_f s}\right)} \qquad \text{(II.15)}$$

The role of the C_f capacitance is to ensure the character of voltage source at the input of the inverter, to provide the reactive energy to the machine, and to absorb the negative current returned by the load. The role of the inductor L_f is to smooth the current id. The filter is of the second order whose cut-off frequency.

$$F_c = \frac{1}{\sqrt{L_f c_f}} \qquad \text{(II.16)}$$

II.3.3. The voltage inverter:

After presenting the model of the machine, we will present the complete drive system where the synchronous machine is associated with a three-phase voltage inverter. So the (figure II.5) illustrates the schematic diagram of this converter-SynRM association [11]:

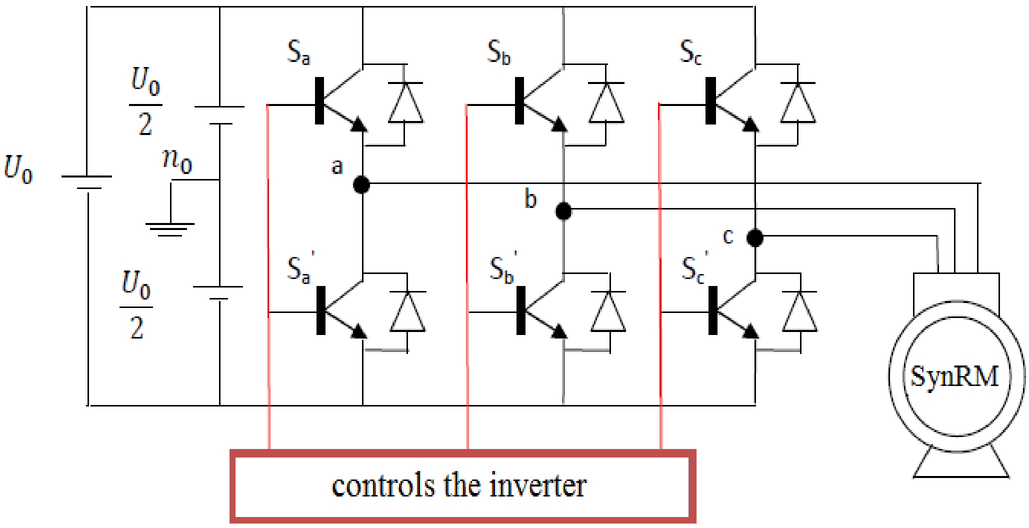


Figure II.6: Diagram of the SynRM – voltage inverter association

II.4. SynRM Mathematical Model:

As mentioned earlier, The SynRM version is quite similar to the induction motor IM. The difference is by neglecting the rotor losses from the IM equations. A SynRM's model is described by the following equations

The voltage equations of the SynRM in rotor reference frame are represented as:

$$v_d = R_s i_d - \omega_e L_q i_q + L_d \frac{di_d}{dt} \quad \text{(II.17)}$$

$$v_q = R_s i_q - \omega_e L_d i_d + L_q \frac{di_q}{dt} \quad \text{(II.18)}$$

where v_d and v_q are the direct and quadrature axes terminal voltages, i_d and i_q the direct and quadrature axes terminal currents.

The electromagnetic torque is stated as:

$$T_e = \frac{3}{2} p \left(L_d - L_q \right) i_{dm} i_{qm} \quad \text{(II.19)}$$

The motor dynamic equation is expressed as:

$$T_e = J \frac{d\omega_m}{dt} + B_m \omega_m + T_L + T_k \quad \text{(II.20)}$$

where T_L is the load torque, J the inertia moment of the system rotating parts, ω_m is the motor mechanical speed, B_m the viscous friction coefficient, T_k the constant friction load and p the number of pole pairs [12].

II.4.1. Pulse width modulation (PWM) control:

The inverter aims to generate at its output, the most sinusoidal voltages possible. The output quantities of the analog or digital controls of the inverter are used to obtain the desired voltages or currents at the terminals of the machine.

The pulse width modulation technique (PWM or Pulse Width Modulation in English) makes it possible to reconstitute these quantities from a fixed frequency and fixed voltage source (usually a direct voltage) via a direct converter.

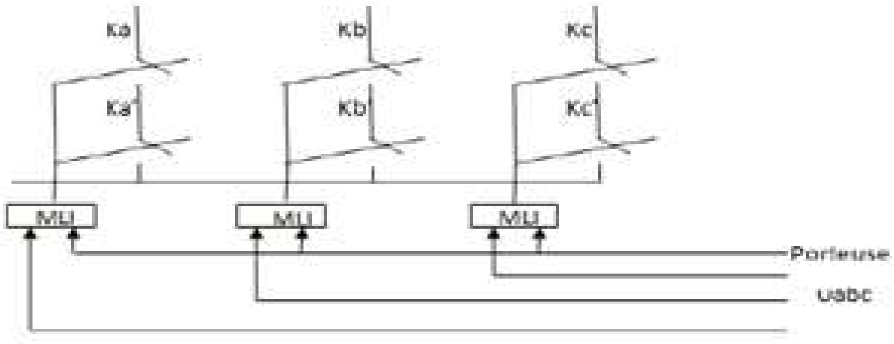


Figure II.7: The equivalent pattern of the PWM inverter

This makes the electrical connections between the source and the load. The adjustment is carried out by the opening and closing times of the switches and by the duty cycles. The pulse width modulation techniques are multiple; however, four categories of PWM have been developed [13]:

- Sine-triangle modulations comparing a reference signal to a carrier, in general, triangular, for our work we use this method.
- Pre-calculated modulations for which switching angles are calculated offline to cancel out certain components of the spectrum.
- Post-computed modulations also called symmetric regular PWM or Field oriented control PWM in which switching angles are calculated online.
- Stochastic modulations for which the objective is spectrum bleaching (constant and minimal noise over the entire spectrum). The widths of the pulses are distributed according to a probability density representing the law of control.

II.5. Rotor field-oriented control

In this control technique, the indirect method is limited.

By applying the principle of Field oriented control (id=idr), and after arrangements necessary, we will have the following system of equations:

$$R_s I_d + L_d \frac{dI_d}{\mathrm{dt}} = V_{sd} - wL_d I_q \tag{II.21}$$

$$R_s I_q + L_q \frac{dI_q}{\mathrm{dt}} = V_{sq} - wL_q I_d \tag{II.22}$$

These equations show that V_{sd} and V_{sq} depend on both the currents on the axes d and q We are therefore led to implement a decoupling as for the asynchronous machine supplied with voltage.

II.5.1. Decoupling by compensation

The principle of this decoupling amounts to defining two new control variables V_{d1} and V_{q1} figure (II. 8)

$$V_{sd1} = V_{sd} + e_q \tag{II.23}$$

$$V_{sq1} = V_{sq} + e_d \tag{II.24}$$

Such that (e_d , e_q) represents the disturbances to be compensated.

The effectiveness of the engine control system is highly dependent on the mathematical model chosen for this engine and the exact knowledge of its parameters. In the case of synchronous machine drives, Park's reference system is adopted because it is widely used in control and command [14].

$$e_d = wL_d I_q \tag{II.25}$$

$$e_q = wL_q I_d \tag{II.26}$$

$$V_{sd} = V_{sd1} - e_q \tag{II.27}$$

$$V_{sq} = V_{sq1} - e_d \tag{II.28}$$

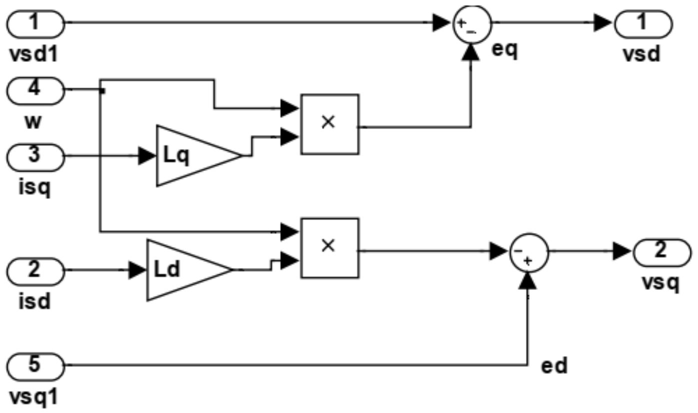


Figure II.8: Compensation block scheme

II.5.2. Calculation of regulators

II.5.2.1. d-axis Current regulator

From equations (II.21,22) and (II.23,24) the following transfer function can be written:

$$Fd(s) = \frac{1/rs}{1T_dS} = \frac{I_d}{V_{sd1}}, \qquad T_{sd} = \frac{L_d}{R_s} \tag{II.29}$$

We can represent the flow control block diagram by figure (II.9)

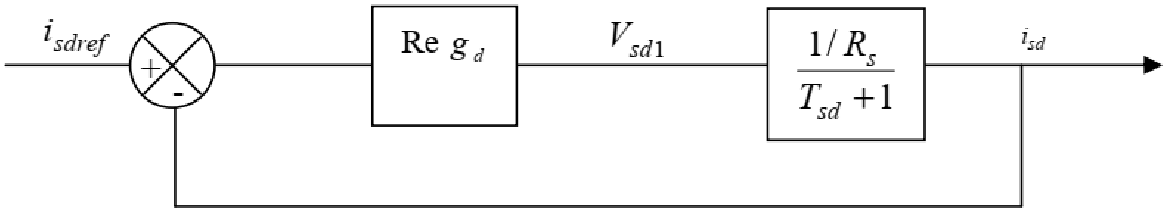


Figure II.9: Flow regulation

The regulator (Reg_d) has a transfer function given by:

$$Reg_d(s) = \frac{1 + T_{sd}s}{s} \tag{II.30}$$

With:

$$FTBO = \frac{K_d}{R_s s} = \frac{K_s'}{s} = T \tag{II.31}$$

Such as

$$K_d' = \frac{K_d}{R_s} \tag{II.32}$$

And

$$FTBF_d = \frac{T}{T+1} = \frac{1}{1+\frac{1}{K_s'}s} = \frac{1}{1+\tau_d s} = \frac{I_{sd}}{I_{sreff}} \quad \text{(II.33)}$$

In order for the current to be established, we chose $\tau_d = T_{sd}$

Or':

$$Reg_d(s) = \frac{R_s}{T_{sd}}\left(\frac{1+T_{sd}s}{s}\right) \quad \text{(II.34)}$$

II.5.2.2. q- axis regulator

Similarly, equations (II.23) (II.24) (II.25) (II.26) make it possible to construct the following block diagram:

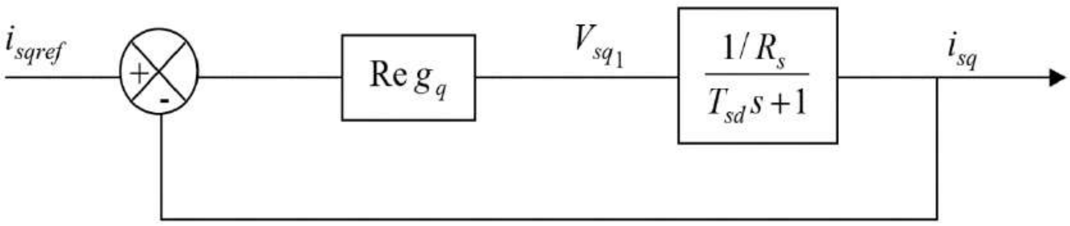


Figure II.10: Torque regulator

Knowing that ($\mathrm{Re}g_q$) has the same form as ($\mathrm{Re}g_d$), and if we choose $\tau_{sq} = T_{sq}$, the transfer function becomes:

$$Reg_q(s) = \frac{R_s}{T_{sq}}\left(\frac{1+T_{sq}}{s}\right), \qquad T_{sq} = \frac{L_{sq}}{R_s} \quad \text{(II.35)}$$

II.5.2.3. Speed regulator control

The transmittance of the PI regulator used can be expressed as follows:

$$KP + \frac{K_i}{P} = \frac{k_i}{P}(1+\tau s) \quad \text{(II.36)}$$

With:

$$\tau = \frac{KP}{K_i} \quad \text{(II.37)}$$

The system transfer function (machine + PI regulator) is given by:

$$\frac{\Omega(s)}{\Omega_i(s)} = \frac{1+\tau s}{\frac{J}{Ki}s^2+\tau s+1} \tag{II.36}$$

Comparing the characteristic equation (II.36) with the standard form of the second order, we find:

$$\frac{K_i}{J} = \omega_0^2 \tag{II.37}$$

$$\tau = \frac{2\xi}{\omega_0} \tag{II.38}$$

With ξ damping coefficient.

From equations (II.37) (II.38) and for ξ = 1, we have:

$$K_i = \frac{4J}{\tau^2} \tag{II.39}$$

The time constant associated with the regulator τ is chosen based on the stator time constant in the q axis by $\tau = \frac{L_{sq}}{R_s}$, which characterizes torque dynamics.

Consequently: $K_p = K_i\tau$

The cruise control loop is given in Figure (II. 11)

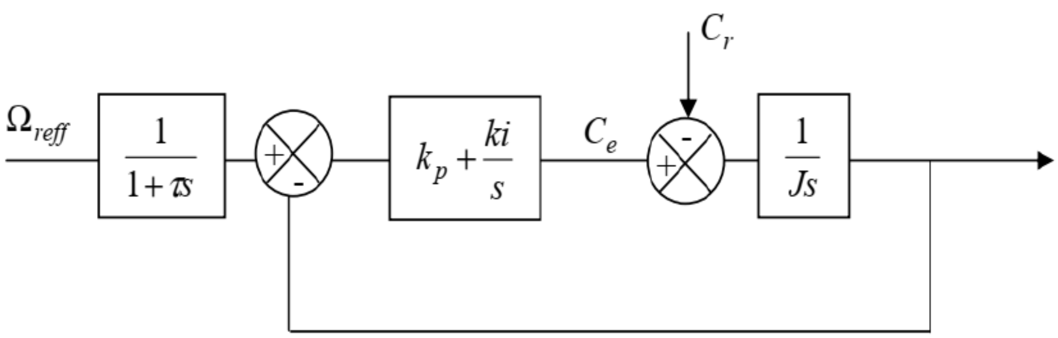


Figure II.11: Speed control

The principle of this method (indirect control structure of the voltage-supplied variable reluctance synchronous machine) is illustrated in Figure (II. 13).

II.5.3. Deflux block

The deflux block allows the exploitation of the magnetic capacities of the machine allows constant torque operation if the speed is lower than the nominal speed. On the other hand, this block makes it possible to weaken the flow inversely to the speed, for operation at constant power when the speed exceeds the nominal speed. It is defined by the following nonlinear relation [8] :

$$\varphi_{ref} = \begin{cases} \varphi_{ref} & si\ |\Omega| \leq \Omega_0 \\ \varphi_{ref}\dfrac{\Omega_0}{|\Omega|} & si\ |\Omega| > \Omega_0 \end{cases} \tag{II.40}$$

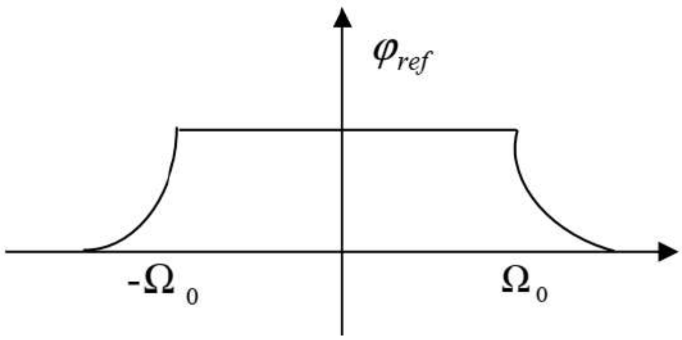


Figure II.12: Deflux block

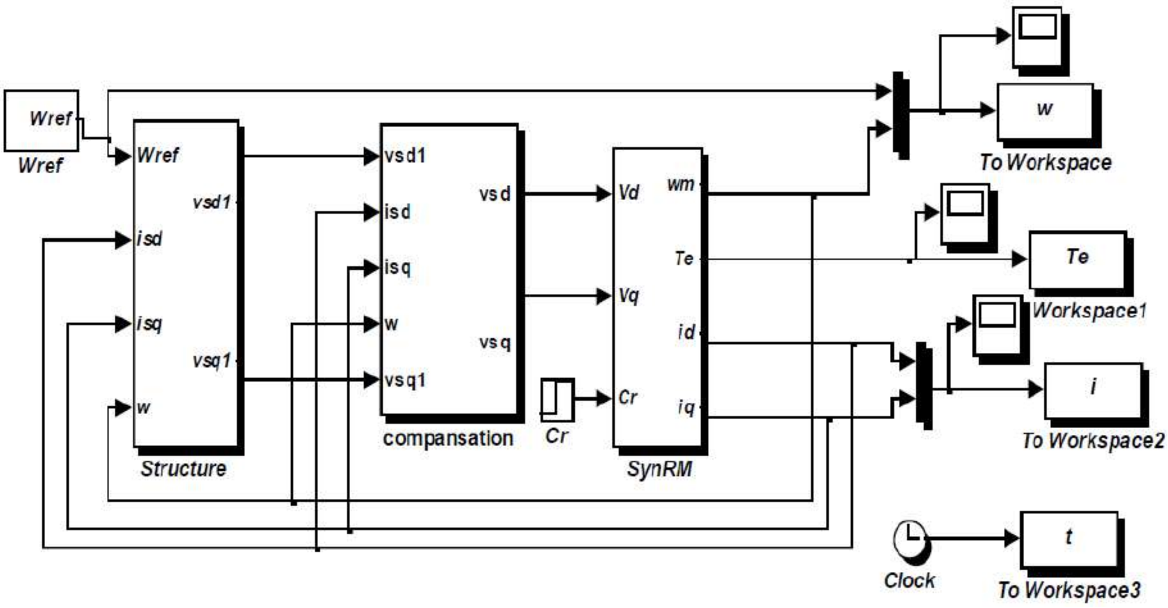


Figure II.13: SynRM simulation diagram

II.6. Simulation results

This section presents the simulation results of the Field oriented control applied to a voltage-supplied MSRV machine.

The simulation results figure (II.14), (II.15), (II.16), show the performance of the control since the speed is obtained without exceeding with a short response time because the machine is empty and the inertia is low.

During start-up, the torque reaches the limit value 2.8Nm and stabilizes at a reference value in steady state.

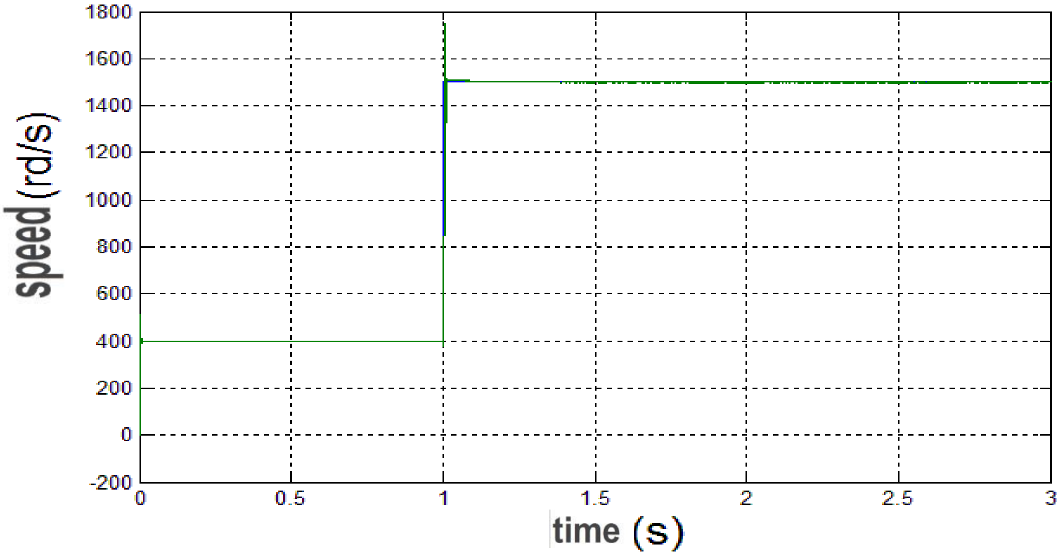
The response of the two components of the stator current.

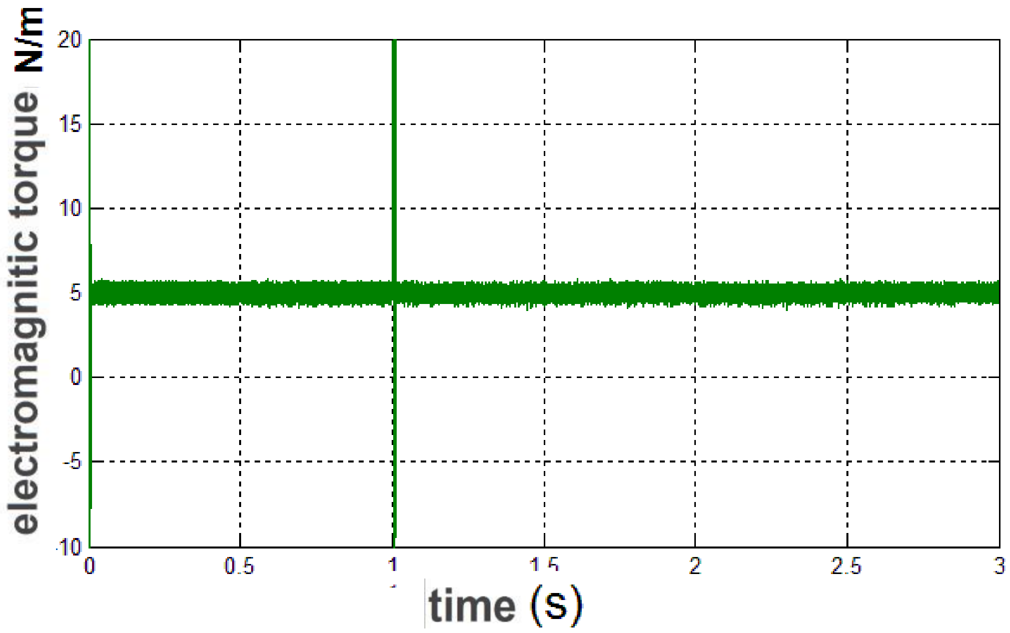
The response of the two components of the stator current shows the decoupling introduced by the Field oriented control of the machine with the electromagnetic torque which depends only on the component (iq).

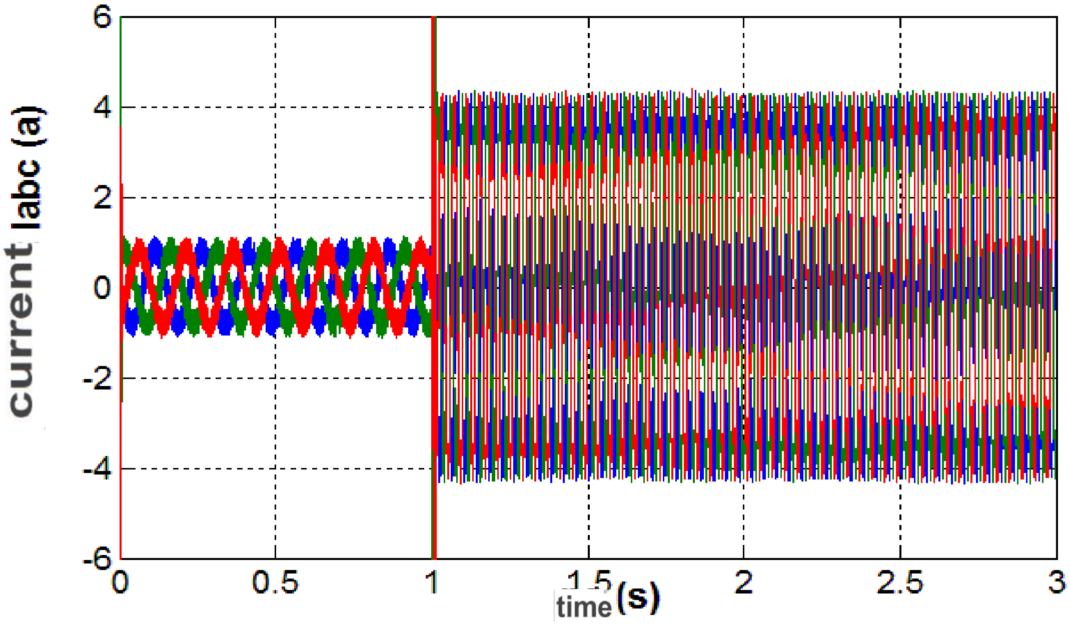
II.6.1. Simulation results of the Field oriented control of the SynRM:

II.6.1.1. Speed Variation:

a. speed variation 400 to 1500 rpm







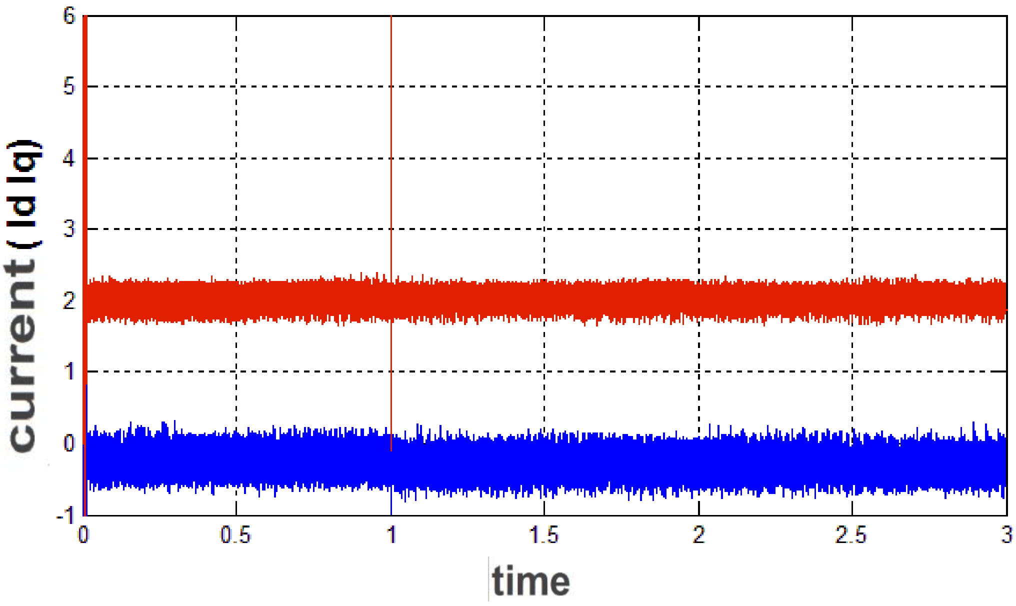


Figure II.14: Simulation results when simultaneously varying speed parameters 400 rd/s

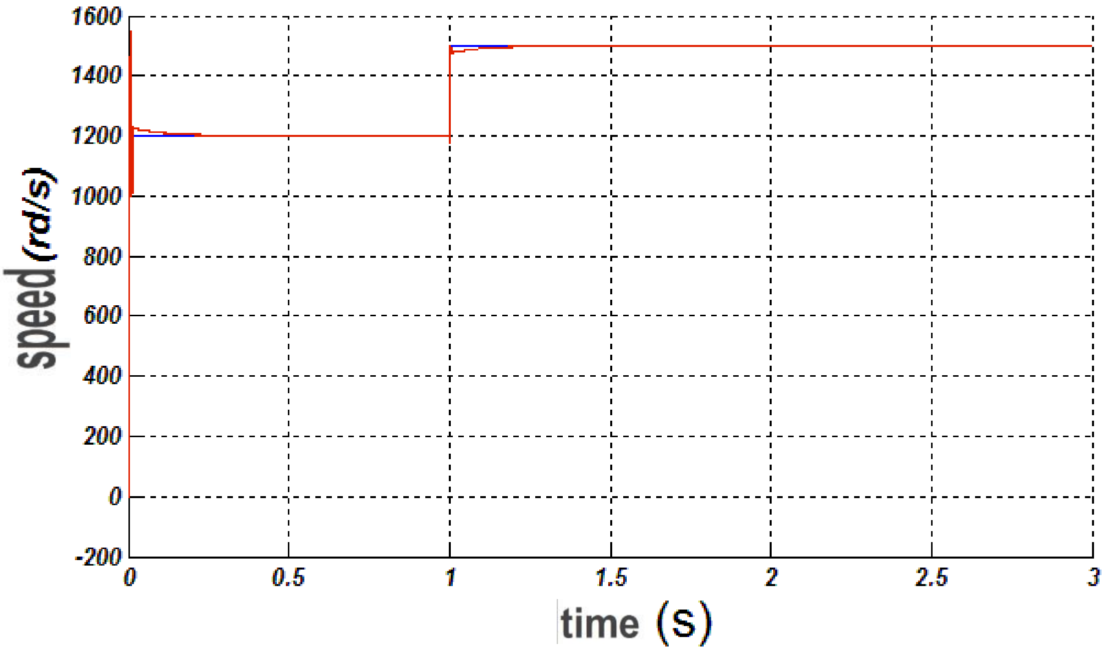
Based on the simulation results of the Field oriented control of the SynRM, it appears that the system is capable of achieving smooth and accurate speed variation between 400 to 1500 rpm. This is a promising result, as it suggests that the Field oriented control approach is effective in regulating the motor's speed and maintaining it at the desired level.

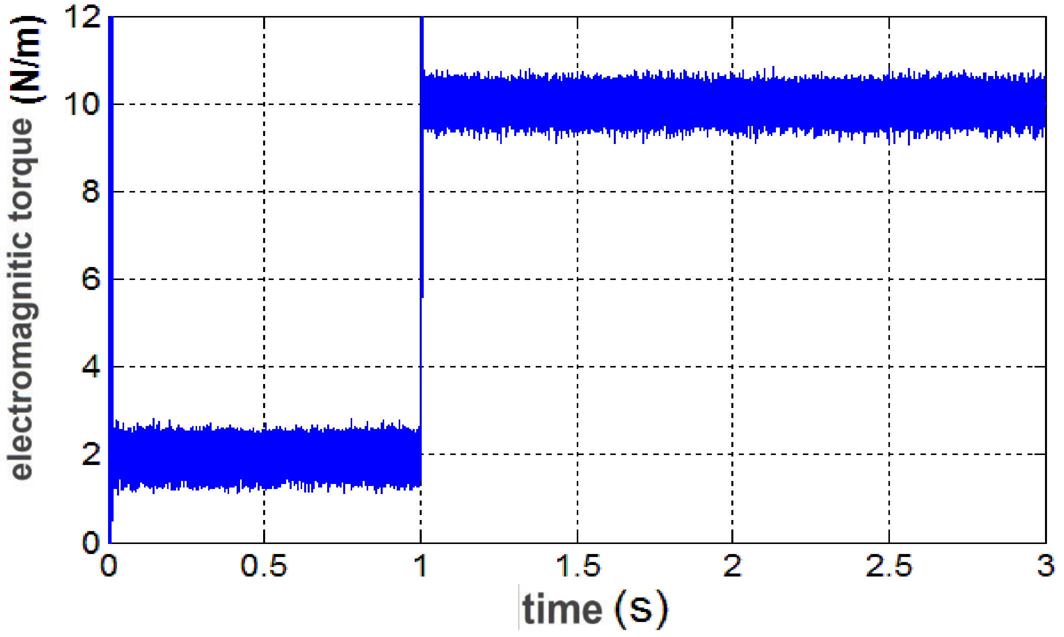
The ability to control motor speed is critical in many industrial applications, and the SynRM's Field oriented control system's performance in this regard is a significant advantage.

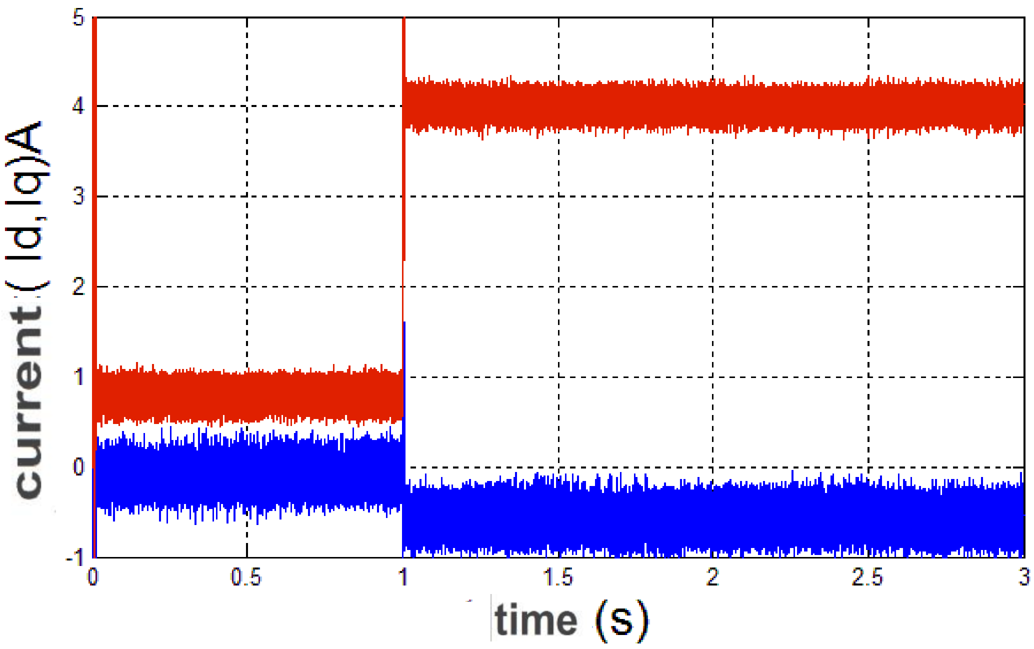
The smooth and accurate speed variation achieved can help improve the motor's efficiency, reduce energy consumption, and minimize wear and tear on the motor.

Overall, the simulation results suggest that the Field oriented control approach is a viable option for controlling the SynRM's speed, and further testing and validation could lead to its widespread adoption in industrial applications.

b. Speed Variation from 1200 to 1500 rpm







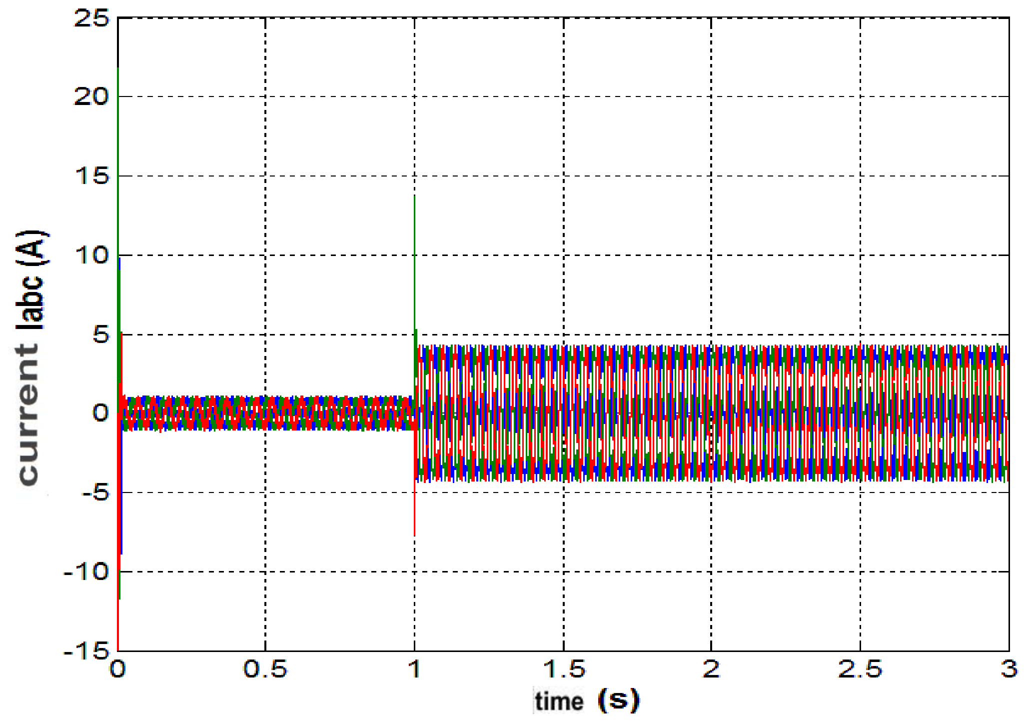


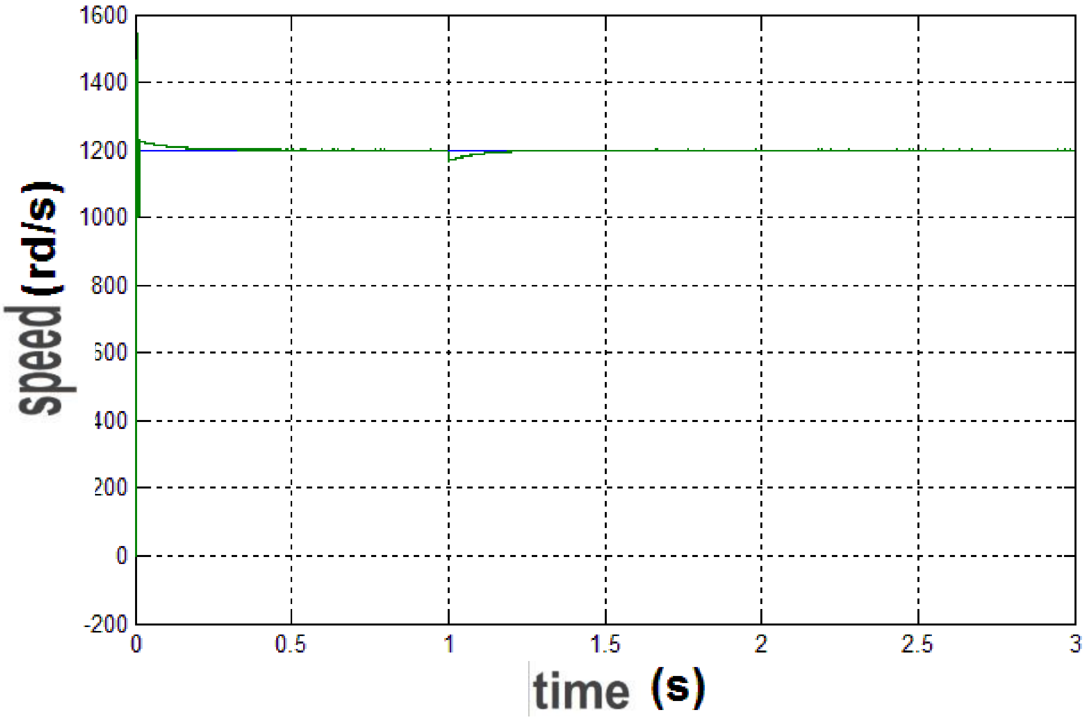
Figure II.15: Simulation results when simultaneously varying parameters speed 1200 rd/s

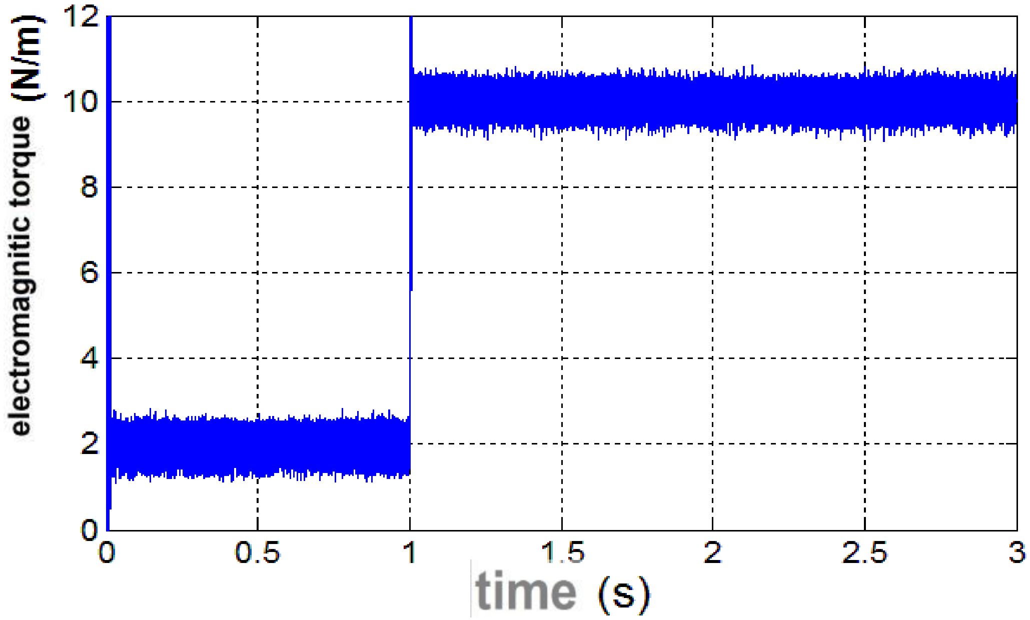
Figure II.15 shows the simulation results of the Field oriented control of the SynRM when simultaneously varying speed parameters from 400 to 1200 rpm, and then to 1500 rpm. The results indicate that the Field oriented control system is capable of smoothly and accurately adjusting the motor speed in response to these changes.

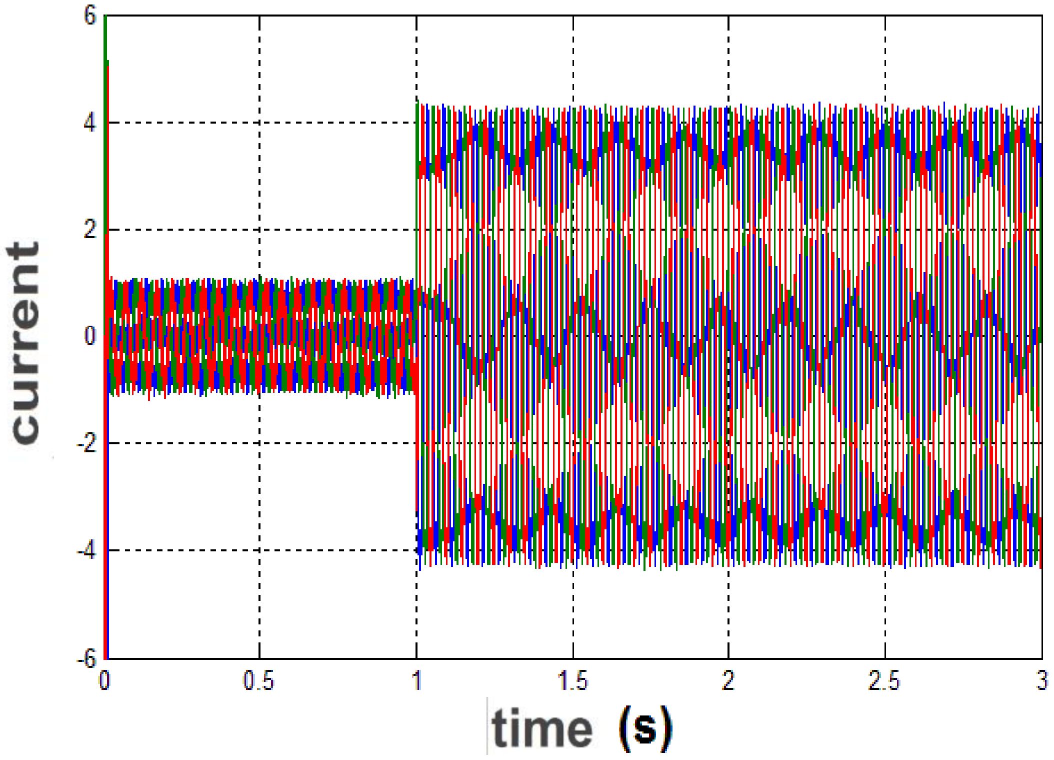
In particular, the gear change from 1200 to 1500 rpm is a challenging scenario that can result in significant disturbances to the motor speed. However, the simulation results show that the Field oriented control system is able to respond quickly and effectively to these disturbances, resulting in a smooth transition to the new speed setting.

Overall, the simulation results presented in Figure II.15 are promising, as they suggest that the Field oriented control approach can effectively regulate the motor speed even under challenging scenarios. Further testing and validation of the approach could help confirm its effectiveness in real-world industrial applications.

c. Torque Variation from 2-10N.m







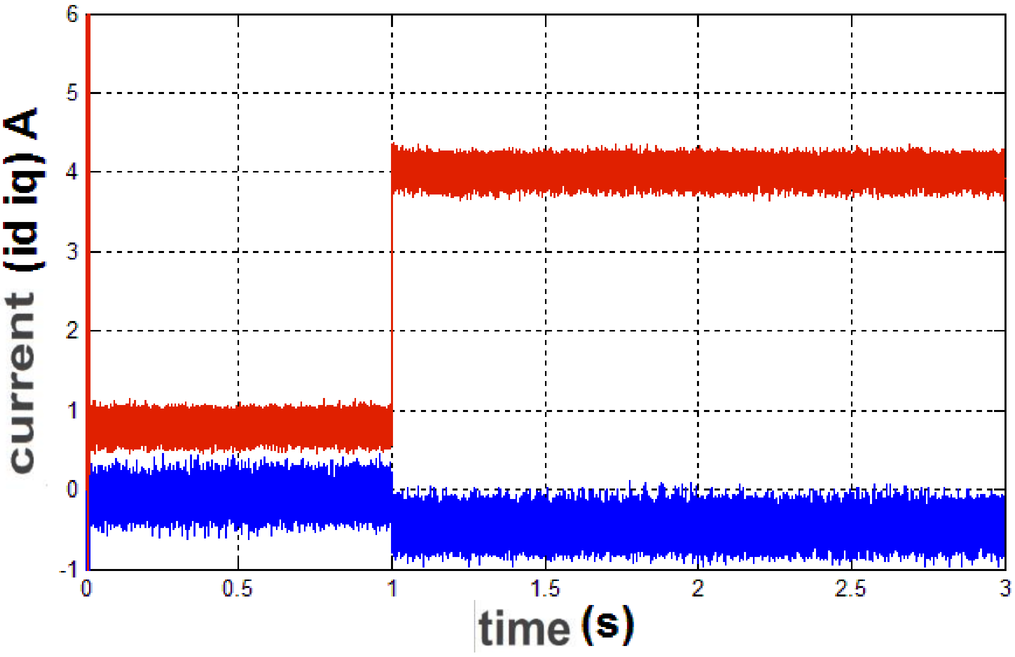


Figure II.16: Simulation results change Torque 2-10

Figure II.16 presents the simulation results of the Field oriented control of the SynRM when simultaneously varying parameters speed at 1200 rd/s and changing the charging torque from 2 to 10. The results indicate that the Field oriented control approach can effectively regulate the motor speed under varying load conditions.

The simulation results show that the motor's speed is maintained at the desired level, despite significant variations in load torque. This is a critical feature for industrial applications where the motor is subjected to varying loads, and precise speed control is essential.

Moreover, the simulation results suggest that the Field oriented control approach is robust and can handle significant variations in load torque without compromising the motor's performance. This is an important consideration for industrial applications where the motor must operate reliably and consistently in changing operating conditions.

Overall, the simulation results presented in Figure II.16 demonstrate the effectiveness of the Field oriented control approach in regulating the SynRM's speed under varying load conditions. Further testing and validation could help confirm the approach's effectiveness in real-world industrial applications.

II.7. Conclusion

The work presented is in the field of control of permanent magnet synchronous machines.

Since the speed control is the main control lever of such a motor, we have focused our work on the study and analysis of the performance of the autopilot of the SynRM powered by PWM voltage inverter is controlled by Field oriented control.

In this chapter we presented the study and modeling of a voltage inverter controlled by PWM, the choice of this technique allowed us to optimize the operation of the SynRM by eliminating the maximum of low rank harmonics.

Chapter III

Model Predictive Current Control of Synchronous Reluctance Motors

III.1. Introduction

Currently, with advances in digital computers, it is almost impossible to find a sector of human activity that is not affected by this phenomenon.

The use of computers in control processes has allowed the implementation of complicated and sophisticated techniques that allow the development of effective strategies while remaining at reasonable cost which was practically impossible to envisage with the previous mechanisms and devices.

Examples of such techniques include nonlinear control, multi-variable control, robust control, and predictive control [20].

Predictive control was born out of a real need in the industrial world. A need for control systems capable of performing higher than conventional controllers, i.e. PID, while respecting ever higher operating and production constraints.

Predictive control is an advanced control technique of automatic. Its objective is to control complex industrial systems. The principle of this technique is to use a dynamic model of the process inside the controller in real time in order to anticipate the future behavior of the process.

Predictive control is part of Internal Model Controller (IMC) techniques. In English we use the term MPC or MBPC to qualify the predictive command, Model (Based) Predictive Control.

Predictive control differs from other control techniques by the fact that must be solved online, it consists in optimizing, from the inputs / outputs of a system (state, torques,), the predicted future behavior of the system considered. The prediction is made from an internal model of the system over a finite time interval called the prediction horizon. The solution of the optimization problem is a control vector whose first input of the optimal sequence is injected into the system. The issue is resolved again on the next time interval using updated system data [21].

Predictive control is also called sliding or leaking horizon control, referring to how the time window considered for calculations is shifted with each iteration. The main advantage of predictive control is its ability to take into account in its very expression the functional constraints and operating constraints of the system considered.

The disadvantage of such a method is the calculation time especially when the model used is non-linear. For this reason, it has been mainly used in the process engineering industry where controlled systems are slow enough to allow implementation with fairly long sampling periods [22].

Predictive control can be used to control complex systems with multiple inputs and outputs where the simple PID controller is insufficient. This technique is particularly interesting when systems have long delays, reverse responses, and many disturbances.

The main users of predictive control are oil refineries, the chemical and food industry, metallurgy, aerospace... The main advantages of predictive control are [20], [21]:

- The ordering strategy can be developed using limited knowledge of the process to be ordered and without imposing a specific type of model.
- Taking into account delays is part of the approach and makes it possible to respect the constraints on the controlled and manipulated variables.
- Avoids excessive variations on the manipulated variables, the control is smoother. This allows a better use of actuators (cylinders, valves, motors) and their service life is thus increased.
- When signals and actuators fail, control as much of the process as possible.
- In the event of measurable disturbances, the system adapts automatically.
- Multivariate cases can be dealt with quite easily.
- This approach is very useful when the reference signals are known and usually allows a real financial gain.
- The implementation of the control law is simple and the calculation time is not prohibitive.

In this chapter we present the strategy and a historical summary of predictive control, then we expose the description and theoretical analysis of the MPC algorithm in, plus model-based predictive control is studied in order to improve the performance of this MPC.

Finally, a demonstration of the simulation results indicating the performance of the MPC controller applied to the MSAP is presented in the last part.

III.2 Predictive control

Predictive control is an advanced control technique of automatic. Its objective is to control complex industrial systems. It was born out of a real need in the industrial world. A need for control systems capable of higher performance than conventional controllers, namely PID, while respecting ever higher operating and production constraints. The principle of this technique is to use a dynamic model of the process inside the controller in real time in order to anticipate the future behavior of the process Predictive control is part of internal model controller (IMC) techniques. In English we use the term MPC or MBPC to qualify the predictive command, Model (Based) Predictive Control [23] .

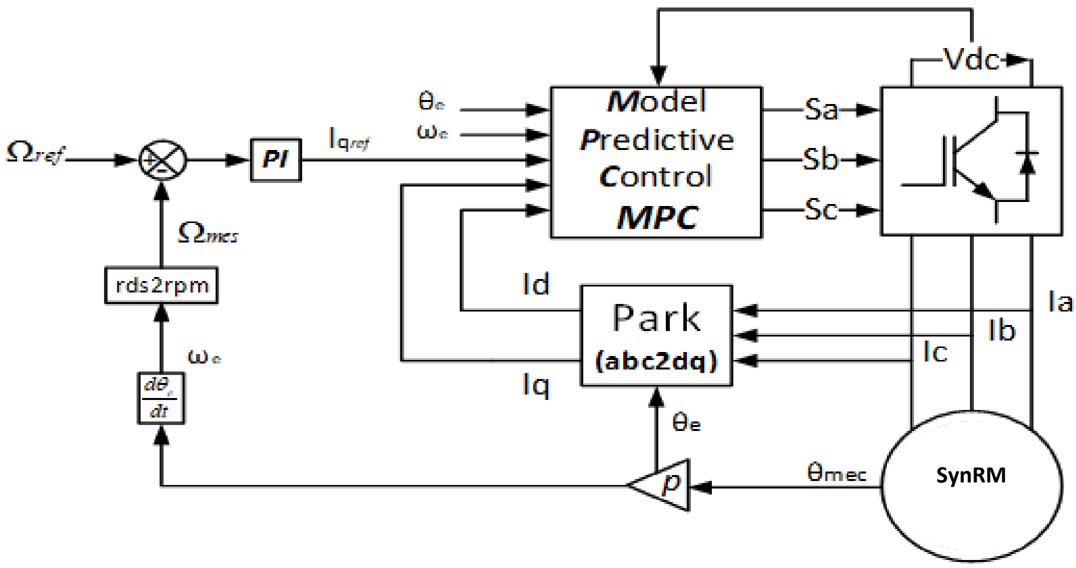


Figure III.1: Schematic diagram of predictive control.

The proposed predictive control strategy is based on the fact that only one finite number of possible switching states can be generated by a static power converter and that the system can be used to predict the behavior of variables for each switching state.

For the choice of the appropriate switching state to be applied, a selection criterion must be defined. This criterion consists of a cost function that will be evaluated for the predicted values of the variables to be controlled. The prediction of the future value of these variables is calculated for each possible switching state, and then the state that minimizes the cost function is selected.

The purpose of the control system is to minimize the error between the measured currents and their reference values. This requirement can be written as a cost function that can be expressed in orthogonal coordinates (α , β) or in rotating coordinates (d ,q). And it measures the error between the predicted references and currents as follows [24]:

$$g = \left(i_d(k+1)\right)^2 + \left(i_q^* - i_q(k+1)\right)^2 \qquad \text{(III.1)}$$

With:

- $i_d(K+1)$ and $i_q(K+1)$ are the predicted direct and quadrature components of the load current.
- i_d^* and i_q^* are the reference currents that can be obtained from an external control loop such as: the FOC control.

The derivative of the charge current d_i/d_t is replaced by a forward Euler approximation. This approximation is of the form:

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T_e} \qquad \text{(III.2)}$$

where: T_e: the sampling period

Starting from the mathematical equations of the MSAP in Park's rotating reference frame; The expressions of the currents predicted at time k+1 can be written as follows:

$$\begin{cases} i_d(k+1) = \left(1 - \left(\frac{R}{L}.T_e\right)\right) i_d(k) + \left(T_e.\omega_e.i_q(k)\right) + \frac{V_d(k)}{L}.T_e \\ i_q(k+1) = \left(1 - \left(\frac{R}{L}.T_e\right)\right) i_q(k) - \left(T_e.\omega_e.i_d(k)\right) - (\varphi_r.\omega_e.T_e) + \frac{V_q(k)}{L}.T_e \end{cases} \qquad \text{(III.3)}$$

With:

$V_{d,q}(k)$: the components of the 7 values of the voltage vector generated by the inverter according to the states of the keys S_{abc} as follows:

S_a	S_b	S_c	Voltage vector V
0	0	0	$V_0 = 0$
1	0	0	$V_1 = \frac{2}{3}V_{dc}$
1	1	0	$V_2 = \frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	0	$V_3 = -\frac{1}{3}V_{dc} + j\frac{\sqrt{3}}{3}V_{dc}$
0	1	1	$V_4 = -\frac{2}{3}V_{dc}$
0	0	1	$V_5 = -\frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
1	0	1	$V_6 = \frac{1}{3}V_{dc} - j\frac{\sqrt{3}}{3}V_{dc}$
1	1	1	$V_7 = 0$

Table (III.1): Voltage vectors according to key states in the plane (α, β)

The optimization of the cost function makes it possible to choose the appropriate voltage vector to apply to the converter and this makes it possible to generate the components V_d (k) and V_q (k) from the following transformation:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & \sin(\theta_e) \\ -\sin(\theta_e) & \cos(\theta_e) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{III.4}$$

where: $V_x = V_\alpha + jV_\beta$ With: $x \in \{0,1,\ldots,7\}$

III.3 General strategy of predictive control

In general, the predictive control law is obtained from the following methodology:

- Predict future outputs of the process on the defined prediction horizon, using the prediction model. Denote *y(t+k / t)* , *k =0....... N*, the predicted outputs and by N the prediction horizon. These outputs are dependent on the known output and input values of the process to be controlled up to time t.
- Calculate the sequence of control signals, denoted by you *(t + k /t), k = 0.....N-1*, minimizing a performance criterion in order to lead the output of the process to a reference output. We denote by *w(t+k/t), k=0.......N*, usually the performance criterion to be minimized is a compromise between a quadratic function of errors between *y(t+k/t)* and *w(t+k/t)* and a cost of control effort. Moreover, the minimization of such a function can be subject to constraints on the state and more generally to constraints on the control.
- The *u(t/t)* control signal is sent to the process while the other control signals are forgotten. At time *t+1* we acquire the real output *y(t+k/t)* and we start again at the first [20].

Figure III.1 illustrates this methodology and its implementation uses the basic structure shown in Figure III.3. The two fundamental loops to notice in this figure are the model and the optimizer. The model must be able to capture process dynamics, predict future outputs accurately and its implementation must be easy, the optimizer provide control actions.

In the presence of constraint, the solution is obtained via iterative algorithms, with more computational time, of course [11].

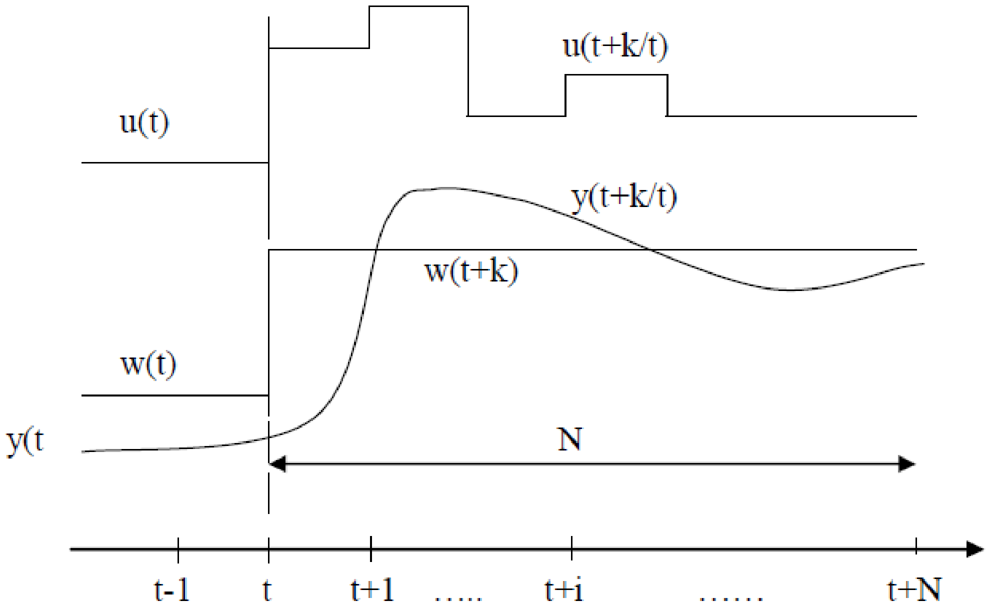


Figure III.2: The methodology of the OAG

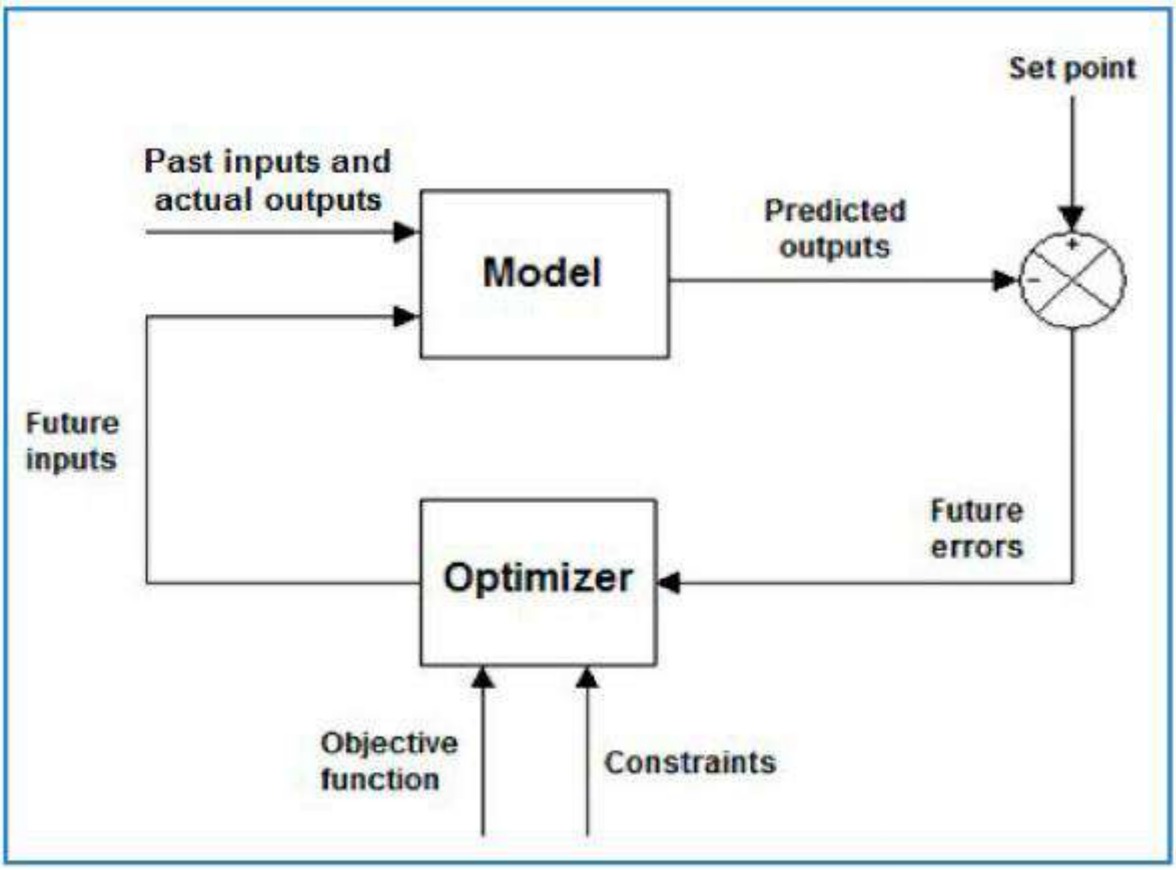


Figure III.3: The block diagram of the basic structure of MPC algorithms

III.4. Comparison of predictive control with vector control

First, a comparison between predictive control and vector control has been made in this table in order to know the specification of the two control techniques that appear in table (III.2), or table (III.3) illustrates the advantages and disadvantages of two techniques.

Elements	**Vector**	**MPC**
frame	d,q	d,q
Controlled variables	Axes d, q	Axes d, q
Rotor Position	Required	Required
Modulator	Required	No Required
Switching frequency	Constant	Varies around average frequency
Controllers	Full proportional regulators (PI)	Cost function optimization

Table III.2: The different characteristics of two techniques

Elements	**Vector**	**MPC**
Benefits	• Compatibility and simple implementation • Precise current control • High steady-state performance	•Integration of nonlinearities, constraints and variables. • High dynamics • Quick response
Disadvantages	• Low dynamics • High calculation • Low robustness	• High load for multilevel converters

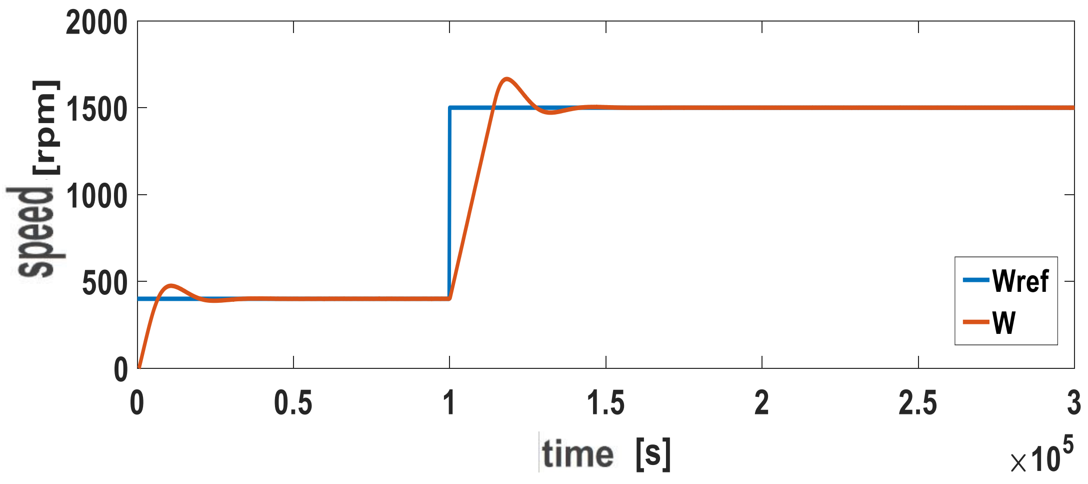
Table III.3: The advantages and incontinence of MPC and Vector Control

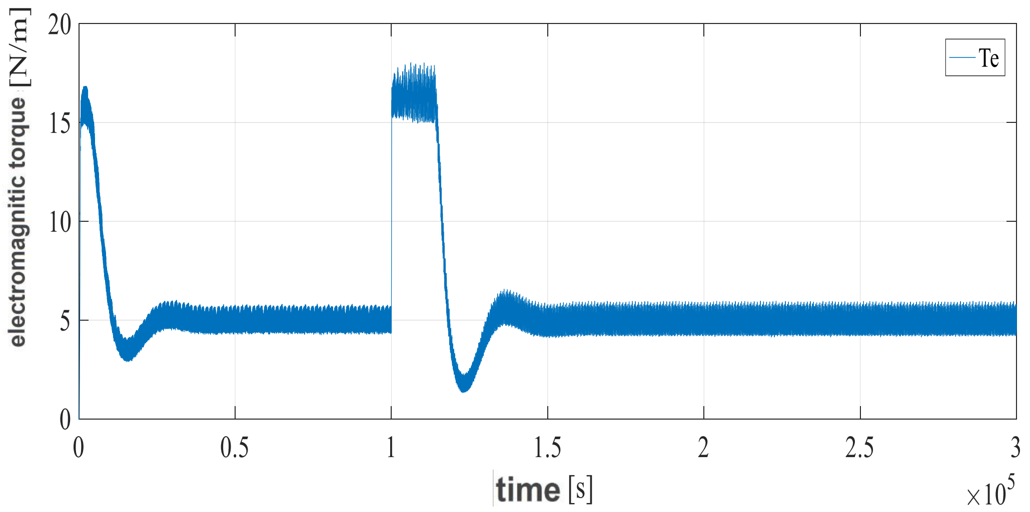
III. 5 Simulation result

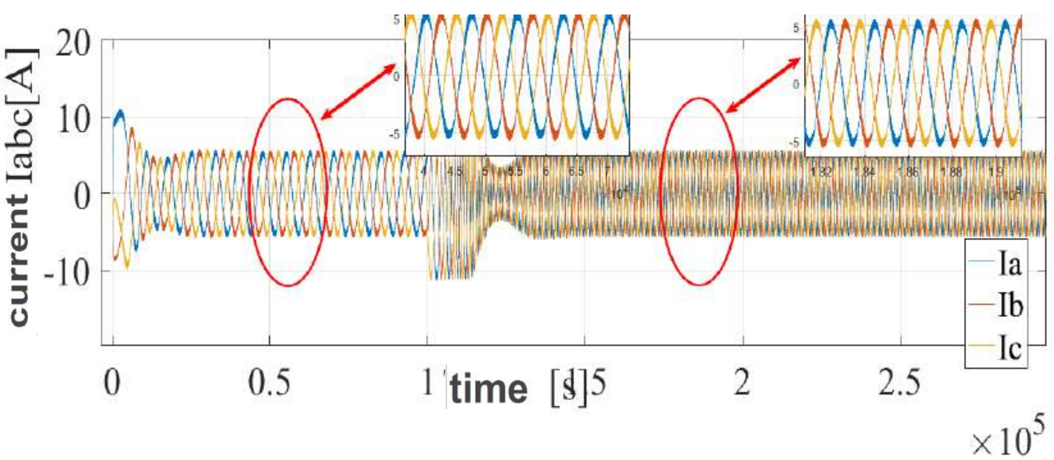
III.5.1. Simulation results of the predictive control of the SynRM:

III.5.1.1. Speed Variation:

a. speed variation 400 to 1500 rpm







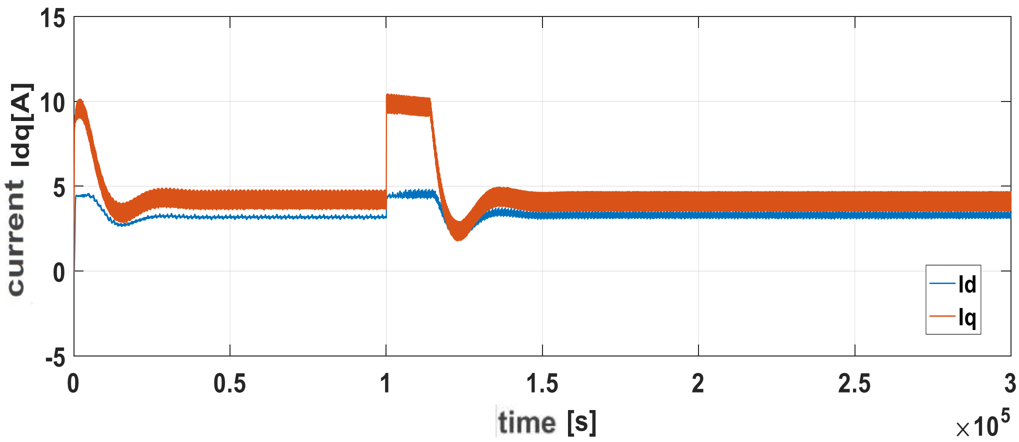


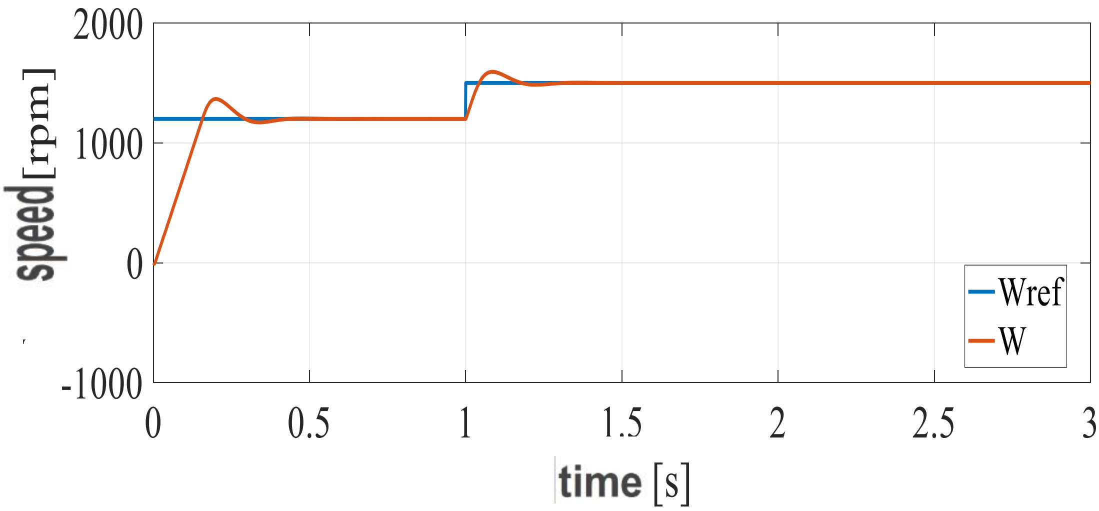
Figure III.4: Simulation results when simultaneously varying speed parameters 400 rd/s

Figure III.4 shows the simulation results of the predictive control of the SynRM when simultaneously varying speed parameters from 400 to 1200 rpm, and then to 1500 rpm. The results indicate that the predictive control system is capable of smoothly and accurately adjusting the motor speed in response to these changes.

In particular, the gear change from 1200 to 1500 rpm is a challenging scenario that can result in significant disturbances to the motor speed. However, the simulation results show that the predictive control system is able to respond quickly and effectively to these disturbances, resulting in a smooth transition to the new speed setting.

Overall, the simulation results presented in Figure III.4 are promising, as they suggest that the predictive control approach can effectively regulate the motor speed even under challenging scenarios. Further testing and validation of the approach could help confirm its effectiveness in real-world industrial applications.

b. Speed Variation from 1200 to 1500 rpm



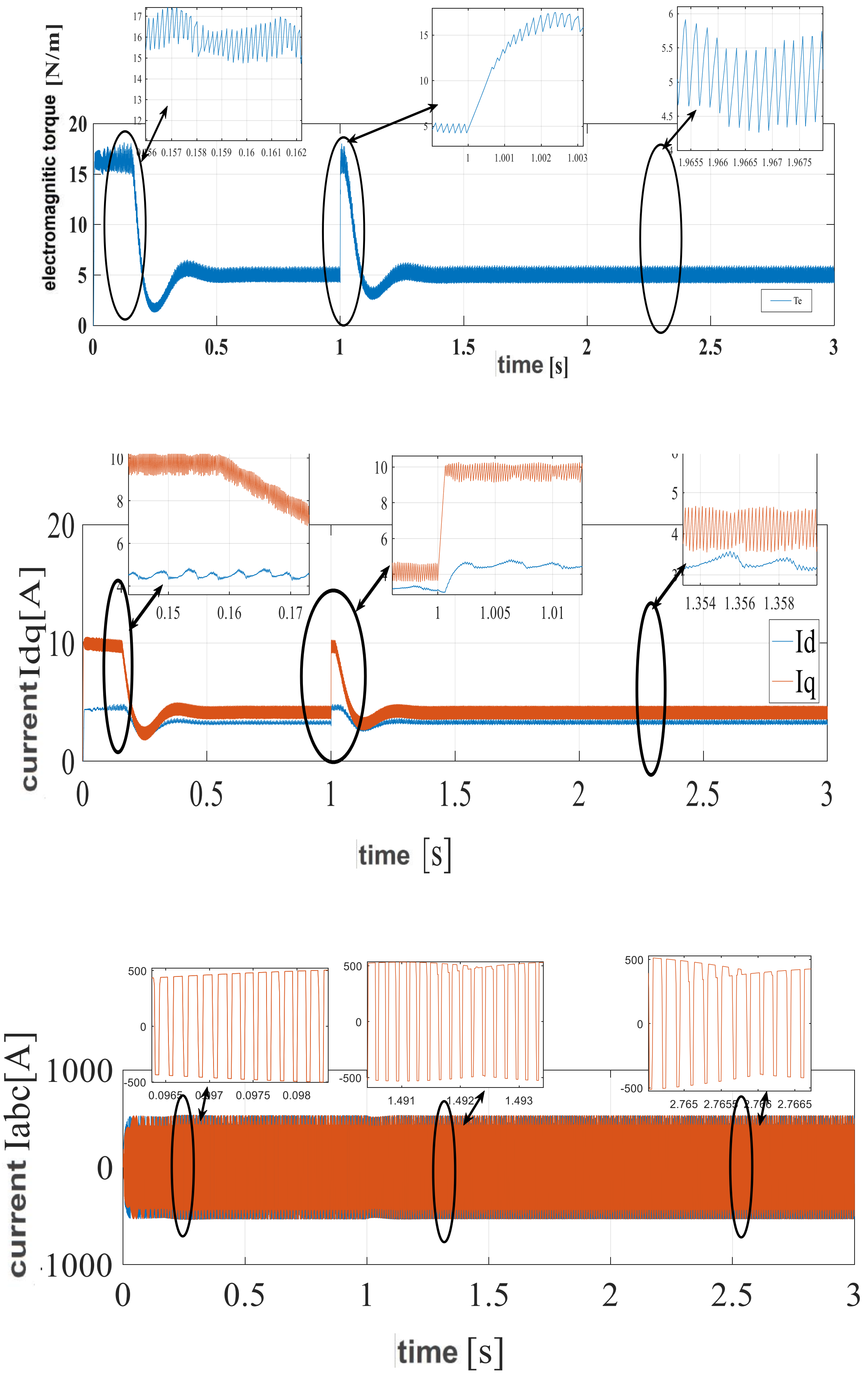


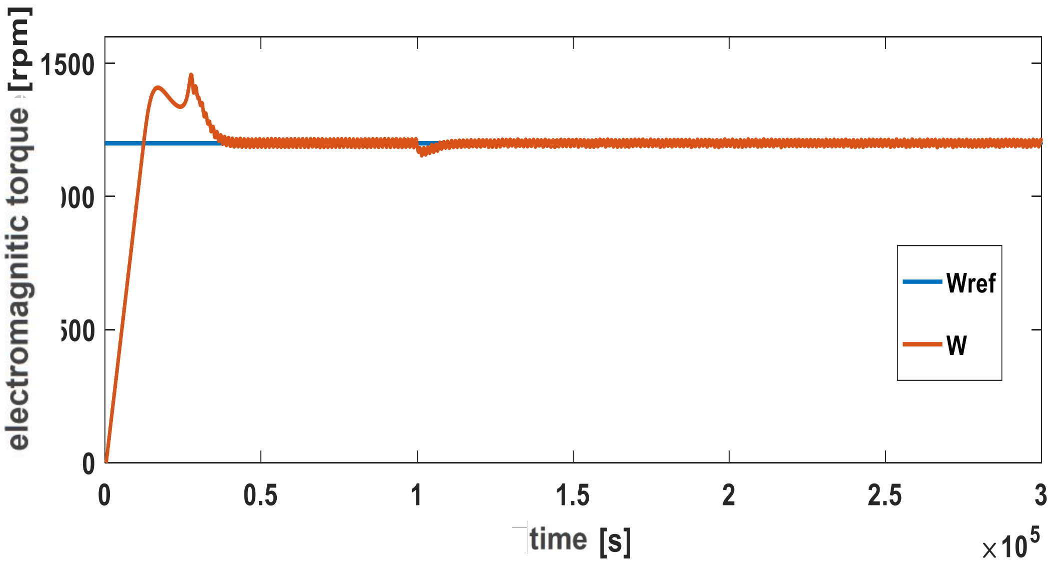
Figure III.5: Simulation results when simultaneously varying parameters speed 1200 rd/s

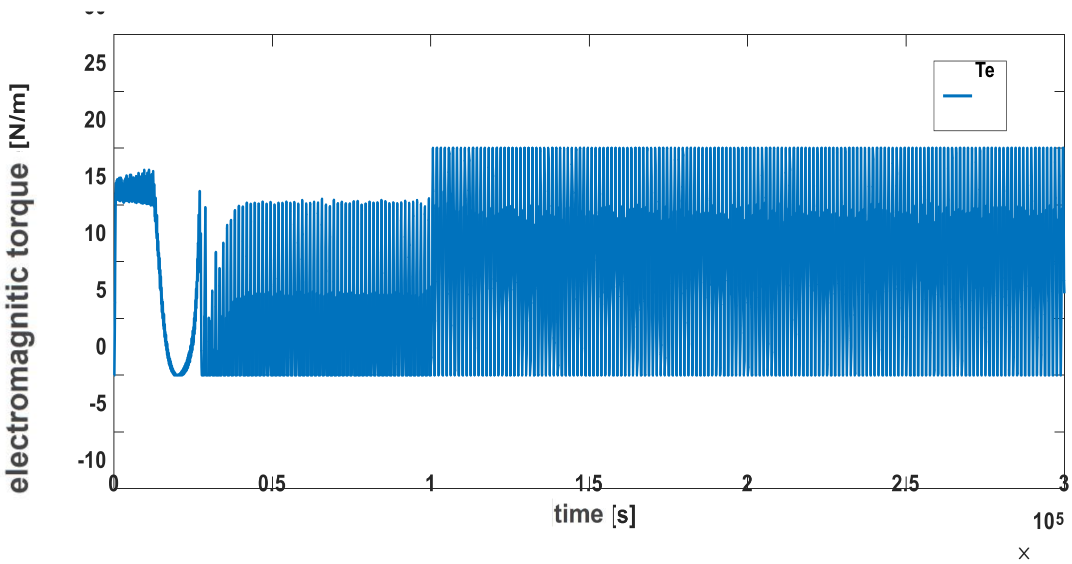
Figure III.5 shows the simulation results of the predictive control of the SynRM when simultaneously varying speed parameters from 400 to 1200 rpm, and then to 1500 rpm. The results indicate that the predictive control system is capable of smoothly and accurately adjusting the motor speed in response to these changes.

In particular, the gear change from 1200 to 1500 rpm is a challenging scenario that can result in significant disturbances to the motor speed. However, the simulation results show that the predictive control system is able to respond quickly and effectively to these disturbances, resulting in a smooth transition to the new speed setting.

Overall, the simulation results presented in Figure III.5 are promising, as they suggest that the predictive control approach can effectively regulate the motor speed even under challenging scenarios. Further testing and validation of the approach could help confirm its effectiveness in real-world industrial applications.

c. Load Torque Variation 2 to 10 N.m





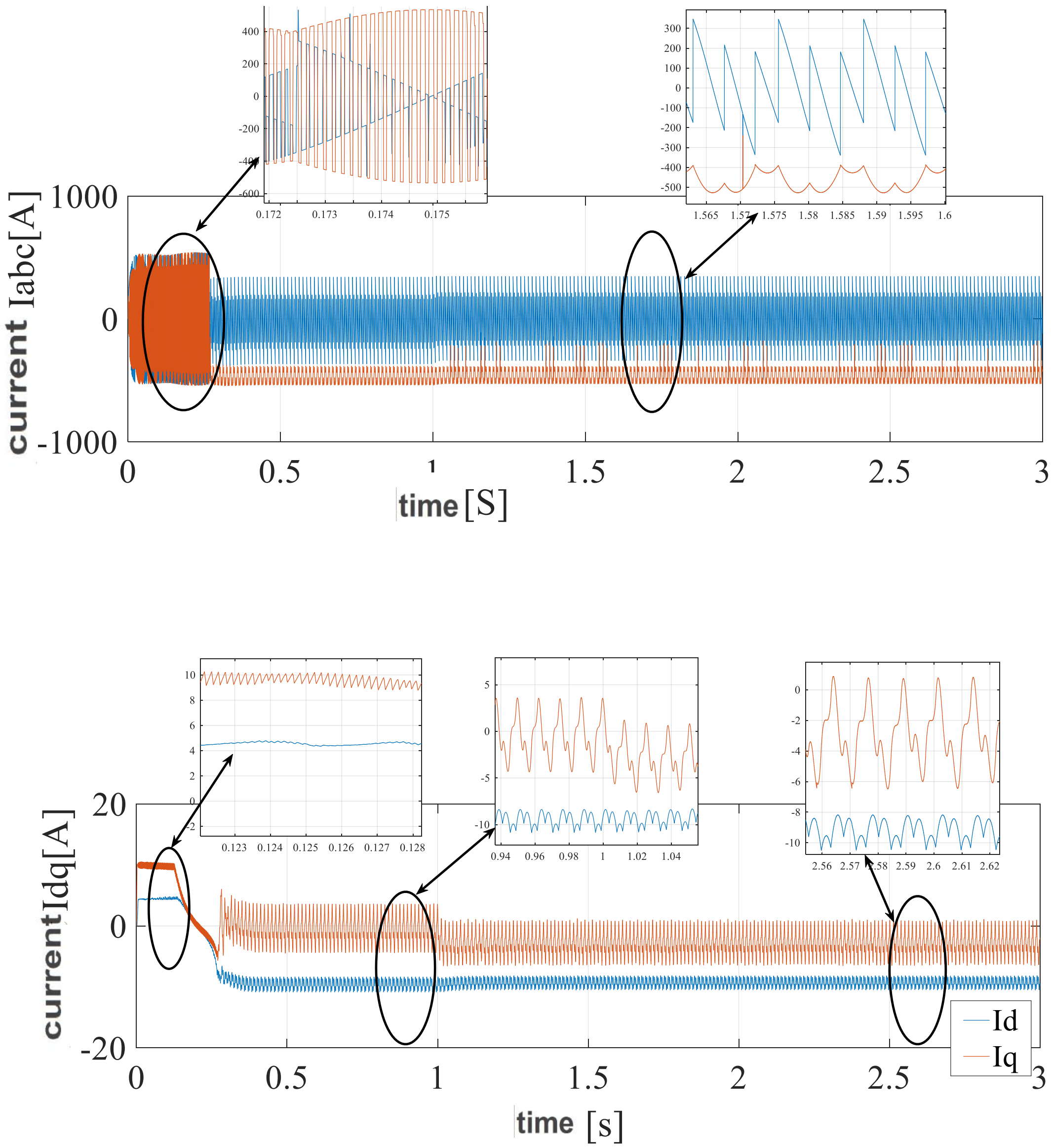


Figure III. 6: Simulation results Torque Variationfrom 2-10 N.m

Figure III.6 presents the simulation results of the predictive control of the SynRM when simultaneously varying parameters speed at 1200 rd/s and changing the charging torque from 2 to 10. The results indicate that the predictive control approach can effectively regulate the motor speed under varying load conditions.

The simulation results show that the motor's speed is maintained at the desired level, despite significant variations in load torque. This is a critical feature for industrial applications where the motor is subjected to varying loads, and precise speed control is essential.

Moreover, the simulation results suggest that the predictive control approach is robust and can handle significant variations in load torque without compromising the motor's performance. This is an important consideration for industrial applications where the motor must operate reliably and consistently in changing operating conditions.

Overall, the simulation results presented in Figure III.6 demonstrate the effectiveness of the predictive control approach in regulating the SynRM's speed under varying load conditions. Further testing and validation could help confirm the approach's effectiveness in real-world industrial applications.

III.6. Conclusion

In conclusion, Synchronous Reluctance Motors (SynRMs) have emerged as an enticing option for motor applications in recent years. Their straightforward structure, robust characteristics, and impressive efficiency even under high temperature conditions have garnered significant interest. With the advent of novel rotor geometric configurations, SynRMs have become a viable alternative to Induction Motors (IMs) and Permanent Magnet Synchronous Motors (PMSMs), offering advantages such as cost-effectiveness and enhanced durability by eliminating the need for magnetic materials on their rotors.

To ensure optimal performance, advanced control techniques have been employed for SynRM drives. Vector control, direct torque control, and model predictive control (MPC) methods have been widely utilized. Among these, Finite-Control-Set MPC (FCS-MPC) has garnered substantial attention due to its intuitive concept, ability to accommodate nonlinear constraints, and rapid control dynamics. This makes FCS-MPC a promising choice for power electronics and drive systems. Previous research has successfully applied FCS-MPC in various domains, including AC motor drives, matrix converters, back-to-back converters, and multilevel converters.

However, the control performance of SynRMs is significantly influenced by magnetic saturation and iron losses. Magnetic saturation can result in inaccurate modeling, while iron losses can compromise the developed torque. Consequently, extensive efforts have been devoted to addressing these challenges. Techniques such as magnetic saturation compensation and iron losses identification have been proposed to mitigate these effects and improve the performance of SynRM drives.

In this study, a novel FCS-MPC technique is presented, incorporating both magnetic saturation and iron losses in SynRMs. Lookup tables are employed to incorporate the resistance of iron losses and direct/quadrature inductances into the control scheme. These table values are dynamically selected based on the specific operating conditions. Comparative analysis is performed against a similar control approach where constant inductance values are assumed, and iron losses are disregarded. The experimental and simulation results, obtained using a high-efficiency SynRM, validate the effectiveness of the proposed predictive control scheme.

Overall, this study highlights the significance of considering magnetic saturation and iron losses in the control of SynRMs. By integrating these factors into the FCS-MPC technique, the motor's performance can be substantially enhanced. The findings of this research contribute to the ongoing advancement of SynRM technology and pave the way for improved control strategies in various industrial applications.

General Conclusion

GENERAL CONCLUSION

In conclusion, both the second and third chapters of this research work have made significant contributions to the understanding and application of advanced control techniques in the Synchronous Reluctance Motor.

The second chapter focused on the important topic of Field-Oriented Control (FOC), emphasizing the role of inverters in electric motor speed drives. The introduction of FOC as a control method, enabling independent control of magnetic field and torque components, showcased its potential in addressing the complexity of SynRM. Moreover, the simulation testo of FOC with SynRM under speed and Load torque variation iprove that this control is reliable under different operating condition but need more tuning efforts since it need three PI regulators. On the other hand, the third chapter was focus on predictive control, with a particular focus on Model Predictive Current Control (MPC). It presented the historical background and theoretical foundations of MPC as an advanced control strategy. The development of a simulation program using Simulink/Matlab enabled the validation of the theoretical framework, demonstrating the impressive performance of Model Predictive Control (MPC) on a SynRM through simulation results.

Although both chapters provided valuable insights into the field of control strategies for SynRMs, the third chapter, which focuses on predictive control and the demonstration of MPC through simulations, offers a more comprehensive and advanced approach. Moreover, the utilization of MPC and the ability to consider constraints and optimize control actions within a specified time frame prove the superiority of MPC in addressing the complexities of nonlinear systems.

The last chapter's emphasis on predictive control and its practical application through simulations elevates it as a more advanced and effective approach compared to field-oriented control. This research work establishes the importance of predictive control techniques and their potential for enhancing the performance and efficiency of electric motor systems in various industrial applications.

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