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FS-MPC predictive control of matrix converters

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Dedication

I dedicate this modest work to the stars
that light my life, my source of tenderness
"my parents"
These two beings, who knew how to educate me,
who were always behind me
and who pushed me to
move forward.
to our aunts and uncles.
Finally, to all our brothers and sisters.

Thanks:

Before all else we thank "ALLAH" almighty
for giving us strength, determination and patience
to complete this humble work. We would like
to express my thanks to «**Dr. Chikha Said** »
for gave us complete assistance and guidance,
as well as his valuable advice and continuous
encouragement with all gratitude and appreciation .

Abstract

Doubly-fed induction motors (DFIG) play an increasingly important role in industrial applications and renewable energy due to their numerous advantages such as flexible speed control and the ability to operate as a generator. In this context, model predictive control plays a pivotal role in achieving high performance for doubly-fed induction motors. Model predictive control (FS-MPC) is characterized by its ability to accurately model the system and take into account operational constraints, enabling optimal control of key variables such as speed, torque, and electrical currents. We also use a Direct Matrix Converter (DMC), which is a direct AC/DC converter connected to the grid, which connects between the AC source and the AC load without the need for energy storage elements such as capacitors. Additionally, model predictive control can achieve multiple objectives such as reducing power losses and improving torque response simultaneously. This thesis focuses on developing and testing model predictive control strategies for doubly-fed induction motors in different operating scenarios, with an emphasis on dynamic performance and efficiency.

Keywords: Doubly-fed induction motor (DFIG), model predictive control (FS-MPC)**.**Direct Matrix Converter (DMC)

Résumé

Les machines asynchrones à double alimentation (MADA)jouent un rôle de plus en plus important dans les applications industrielles et les énergies renouvelables en raison de leurs nombreux avantages tels que le contrôle flexible de la vitesse et la capacité de fonctionner comme un générateur. Dans ce contexte, le contrôle prédictif des modèles joue un rôle central dans l'obtention de performances élevées pour les moteurs à induction à double alimentation. Le contrôle prédictif de modèle (FS-MPC) se caractérise par sa capacité à modéliser avec précision le système et à prendre en compte les contraintes opérationnelles, permettant un contrôle optimal des variables clés telles que la vitesse, le couple et les courants électriques. Nous utilisons également un convertisseur matriciel direct (DMC), qui est un convertisseur AC/DC direct connecté au réseau, qui relie la source AC et la charge AC sans avoir besoin d'éléments de stockage d'énergie tels que des condensateurs. De plus, le contrôle prédictif du modèle peut atteindre plusieurs objectifs, tels que la réduction des pertes de puissance et l'amélioration simultanée de la réponse en couple. Cette thèse se concentre sur le développement et le test de stratégies de contrôle prédictif de modèles pour moteurs à induction à double alimentation dans différents scénarios de fonctionnement, en mettant l'accent sur les performances dynamiques et l'efficacité.

Mots clés : Moteur asynchrone double alimentation (MADA), contrôle prédictif modèle (FCS-MPC).

ملخص

تلعب المحركات غير المتزامنة ثنائية التغذية دوًرا متزايد الأهمية في التطبيقات الصناعية والطاقة المتجددة بفضل مزاياها العديدة مثل التحكم المرن في سرعة الدوران وإمكانية التشغيل كمولد. في هذا السياق، يلعب التحكم التنبؤي دوًرا محورًيا في تحقيق أداء للمحركِل عا ات غير المتزامنة ثنائية التغذية. يتميز التحكم التنبؤي بقدرته على النمذجة الدقيقة للنظام ومراعاة القيود التشغيلية، مما يسمح بالتحكم الأمثل في المتغيرات الرئيسية مثل السرعة والعزم والتيارات الكهربائية.كما نستخدم محول المصفوفة المباشر و هو عبارة عن محول التيار المتردد / التيار المتردد المباشر المتصل بـالشبكة ،التي تتصل بين مصدر ACوحمل ACدون الحاجة إلى عناصرتخزين الطاقة مثل المكثفات ، بالإضافة إلى ذلك، يمكن للتحكم التنبؤي تحقيق أهداف متعددة مثل تقليل فقد الطاقة وتحسين استجابة العزم في نفس الوقت. تركز هذه الأطروحة على تطوير واختبار استراتيجيات التحكم التنبؤي للمحركات غير المتزامنة ثنائية التغذية في سيناريوهات تشغيل مختلفة، مع التركيز على الأداء الديناميكي والكفاءة.

الكلمات المفتاحية: محرك غير متزامن ثنائي التغذية، تحكم تنبؤي , محول المصفوفة المباشر

SUMMARY

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List of Symbols and Notations

Cem	**Electromagnetic torque of DFIG**	[Nm]
g	**DFIG slip**	-
p	**Number of machine poles**	-
m_s	**Stator pulsation of the DFIG**	[rad/s]
Ω_n	**Nominal angular rotation speed of the turbine**	[rad/s]
R_S	**Resistance of the stator winding of the DFIG**	[Ω]
R_f	**Filter resistance RL**	[Ω]
L_f	**Filter inductance RL**	[Ω]
T_s, T	**Sampling period**	[s]
U_s	**Effective value of stator compound voltages**	[V]
V_s	**Effective value of simple stator voltages**	[V]
φ_s	**Effective value of the stator flux of the DFIG**	[Wb]
i_{abc_r}	**Rotor Currents of the DFIG in the three-phase reference**	[A]
i_{abc_s}	**Stator Currents of the DFIG in the three-phase reference**	[A]
i_{abc_g}	**Network Currents in the three-phase reference**	[A]
i_{dq_r}	**Rotor Currents of the DFIG in the two-phase reference**	[A]
i_{dq_s}	**Stator Currents of the DFIG in the two-phase reference**	[A]
i_{dq_g}	**Network Currents in the two-phase reference**	[A]
P_s	**Stator active power of DFIG**	[W]
Q_s	**Stator reactive power of DFIG**	[Var]
v_{ds} , v_{qs}	**DFIG stator voltages in the Park benchmark**	[V]

Abreviations list

AC	**Alternating Current**
DC	**Direct Current**
DMC	**Direct Matrix Converter**
DFIG	**Doubly Fed Induction Generator**
E.M.F	**The Electromotive Force**
EMI	**Electromagnetic Interference**
FS-MPC	**Finite set model predictive control**
GPC	**Generalized Predictive Control**
GSC	**Grid-side converter**
IGBT	**Insulated Gate Bipolar Transistor**
IM	**Induction Machine**
MC	**Matrix Converter**
MPPT	**Maximum Power Point Tracker**
PS	**Power Factor**
RSC	**Rotor-Side Converter**
VSC	**Voltage Source Converters**

General introduction

General Introduction

Power electronics has inevitably become in response to the rising electrical energy consumption and the growing demand for control and energy efficiency. Because of its ability to manage electrical amounts, it is also essential. It is only possible to obtain very good yields. As a result, the use of electronic converters has gradually expanded from industrial to residential settings. Power supply is one of the rapidly expanding fields for power electronics. speed variators, which enable fine torque or speed control over rotating equipment, are used in conjunction with electric motors.

Double fed induction generators (DFIGs) are the most widely used topologies in electrical power conversion systems because of their advantages in medium and high-power applications, including variable speed operating range and operating capacity in all four quadrants. Usually, the rotor is connected to the network through a cascade of two power converters that are positioned in back-to-back mode, whereas the DFIG stator is connected directly to the network.

Enhancing electrical machine control performance is a persistent challenge that is driving the evolution of control structures and philosophies. An intriguing substitute for this was the recently released command finite set predictive control, also known as Finite States Model Predictive Control (FS-MPC).

Finite-state, and occasionally finite-set, predictive control (FS-MPC), first introduced in 2004 by J. Rodriguez and colleagues, presents a compelling substitute and a radically distinct and potent control strategy. converter-machine associations due to the modulator's (PWM or SVM) entirely different approach from internal regulation loops, its fast dynamic response, flexibility in taking constraints into account, and its ability to be implemented with standard commercial microprocessors.

We have organized this memory in III chapters:

The first chapter gives a general explanation of DFIG and Matrix converters, including how to use them, their benefits and drawbacks, and how MC feeds DFIG.

In the second chapter, we focused on the electrical modeling of the double-fed induction generator and the Park conversion used to change it from three-phase to two-phase. We then discuss the modeling and operation of the matrix converter.

In the third chapter, we discussed predictive control applications on DFIG supported by Matrix Converter software and presented the results obtained.

This work will conclude with a general conclusion that enumerates all of the findings.

CHAPTER I: Generalities about the Doubly Fed Induction Generator (DFIG) fed by a Matrix Converter

I.1 Introduction:

This chapter introduces the operation and control of a Doubly-fed Induction Generator (DFIG) system. The dynamic system must be capable of operating over speed range in order to achieve optimum dynamic efficiency by tracking the optimum tip-speed ratio. Therefore, the generator's rotor must be able to operate at a variable rotational speed. the DFIG system therefore operates in both sub- and super-synchronous modes with a rotor speed range around the synchronous speed. The stator circuit is directly connected to the grid while the rotor winding is connected via slip-rings to a three-phase converter. For variable-speed systems where the speed range requirements are small, for example ±30% of asynchronous speed, the DFIG offers adequate performance and is sufficient for the speed. The power electronic converters need only be rated to handle a fraction of the total power – the rotor power – typically about 30% nominal generator power. Therefore, the losses in the power electronic converter can be reduced, compared to a system where the converter has to handle the entire power, and the system cost is lower due to the partially-rated power electronics.

This chapter will introduce the basic features and normal operation of DFIG systems.

1.2 The different conversions of electrical energy:

Static converters allow the signal's spectrum (amplitudes, frequencies, and phases) to be altered. Complex systems consisting of "switches" made of electronic components perform this transformation.

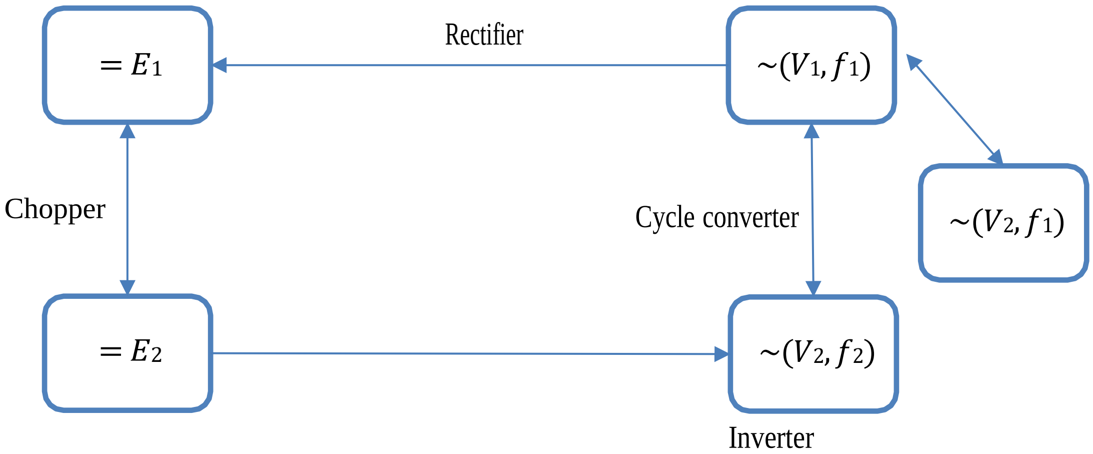


Figure I.1: types of static converters

There are generally four functions of converters in electronics power: DC to DC, AC to DC, DC to AC and AC to AC conversion.

But in addition to these purely functional names, particular names have been given to certain converters.

A converter can play two roles:

1. Modify the form of electrical quantities: current or voltage.
2. Adjust the power of a system

- DC-DC conversion: Chopper
- AC-DC conversion: rectifier
- DC-AC conversion: inverter
- Alternative-alternative conversion: cycle converters.

  In our study, we are interested in AC-AC conversion. Two types of processes can be used to obtain

variable output voltage and frequency values from the network at constant voltage v_i and frequency f_i:

1. Indirect converter: we rectify the network voltages then we undulate the rectified voltage so as to obtain the desired alternating voltages.
2. Direct converter: the cycle converter technique.

I.3 Applications of Power Converters and Drives:

Power converters and drives are used in diverse sectors, ranging from industrial to residential applications [1, 2]. Several application examples for different sectors are shown in Figure (I. 2), where a diagram of the system configuration is shown as an example for each group, marked with $*$.

From the drive applications used in industry, pumps and fans are those that account for most of the energy consumption, with power ratings up to several megawatts. The use of adjustable speed drives can bring important benefits to these kinds of systems in terms of performance and efficiency. Many interesting applications of high-power drives can be found in the mining industry, for example, in downhill belt conveyors. A block diagram of one of these systems is shown in Figure (I. 2), where three-level converters with front-end rectifiers are used for regenerative operation, that is, power flowing from the motors to the grid [3, 4].

Common applications of drives can be found in transportation, where electric motors are used for traction and propulsion. In electric trains, the power is transferred from the overhead lines to the motors using a power converter like the one shown in the figure. This converter generates the required voltages for controlling the torque and speed of the electric motor. High-power drives can be found in ships, where diesel engines are used as generators and the propulsion is generated by electric motors. Newer applications transportation can be found in electric and hybrid vehicles, and in aircraft.

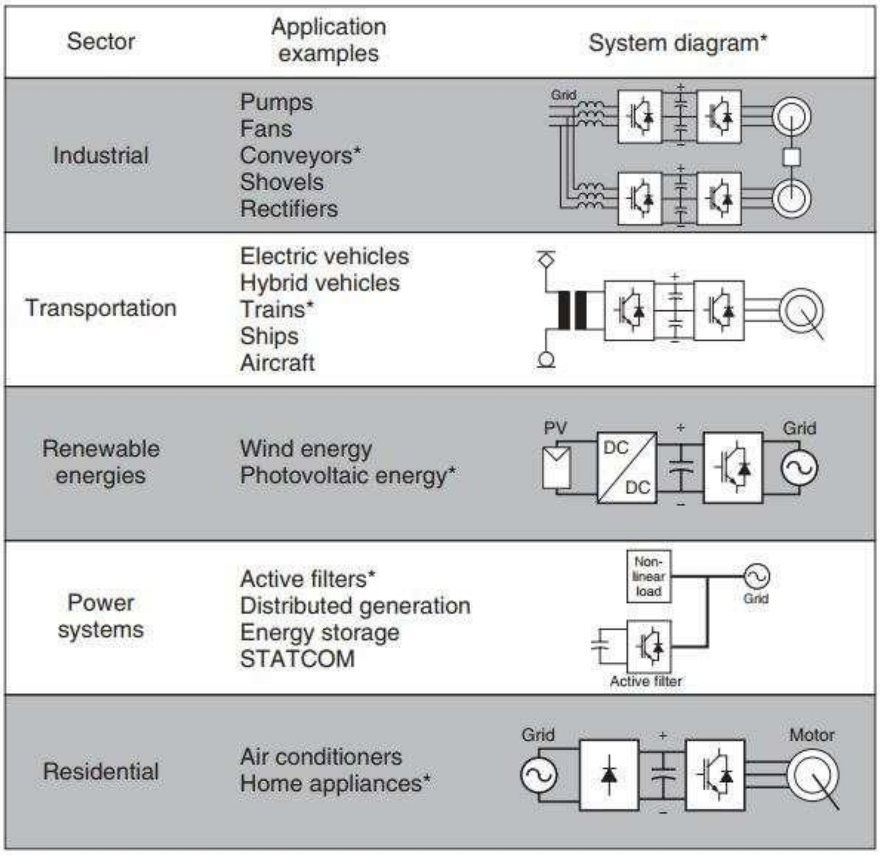


Figure I.2**:** Power converter applications

Low-power drives and converters offer many possibilities in residential applications. The use of adjustable speed drives can increase the efficiency of systems like air conditioners and other home appliances [1,5].

I.4 Association of power converter with DFIG:

DFIG architecture employing both series grid side converter and parallel grid side rectifier is presented. As in conventional DFIG, the main stator windings of the machine are connected, via transformer, the rotor windings of the machine are accessed via slip rings and connected to a voltage source converter referred to as the machine side converter (RSC). The dc link is also connected to a second voltage source converter called the series grid side converter (GSC). The three phase terminals of the GSC are connected in series with the three phase terminals of the stator circuit and the line. Thus, the injected stator power also passes through the GSC, providing the active mechanism necessary for providing ride through during grid disturbances in an effective manner.

I.4.1 DFIG fed by 2L back to back converter:

A DFIG is essentially a standard wound rotor induction machine whose stator windings directly connected to the grid and rotor windings connected to the grid through a back-to-back converter as shown in figure (1.3) The back-to-back converter consists of two converter switch two voltage levels (2L), rotor-side converter (RSC) and line-side converter (GSC).the rectifier (RSC) consists of six low-voltage-controlled bidirectional switches (IGBTs), and the (GSC) also has the same number and type of switches.. Between the two converters a dc-link capacitor is placed, as energy storage, in order to reduce voltage variations (or ripple) in the dc-link. The RSC is used to control the torque, speed or the powers of the DFIG and also the power factor at the stator terminals, while the GSC is used for keeping the dc-link voltage constant [6]. In grid-connected systems, the power-factor correction control of GSC is also generally applied. The GSC can be used as reactive power compensator or active filter by adding an additional function, rather than previously defined function. For the operation within a sub synchronous range of speed, the GSC can be replaced with a simple three-phase diode rectifier.

In terms of technology status and market penetration, this converter topology has mature power and is used by 90% of applications in conversion systems

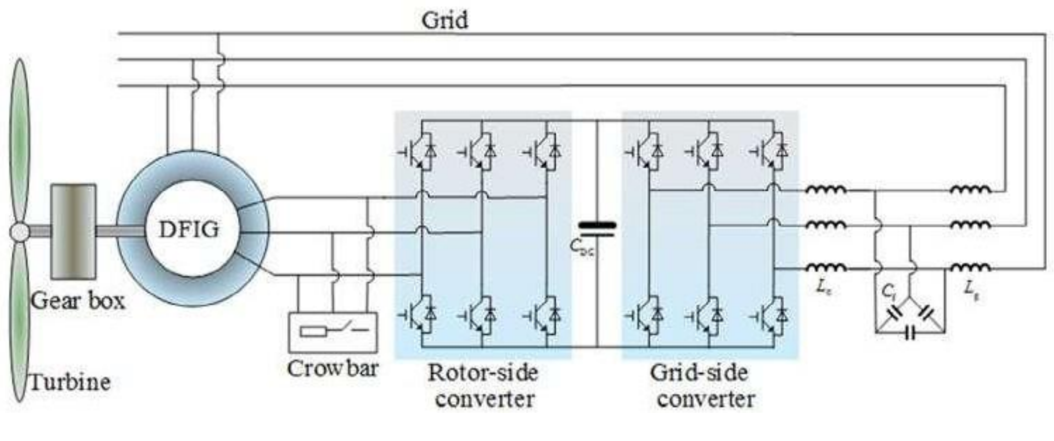


Fig I. 3.: Schematic of a typical DFIG system.

The nominal power of the converter is generally 30% of the generator's rated power. For example, a 2.5MW DFIG machine only requires a 0.75 power converter MW. The achievable speed range is decided based on the rated power of power converter [7]. A power converter at 30% of its capacity nominal can control the speed of the DFIG at 30% of its synchronism speed, this which is sufficient to perform a variable speed operation. The static converter in the rotor circuit allows the bidirectional transit of the energy flow from the rotor to the network or vice versa [8]

a Presentation of DFIG fed by 2L back to back converter:

The Doubly-Fed Induction Generator (DFIG) is a type of wound-rotor induction generator. It is equipped with a power converter that is responsible for controlling the rotor currents and, consequently, the active and reactive power flow between the rotor circuit and the grid.

The power converter in a DFIG system typically consists of two back-to-back connected voltage source converters (VSCs): the rotor-side converter (RSC) and the grid-side converter (GSC). These converters are connected through a common DC-link.

The power converter in a DFIG system typically handles only a fraction (typically 20-30%) of the total power generated. This is because the converter is connected to the rotor circuit, which carries a relatively smaller amount of power compared to the stator circuit, which is directly connected to the grid.[4]

The role of the power converter in a DFIG system is as follows:

1. Rotor-Side Converter (RSC):
   - The RSC controls the rotor currents, which in turn control the active and reactive power flow between the rotor circuit and the grid.
   - It allows the DFIG to operate in a wider range of speeds, both above and below the synchronous speed, enabling variable-speed operation.
   - By adjusting the rotor currents, the RSC can control the torque and power output of the generator.
2. Grid-Side Converter (GSC):
   - The GSC controls the flow of active power between the DC-link and the grid, as well as the reactive power exchanged with the grid.
   - It maintains a constant DC-link voltage by regulating the active power flow to/from the rotor circuit.
   - The GSC can also provide reactive power compensation for the system, improving the power factor and voltage regulation.

b Advantages and disadvantages of 2L back to back:

Two-level (2L) back-to-back converters are a common type of power converter used in doubly-fed induction generator (DFIG) systems. Here are some advantages and disadvantages of 2L back-to-back converters

Advantages:

1. Reduced converter rating: In a DFIG system, the 2L back-to-back converter only needs to handle a fraction of the total power (typically 20-30%), resulting in a lower converter rating and cost compared to a full-scale converter.
2. Simple topology: The 2L back-to-back converter has a straightforward topology, consisting of two three-phase voltage-source converters connected through a DC link, making it relatively simple to design and control.
3. Mature technology: Two-level converters are a well-established and mature technology, with extensive research and industry experience, ensuring reliable operation and ease of maintenance.
4. Bi-directional power flow: The back-to-back configuration allows for bi-directional power flow, enabling regenerative braking and low-voltage ride-through capabilities, which are essential for grid integration and fault handling.
5. Efficient operation: With advanced control strategies, such as vector control and direct torque control, 2L back-to-back converters can operate efficiently, maximizing energy capture and minimizing losses.

Disadvantages:

1. Limited voltage levels: Two-level converters can only produce two voltage levels (positive and negative), limiting their ability to generate high-quality waveforms and potentially leading to higher harmonic distortion.
2. High switching losses: At higher power ratings and switching frequencies, the switching losses in 2L converters can become significant, reducing overall efficiency and increasing cooling requirements.
3. Limited fault handling capability: During certain fault conditions, such as short circuits, the 2L converter may not be able to handle the high currents effectively, potentially leading to device failure or system shutdown.
4. Electromagnetic interference (EMI) issues: The high switching frequencies used in 2L converters can generate significant EMI, which may interfere with other

electronic components or systems nearby, requiring additional filtering and shielding measures.

5. Limited reactive power control: While 2L back-to-back converters can provide reactive power control, their capability may be limited compared to higher-level converters, such as three-level or multi-level converters.

I.4.2 DFIG fed by DMC:

Matrix Converter:

The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The circuit scheme is shown in figure (1.4). The input terminals of the converter are connected to a three-phase voltage-fed system. Usually the grid, while the output terminals are connected to a three-phase current-fed system, like a DFIG might be. The capacitive filter on the voltage-fed side and the inductive filter on the current-fed sides represented in the scheme of figure (1.4) are intrinsically necessary. Their size is inversely proportional to the matrix converter switching frequency [4] It is worth noting that, due to its inherent bi-directionality and symmetry, a dual connection might also be feasible for the matrix converter: a current-fed system at the input and a voltage-fed system at the output

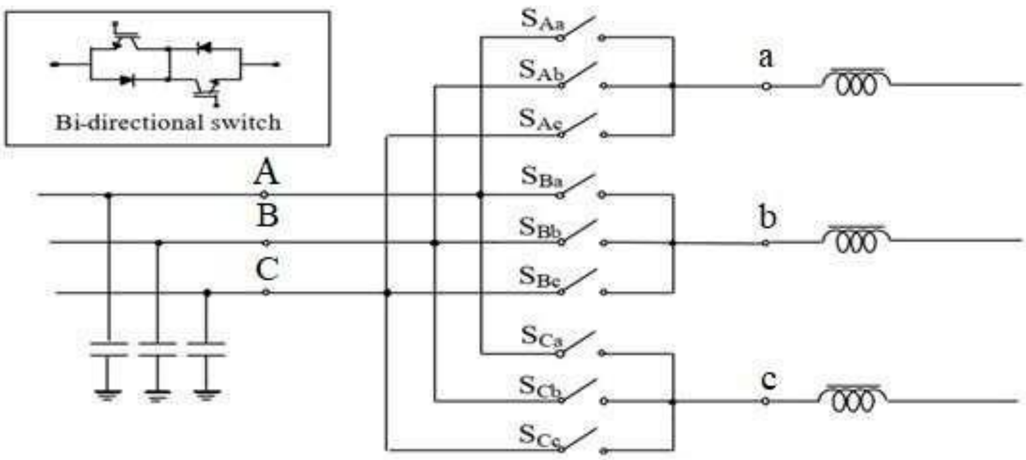


Fig. I.4: Circuit scheme of a three phase to three phase matrix converters.

The matrix is powered by the three phase voltages V_A, V_B and V_C. The asynchronous motor is connected to the output of the converter. The output voltages are denoted by V_a, V_b and V_c.

Because there is no need for an intermediary circuit to store energy, the conversion is referred to as a direct frequency conversion.

Input quantities:

The input vector can be defined by vector of amplitude V_i and frequency f_i equation (1.1) and the input line current defined by the amplitude I_i and in phase with its voltage is defined by the relationship (1.2).

$$\begin{pmatrix} V_A \\ V_B \\ V_C \end{pmatrix} = V_i \begin{pmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + 2\frac{\pi}{3}) \\ \cos(\omega_i t + 4\frac{\pi}{3}) \end{pmatrix} \quad (1.1)$$

$$\begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} = I_i \begin{pmatrix} \cos(\omega_i t + \varphi_i) \\ \cos(\omega_i t + 2\frac{\pi}{3} + \varphi_i) \\ \cos(\omega_i t + 4\frac{\pi}{3} + \varphi_i) \end{pmatrix} \quad (1.2)$$

$\omega_i = 2\pi f_i$:Input pulse.

φ_i: Phase shift with input voltage.

Output quantities:

The output network voltage vector can be defined by equation (1.3), of amplitude V_o isof frequency f_o. Likewise, the output currents of amplitude equal to I_o and phase shift of φ_o with respect to the simple output voltages are defined by equation (1.4)

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = V_o \begin{pmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + 2\frac{\pi}{3}) \\ \cos(\omega_o t + 4\frac{\pi}{3}) \end{pmatrix} \quad (1.3)$$

$$\begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} = I_i \begin{pmatrix} \cos(\omega_i t + \varphi_o) \\ \cos(\omega_i t + 2\frac{\pi}{3} + \varphi_o) \\ \cos(\omega_i t + 4\frac{\pi}{3} + \varphi_o) \end{pmatrix} \quad (1.4)$$

$\omega_o = 2\pi f_o$:Output pulse. φ_o: Phase shift with output voltage.

Direct Matrix Converter:

The concept of a direct MC appeared in the literature as early as the 1970s [2-3]. More extensive search started with the work of venturini and alesina in the 1980s [4-6]. A MC is composed of an array of controlled bidirectional switches that perform direct energy conversion without any energy storage elements in an intermediate link. A three-phase direct MC comprises nine bidirectional semiconductor switches arranged in a 3×3 matrix.

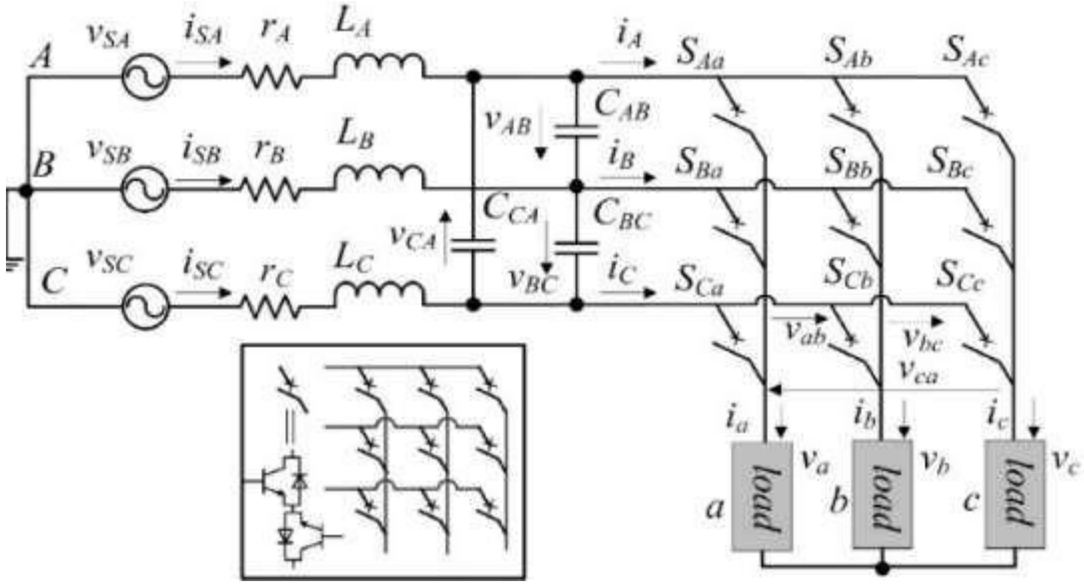


Figure. I.5: Three-phase direct MC circuit

A three-phase direct MC is shown in figure (1.5). In contrast to the conventional AC- DC-AC conversion, the MC does not require the DC-link capacitor, and completes the power transformation one stage. The absence of the DC-link capacitor reduces the volume, enhances the efficiency, increases the lifetime and simplifies the control schemes. It only requires small filters to suppress the ripples generated by the switching actions [7]. The MC has received attention because of its advantages: sinusoidal input and output waveforms, controllable power factor, bidirectional power flow and the compact nature [4].

I.5 Presentation of DFIG fed by DMC:

A doubly-fed induction generator (DFIG) is a type of wound-rotor induction generator. It is called "doubly-fed" because both the stator and the rotor windings are connected to external electrical sources, allowing bidirectional power flow. The DFIG is typically fed by a direct matrix converter (DMC), which is a type of power converter that directly converts the input AC voltage to a variable output AC voltage without the need for a DC-link.[11]

The DMC has several advantages over traditional back-to-back converters when used with DFIGs, including:

1. Reduced component count and increased power density due to the absence of a DC-link capacitor.
2. Bidirectional power flow capability without the need for additional hardware.
3. Sinusoidal input and output waveforms with low harmonic distortion.

4. Compact design and potential for higher efficiency.

I.5.1 Advantages and disadvantages of DMC:

a **Advantages of Direct Model Predictive Control (DMC):**

1. Enhanced Performance: DMC excels in predicting future system behavior using a model. This translates to tighter control over variables such as active and reactive power in DFIG, resulting in smoother operation and improved adherence to set points.
2. Reduced Fluctuations: By anticipating future behavior, DMC proactively modifies control actions to reduce torque and power variations in the DFIG system. This decreases stress on turbine components while improving overall stability.
3. Enhanced Stability. DMC's ability to account for these variances enables improved control of the DFIG system, boosting grid stability and reliable electricity generation.
4. Constraint Handling: DMC can include system restrictions in its calculations. This ensures that control activities for the DFIG and linked grid do not exceed safe operational limitations.
5. Multi-Objective Optimization: DMC can handle many control objectives at once. For example, it can maximize power output while reducing component wear.

b the disadvantages of direct model predictive control (DMC):

1. Computational Complexity: DMC's main feature, the capacity to forecast future behavior, also poses a hurdle. The calculations required can be computationally intensive, particularly for complex systems. This may need high-performance hardware for real-time implementation.
2. Model Dependence: The accuracy of DMC is strongly dependent on the quality of the mathematical model utilized. Model errors can result in inefficient control actions and lower performance advantages. Keeping an accurate and up-to-date model is critical.
3. Tuning Challenges: To ensure best performance, DMC must be carefully tuned using a variety of control parameters. This can be a difficult task for engineers and may require trial-and-error changes.

4. Limited applicability: While DMC has certain advantages, it may not be appropriate for all control applications. Simpler control strategies may be sufficient for less complicated systems if computational limits are present.

I.6: Conclusion:

In this chapter, we talked about Doubly-fed Induction Generator (DFIG), Back-to-back conversion system and basic vector control techniques are summarized, with practical application issues briefly summarized. And on the advantages and disadvantages of the back-to-back conversion system, we also talked about the matrix converter together advantages and disadvantages, despite the emergence of new system topologies with improved performance in both academia and industry, DFIG is the most competitive option in terms of the balance between technical performance and economic costs.

CHAPTER **II**: *Modeling of the Doubly Fed Induction Generator (DFIG) fed by a Direct Matrix Converter*

Ⅱ.1: Introduction

Modeling is the mathematical description of a technical process of a system this is a very important stage of the preliminary study.

The different modeling is generally based on models three-phase or two-phase mathematics for a vector representation of the different electrical and mechanical quantities of the machine. The vector representation, like asserted by some authors, is a powerful tool which facilitates the evaluation of the performance of the machine because it reduces matrix calculations and simplifies the resolution of equations electrical and mechanical.

In this chapter, we will study and give a model of the double fed induction machine. Firstly, we present the electrical equations by accepting certain simplifying hypotheses, and we will also see the different modes of operation of the DFIG in motor mode (hypo and hyper asynchronous) and in generator (hypo and hyper asynchronous), we will then use the PARK transformation.

Finally, we give also the model of the Direct Matrix Converter (DMC) in order to fed the DFIG. a DMC is a direct AC-AC converter that eliminates the need for a DC-link, facilitating direct power conversion between the rotor circuit and the grid. This innovative approach not only offers a compact and efficient solution but also enhances the overall system performance.

Ⅱ.2: Modeling of DFIG:

Ⅱ.2.1: Equation of the DFIG in the three-phase reference frame (a, b, c):

the distribution windings of the dual-supply asynchronous machine and its own geometry is too complex to lend itself to an analysis taking into account its exact configuration. It is then necessary to adopt simplifying assumptions. The dual-supply asynchronous machine, with the distribution of its windings and its own geometry is too complex to lend itself to an analysis taking into account its exact configuration. It is then necessary to adopt simplifying assumptions. following in order to be able to develop a simple model (known as the Park model) [15].

- The electromotive force (fem). created in one phase at the stator and rotor, is with sinusoidal distribution along the air gap.
- The machine is symmetrical and has a constant air gap.

- The influence of the temperature effect is not taken into account, it follows. that all the own inductance coefficients are constant and that the coefficients the mutual inductances are a function of the position of their magnetic axes.
- The magnetic circuit is not saturated and perfectly laminated; it follows that the iron and hysteresis losses are negligible and only the windings are traversed by currents

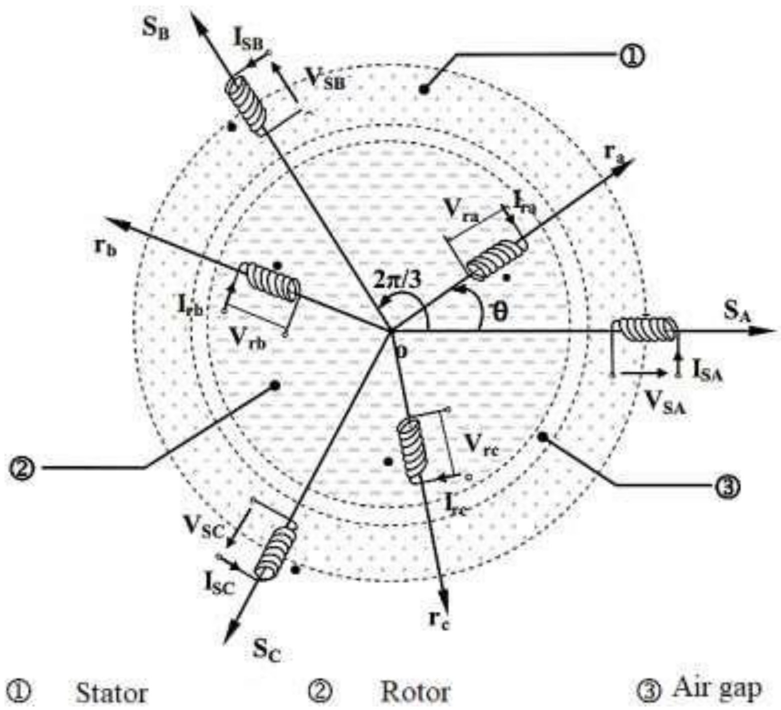


Figure (II. 1): Simplified diagram of the DFIG

The DFIG model can be described as having three windings in the stator and three windings in the rotor, as shown in Figure (II. 1). The equations of the stator and rotor phase voltages are expressed by:

$$\begin{cases} v_{a,b,c\_s}(t) = R_s . i_{a,b,c\_s}(\text{t}) + \frac{d}{dt}\Psi_{\text{a,b,}c\_s}(t) \\ v_{a,b,c\_r}(t) = R_r . i_{a,b,c\_r}(\text{t}) + \frac{d}{dt}\Psi_{\text{a,b,}c\_r}(t) \end{cases} \quad (2.1)$$

with:

R_s , R_r : stator and rotor resistance respectively

$i_{a,b,c_s}(t)$, $i_{a,b,c_r}(t)$: stator and rotor currents of phases a, b and c respectively.

$v_{a,b,c\_s}(t)$: supply voltages for the stator imposed by the electrical network (fixed amplitude and frequency under normal conditions).

$v_{a,b,c\_r}(t)$: rotor pensions imposed by the control from the power converter.

$\Psi_{a,b,c_s}(t)$, $\Psi_{a,b,c\_r}(t)$: stator and rotor flows.

If we neglect the resistance of the stator winding R_s, which constitutes a hypothesis. realistic for high power generators used in wind power systems [16]. The previous equation becomes:

$$v_{a,b,c\_s}(t) \approx \frac{d}{dt}\Psi_{a,b,c\_s}(t) \tag{2.2}$$

This equation demonstrates that the stator voltage and stator flux rotate every two at the same speed. However, the voltage is $\pi\ /2$ radians ahead of the flux stator.

II.2.2: DFIG model in Park:

The model of the machine (DFIG) in the Park frame (d ,q) linked to the rotating field stator is given by the equations below, [17-18]:

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_s \Psi_{qs} \\ V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \end{cases} \tag{2.3}$$

$$\begin{cases} V_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_r \Psi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + \omega_r \Psi_{dr} \end{cases} \tag{2.4}$$

With ω_s and ω_r are respectively the pulsations of the stator and rotor quantities. The magnetic equations are expressed by:

$$\begin{cases} \Psi_{ds} = L_s i_{ds} + M i_{dr} \\ \Psi_{qs} = L_s i_{qs} + M i_{qr} \end{cases} \tag{2.5}$$

$$\begin{cases} \Psi_{dr} = L_r i_{dr} + M i_{ds} \\ \Psi_{qr} = L_r i_{qr} + M i_{qs} \end{cases} \tag{2.6}$$

The electromagnetic torque is expressed by:

$$C_{em} = p\ (\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) = p\frac{M}{L_r}(\Psi_{qs} i_{dr} - \Psi_{ds} i_{qr}) \tag{2.7}$$

The expressions of the active and reactive stator and rotor powers are given by:

$$\begin{cases} P_s = (V_{ds}i_{ds} + V_{qs}i_{qs}) \\ q_s = (V_{qs}i_{ds} - V_{ds}i_{qs}) \end{cases} \quad (2.8)$$

$$\begin{cases} P_r = (V_{dr}i_{dr} + V_{qr}i_{qr}) \\ q_r = (V_{qr}i_{dr} - V_{dr}i_{qr}) \end{cases} \quad (2.9)$$

Park's three-phase-two-phase transformation is only a Concordia transformation composed with that of rotation of the axes given by:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (2.10)$$

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (2.11)$$

Or θ the transformation angle which represents θs for the stator quantities and θr forrotor quantities.

II.2.3 DFIG model with stator flux orientation:

In order to obtain decoupled stator active and reactive power control, we have chosen a two-phase reference frame d-q linked to the rotating stator field and placing the stator flux vector (ψ_S) on the d axis figure (II. 2). Assuming that the resistance stator reactance (Rs) negligible compared to the stator reactance for machines medium and high power,

We can then define that the stator flux has the following components:

$$\begin{cases} \Psi_{ds} = \Psi_s \\ \Psi_{qs} = 0 \end{cases} \longrightarrow \Psi_s \approx \frac{V_s}{\omega_s} \text{ with } R_s \approx 0 \quad (2.12)$$

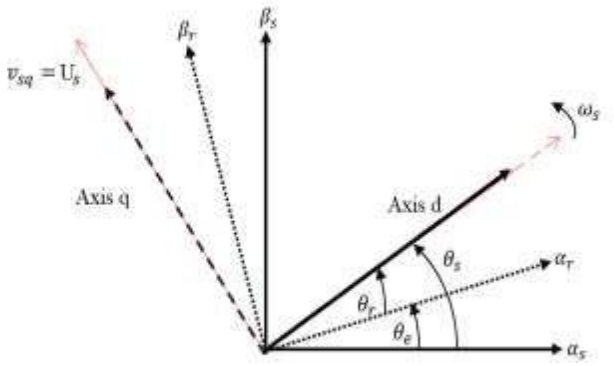


Figure (II. 2): Two-phase reference frame d-q linked to the rotating stator field.

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = U_s = V_s\sqrt{3} \end{cases} \quad (2.13)$$

The DFIG model then becomes:

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = U_s = \omega_s\, \Psi_s \end{cases} \quad (2.14)$$

$$\begin{cases} V_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_r \Psi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + \omega_r \Psi_{dr} \end{cases} \quad (2.15)$$

New expressions of stator currents as a function of rotor currents
are described by:

$$\begin{cases} \Psi_{ds} = \Psi_s = L_s i_{ds} + M i_{dr} \rightarrow i_{ds} = \frac{\Psi_s}{L_s} - \frac{M}{L_s}.i_{dr} \\ \Psi_{qs} = 0 = L_s i_{qs} + M i_{qr} \rightarrow i_{qs} = -\frac{M}{L_s}.i_{qr} \end{cases} \quad (2.16)$$

By replacing these equations in the rotor flux equations :

$$\begin{cases} \Psi_{dr} = L_r i_{dr} + M i_{ds} = L_r i_{dr} + M.\left(\frac{\Psi_s}{L_s} - \frac{M}{L_s}.i_{dr}\right) = \frac{M}{L_s}\Psi_s + \left(L_r - \frac{M^2}{L_s}\right).i_{dr} \\ \Psi_{qr} = L_r i_{qr} + M i_{qs} = L_r i_{qr} + M.\left(-\frac{M}{L_s}.i_{qr}\right) = \left(L_r - \frac{M^2}{L_s}\right).i_{qr} \end{cases} \quad (2.17)$$

The rotor flux equations then become:

$$\begin{cases} \Psi_{dr} = \frac{M}{L_s}\Psi_s + \sigma L_r i_{dr} \\ \Psi_{qr} = \sigma L_r i_{qr} \end{cases} \quad (2.18)$$

With:$\sigma=1-\frac{M^2}{L_s L_r}$: is the dispersion coefficient of the DFIG.

The new expressions of the rotor tensions are then described by:

$$\begin{cases} v_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_r.\sigma L_r i_{qr} + \frac{M}{L_s}.\frac{d\Psi_s}{dt} \\ v_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_r.\sigma L_r i_{qr} + \omega_r.\frac{M}{L_s}\Psi_s \end{cases} \quad (2.19)$$

We assume that the electrical network supplying the DFIG is stable, therefore the derivative of
The stator flux becomes zero and the dynamics of the rotor currents are expressed by:

$$\begin{cases} \frac{di_{dr}}{dt} = \frac{1}{\sigma L_r}\left(V_{dr} - R_r i_{dr} + \omega_r \sigma L_r i_{qr}\right) \\ \frac{di_{qr}}{dt} = \frac{1}{\sigma L_r}\left(V_{qr} - R_r i_{qr} - \omega_r \sigma L_r i_{dr} - \omega_r.\frac{M}{L_s}\Psi_s\right) \end{cases} \quad (2.20)$$

New expressions of electromagnetic torque, active/reactive power stator and rotor active/reactive power are rewritten as follows:

$$C_{em} = p\,\Psi_{ds} i_{qs} = -p\frac{M}{L_s}\Psi_s i_{qr} \quad (2.21)$$

New expressions of electromagnetic torque, active/reactive power stator and rotor active/reactive power are rewritten as follows:

$$\begin{cases} P_s = V_{ds}i_{ds} + V_{qs}i_{qs} = -U_s\frac{M}{L_s}i_{qr} \\ Q_s = V_{qs}i_{ds} - V_{ds}i_{qs} = \frac{U_s\,\psi s}{L_s} - \frac{U_s M}{L_s}i_{dr} \end{cases} \quad (2.22)$$

$$\begin{cases} P_r = V_{dr}i_{dr} + V_{qr}i_{qr} = S\frac{U_s.M}{L_s}i_{qr} \\ Q_r = V_{qr}i_{dr} - V_{dr}i_{qr} = S\frac{M.U_s}{L_s}i_{dr} \end{cases} \quad (2.23)$$

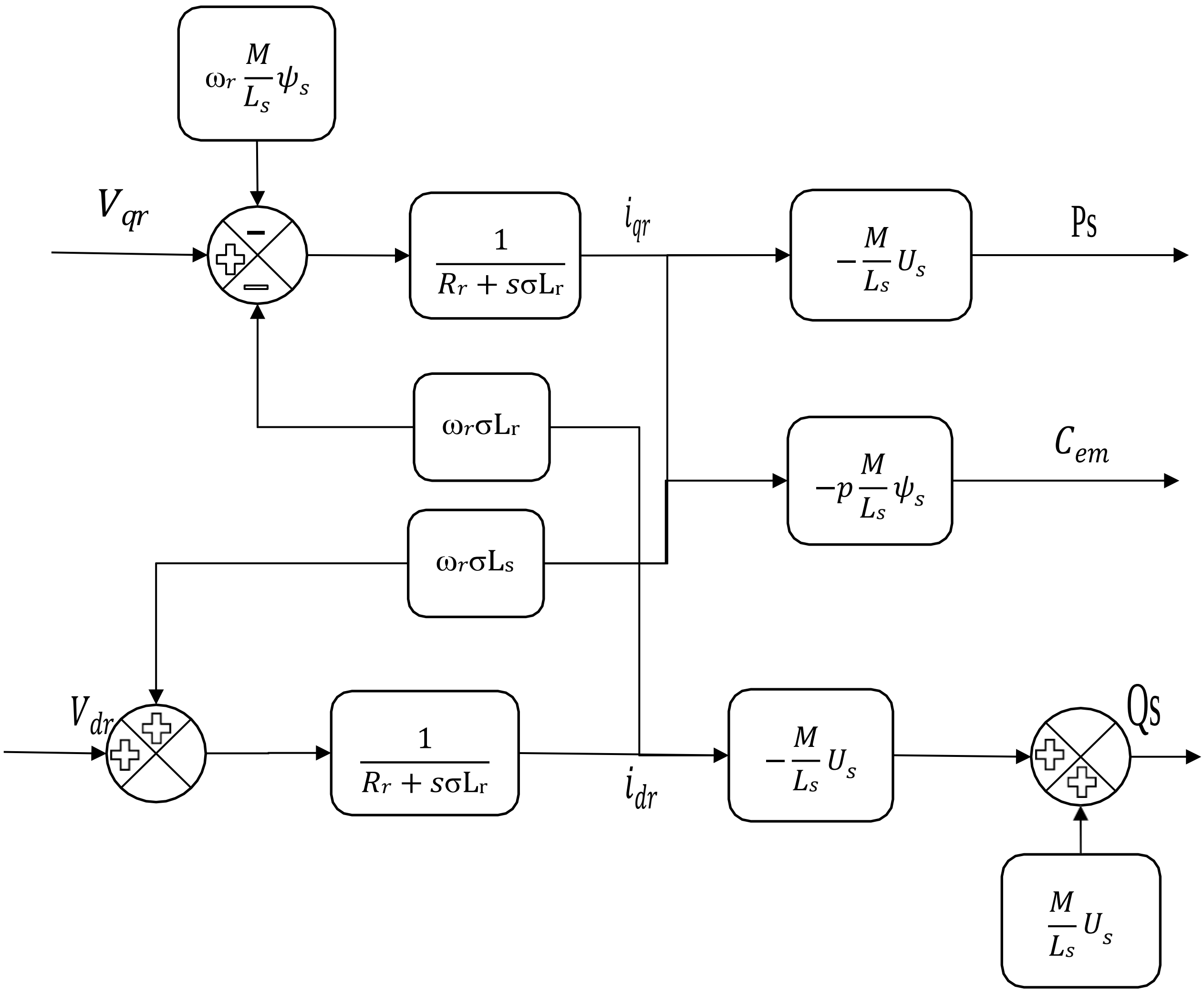


Figure (II. 3): Block diagram of the simplified DFIG model

The previous equations show that it is possible to set up an order. decoupled, given that up to the influence of the couplings, each axis can be ordered separately with its own regulator. The reference quantities will be: The active power for the (q) axis and the reactive power for the (d) axis. The setpoint reactive power will be kept zero to ensure a unity power factor. stator so as to optimize the quality of the energy returned to the network. The equations These precedents make it possible to establish the block diagram of the DFIG electrical system to be controlled figure (II. 3).

II.3: Modeling of DMC:

The matrix converter (MC) is a single-stage power converter. It is used to convert nine AC phase input voltage into three AC phase output, with a control of magnitude and frequency current output, without using an energy storage element, that is to say, direct AC-AC conversion.

The greatest essential characteristics of MCs are as follows:

- A simple and compact power circuit.
- Sinusoidal input and output currents.
- Generation of load voltage with arbitrary amplitude and frequency.
- Regeneration ability. These highly attractive characteristics are the reason for the tremendous interest in this topology.
- Operation with unity power factor.

II.3.1: Matrix Converter Model:

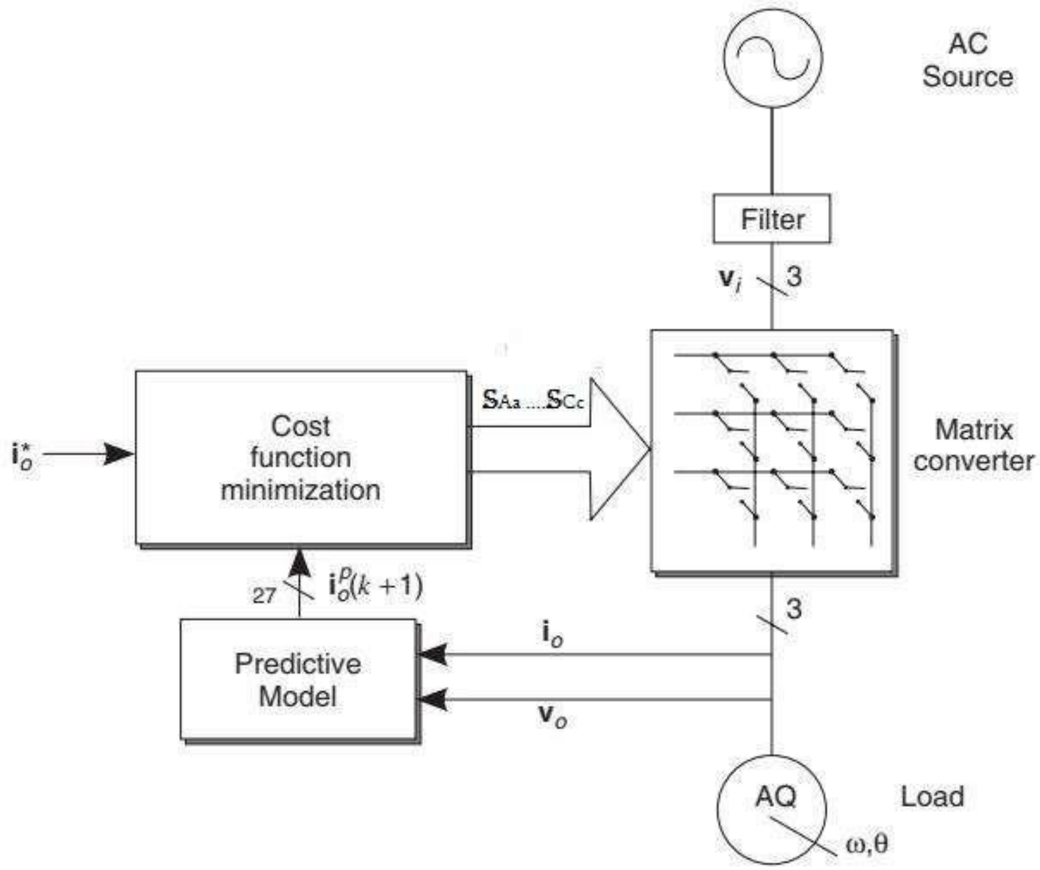
The basic diagram of a three-phase / three-phase matrix converter shown in Figure (II. 4) which is the power circuit of the MC. It uses a set of bidirectional switches to directly connect the three-phase power supply to a three-phase load. This is a 3 × 3 MC. As shown in Figure (II. 4),each bidirectional switch is composed of two power transistors with their parallel diodes in anti-series connection.

The MC is connected to the three-phase source through the input filter L_f , R_f, C_f . This filter has two main purposes:

1. To avoid the generation of over-voltages, produced by the short-circuit impedance of the power supply, due to the fast commutation of currents

i_{eA}., i_{eB}., and i_{eC}.

2. To eliminate high-frequency harmonics in the input currents i_A, i_B, i_C.



Figure(II. 4): Power circuit of the MC.

In Figure (II.4) Shows that each bidirectional switch is associated with a variable defined as S_{Jj} which is $j \in \{a, b, c\}$ and $J \in \{A, B, C\}$.

There switching function S_{Jj} (t) takes the value "0" when the switch is open, and "1",when closed as indicated by the following expressions:

$$\begin{cases} S_{Jj}(t) = 1 \leftrightarrow \text{ when } S_{Jj} \text{ closed} \\ S_{Jj}(t) = 0 \leftrightarrow \text{ when } S_{Jj} \text{ opened} \end{cases} \quad \text{for } j \in \{a,b,c\}, \text{and } y \in \{A,B,C\}. \tag{2.24}$$

The conduction state of each bidirectional switch is determined exclusively by the value of its control signal. S_{xy} is also known as the switching function for switch *(x y)*. S_{xy} = 1 implies that switch *(x y)* is on, closed, or conducting, while S_{xy}= 0 means that the switch is off, open, or in blocking state.

Let kj (k = A, B,C and j = a,b,c) be the rank of the switch placed between the input phase k and the exit phase j. Let S_{kj} be the switching state of the switch with S_{jk}=0 implies that the switch kj is open and S_{kj} =1 implies that the switch is closed.

$$\begin{cases} S_{kj} = 1 \leftrightarrow \text{ The switch } kj \text{ close.} \\ S_{kj} = 0 \leftrightarrow \text{ The switch } kj \text{ close} \end{cases} \tag{2.25}$$

The direct connection of the voltage source (the network and the input filter) to the rotor of the DFIG (current source) requires respecting the specifications of the input sources and output as follows:

The DMC converter must ensure the flow of current through each phase of the load to avoid the open circuit of the current source which is the rotor of the DFIG. On the other hand, the short circuit of two phases of the voltage source is not permitted, it would cause an overcurrent which would destroy the semiconductors. This results in the following relationship:

$$S_{Aj} + S_{Bj} + S_{Cj} = 1 \qquad \forall \qquad j \in \{a, b, c\} \tag{2.26}$$

Referenced to the neutral point *N*, the relation between the load and input voltages of the MC is expressed as

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} . \begin{bmatrix} v_{eA}(t) \\ v_{eB}(t) \\ v_{eC}(t) \end{bmatrix} \quad , \ T_{ph} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \tag{2.27}$$

where *T* is the instantaneous transfer matrix. The input and load voltages can be expressed as vectors as follows:

$$V_i = \begin{bmatrix} v_{eA}(t) \\ v_{eB}(t) \\ v_{eC}(t) \end{bmatrix} \quad , \quad V_o = \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \tag{2.28}$$

Using the definitions of (2.27), the relation of the voltages is given by

$$V_o = T.V_i \tag{2.29}$$

Applying Kirchhoff's current law to the switches, the following equation can be obtained:

$$\begin{bmatrix} i_{eA}(t) \\ i_{eB}(t) \\ i_{eC}(t) \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} . \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}, T^T = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \quad (2.30)$$

Considering the current vectors

$$i_i = \begin{bmatrix} i_{eA}(t) \\ i_{eB}(t) \\ i_{eC}(t) \end{bmatrix} \quad i_o = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad (2.31)$$

the equation for the current is

$$i_i = T^T . i_o \quad (2.32)$$

where T^T is the transpose of matrix T .

II.3.2 Working Principle of the Matrix Converter:

In order to produce a low-frequency voltage with variable amplitude and frequency, the bidirectional switches open and close at a high switching frequency. To accomplish this, create the switching patterns depicted in Figure (II. 5). By taking samples of the input voltages and opening and shutting the bidirectional switches, the low-frequency component of the load voltage is created.

Given T as the sampling period and t_{ij} as the duration of switch S_{ij} being closed (on), we can represent the low-frequency component of the load voltage as

$$\bar{v}_{jN}(t) = \frac{t_{Aj}.v_{eA}(t) + t_{Bj}.v_{eB}(t) + t_{Cj}.v_{eC}(t)}{T} \quad j \epsilon \{a, b, c\} \quad (2.33)$$

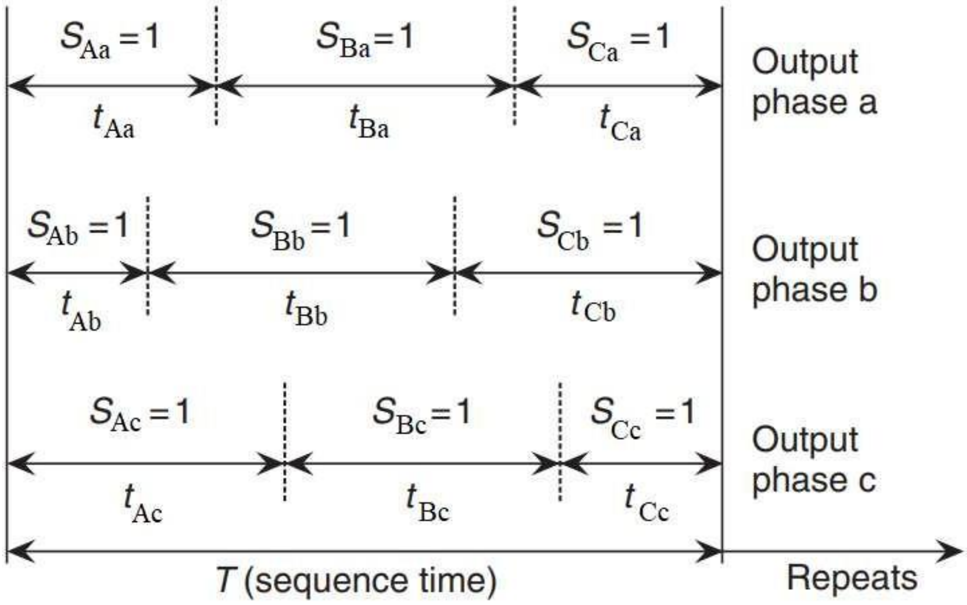


Figure (II. 5):Switching patterns for the MC where $\bar{v_j}_N(t)$ is the low-frequency component (mean value calculated over one sampling interval *T*) of output phase *j*.

From Figure (II. 5)it can observed, for example, that the voltage of phase *a* is generated by delivering load voltage v_{eA} during time t_{Aj}, voltage v_{eB} during time t_{Bj}., and voltage *v we* during timet_{Ac}.

The conduction times must comply with the restriction

$$T=t_{Aj}+t_{Bj}+t_{Cj} \quad \forall \quad j\epsilon\{a,b,c\} \tag{2.34}$$

By defining the duty cycles as

$$m_{Aj}(t)=\frac{t_{Aj}}{T}\ ,m_{Bj}(t)=\frac{t_{Bj}}{T}\ ,m_{Cj}(t)=\frac{t_{Cj}}{T} \tag{2.35}$$

and expanding (2.33) for each phase, the following equations can be obtained:

$$\begin{bmatrix}\bar{v}_{aN}(t)\\ \bar{v}_{bN}(t)\\ \bar{v}_{cN}(t)\end{bmatrix}=\begin{bmatrix}m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t)\\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t)\\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t)\end{bmatrix}.\begin{bmatrix}v_{eA}\\ v_{eB}\\ v_{eC}\end{bmatrix},M(t)=\begin{bmatrix}m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t)\\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t)\\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t)\end{bmatrix}$$

(2.36)

$$\bar{V_o}=\begin{bmatrix}\bar{v}\,aN\\ \bar{v}\,bN\\ \bar{v}\,cN\end{bmatrix} \tag{2.37}$$

$$\bar{V_o}(t)=M(t).\bar{V_i}(t) \tag{2.38}$$

where $\bar{V_o}(t)$ is the low-frequency output voltage vector, $\bar{V_i}(t)$ is the instantaneous input voltage vector, and *M(t)* is the low-frequency transfer matrix of the MC.

By considering an analogous procedure for the input currents, it can be demonstrated that

$$\bar{\imath}_i(t)=M^T(t).i_o(t) \tag{2.35}$$

where $\bar{\imath}_i(t)$ is the low-frequency component of the input current vector and$M^T(t)$ is the transpose of matrix *M(t)*.

II.3.3 Commutation of the Switches:

The instantaneous values of the input currents and the output voltages generated by each switching combination can be determined using the matrices of instantaneous transfer, where

$T_{LL}$is the instantaneous transfer matrix between rows and T_{ph} is the Instantaneous matrix from entry phase to exit phase:

$$T_{LL} = \begin{pmatrix} S_{Aa} - S_{Ab} & S_{Ba} - S_{Bb} & S_{Ca} - S_{Cb} \\ S_{Ab} - S_{Ac} & S_{Bb} - S_{Bc} & S_{Cb} - S_{Cc} \\ S_{Ac} - S_{Aa} & S_{Bc} - S_{Ba} & S_{Cc} - S_{Ca} \end{pmatrix}, T_{ph}=\begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \quad (2.39)$$

N	S_{Aa}	S_{Ab}	S_{Ac}	S_{Ba}	S_{Bb}	S_{Bc}	S_{Ca}	S_{Cb}	S_{Cc}
1	1	0	0	1	0	0	1	0	0
2	0	1	0	0	1	0	0	1	0
3	0	0	1	0	0	1	0	0	1
4	1	0	0	0	0	1	0	0	1
5	0	1	0	0	0	1	0	0	1
6	0	1	0	1	0	0	1	0	0
7	0	0	1	1	0	0	1	0	0
8	0	0	1	0	1	0	0	1	0
9	1	0	0	0	1	0	0	1	0
10	0	0	1	1	0	0	0	0	1
11	0	0	1	0	1	0	0	0	1
12	1	0	0	0	1	0	1	0	0
13	1	0	0	0	0	1	1	0	0
14	0	1	0	0	0	1	0	1	0
15	0	1	0	1	0	0	0	1	0
16	0	0	1	0	0	1	1	0	0
17	0	0	1	0	0	1	0	1	0
18	1	0	0	1	0	0	0	1	0
19	1	0	0	1	0	0	0	0	1
20	0	1	0	0	1	0	0	0	1
21	0	1	0	0	1	0	1	0	0
22	1	0	0	0	1	0	0	0	1
23	1	0	0	0	0	1	0	1	0
24	0	1	0	1	0	0	0	0	1
25	0	1	0	0	0	1	1	0	0
26	0	0	1	1	0	0	0	1	0
27	0	0	1	0	1	0	1	0	0

Tab. (II. 1): Valid commutation combinations for DMC converter

For a three-phase to three-phase DMC converter, the two conditions (2.25) and (2.26) allow you to generate 27 possible combinations to produce currents and load voltages, these combinations are presented in table (II. 1)below:

The instantaneous voltage between phase V_{oll} and the input phase currents i_{iph} can be determined by the following equations [19]:

$$V_{oll} = [V_{ab}\ V_{bc}\ V_{ca}]^T = T_{LL}.[V_A\ V_B\ V_C]^T = T_{LL}.V_i \quad (2.40)$$

$$i_{iph} = [i_A\ i_B\ i_C]^T = T^t{}_{LL}.[i_{ab}\ i_{bc}\ i_{ca}]^T = T^t{}_{LL}.\ i_{oll} \quad (2.41)$$

Or $T^t{}_{LL}$ is the transpose of T_{LL} ; V_{ab} , V_{bc} and V_{ca} are the phase-to-phase output voltages; V_A , V_B and V_C are the input voltages ; i_{ab} , i_{bc} and i_{ca} are the phase-to-phase output currents; i_A , i_B and i_C are the input currents. Furthermore, using the transfer matrix T_{ph}, the Instantaneous output voltage between phase and neutral (V_a, V_b and V_c) and currents input phase can be given by [19]:

$$V_{oph} = (V_a\ V_b\ V_c)^t = T_{ph}(V_A\ V_B\ V_C)^t = T_{ph}V_i \quad (2.42)$$

$$i_{iph} = (i_A\ i_B\ i_C)^t = T_{ph}{}^t(i_a\ i_b\ i_c)^t = T_{ph}{}^t i_{oph} \quad (2.43)$$

Conclusion:

This chapter was devoted to research into the electrical modeling of the dual-supply asynchronous machine. We started with the different operating modes of the dual-feed machine; we saw that the (DFIG) has many advantages and very few disadvantages.

We used the phase-shifted model (d; q) which serves to simplify the model which was three-phase to better represent the behavior of an asynchronous machine. The latter is given by the Park transformation. So, we modeled the mechanical assembly including the multiplier, allowing interconnection with this machine.

CHAPTER III:

Application of Predictive Control to DFIG powered by Matrix Converter

III.1: Introduction

The application of predictive control techniques to DFIG systems powered by matrix converters has gained significant attention in recent years. Predictive control is an advanced control strategy that relies on a mathematical model of the system to predict its future behavior and calculate the optimal control actions to achieve the desired performance.

Predictive control based on the MPC model (Model Predictive Control) is a digital control by nature, based on the concept of prediction necessary in any activity in order to anticipate a predefined trajectory. It is based on knowledge of the digital model of the process to be controlled, which must be able to account for its dynamics in order to precisely predict its future behavior. In addition, compared to conventional linear regulators, it requires a lot of calculations. But it does so with stability, accuracy, and speed guaranteed [19].

The matrix converter direct (CMD) is a topology made up of a single stage by assembling nine. Four-segment type bidirectional switches, they allow the connection of each from the input phases (the source) to any phases of the output (DFIG) .This topology has recently received considerable attention due to its many merits over traditional AC-DC-AC converters, such as the absence of DC bus capacitor Which increases the lifespan of the system, the possibility of bidirectional transfer of electrical power, input-output waveforms sinusoidal and adjustable input power factor [20].

This chapter reviews the application of predictive control to DFIG in a control chain and powered by the matrix converter.

III.2: Model Predictive Control

III.2.1 : Predictive Control Methods for Power Converters and Drives:

Power converters are only recently beginning to use a very broad class of controllers known as predictive control. As suggested in [21], a classification for various predictive control techniques is displayed in Figure (III.1).

Using a system model to forecast how the controlled variables will behave in the future is the primary feature of predictive control. The controller uses this data to determine the best actuation based on a predetermined optimization criterion.

In trajectory-based control, the variables are compelled to follow a predetermined trajectory [22], whereas the optimization criterion in hysteresis-based predictive control is to maintain the controlled variable inside the bounds of a hysteresis area [23]. The ideal action in deadbeat control is the one that causes the error to equal zero at the following sampling instant [24, 25].

Model predictive control (MPC) uses a more accommodating criterion, which is represented as a cost function that needs to be reduced [26].

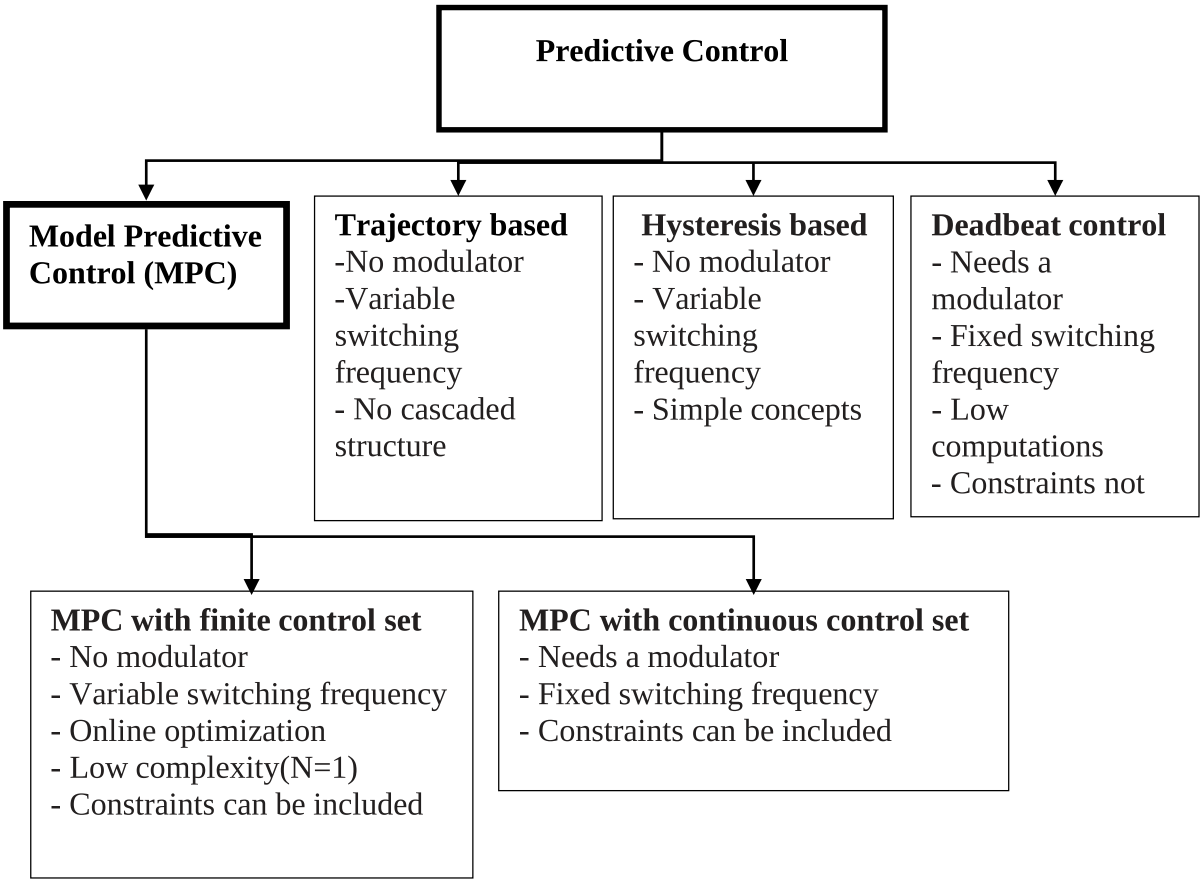


Figure III.1 Classification of predictive control methods used in power electronics

The distinction between both controller groups is that a modulator is necessary for both MPC with continuous control set and deadbeat control to produce the necessary voltage. As a result, the switching frequency will be fixed. Without the use of a modulator, the other controllers produce the switching signals for the converter directly. They will also display a configurable switching frequency. Predictive control has the benefit of having extremely straightforward and natural notions. Implementation can also be straightforward depending on the sort of predictive control, like with finite control set MPC and deadbeat control (particularly for a two-level converter with horizon (N = 1). However, if the continuous control set is taken into account, some MPC implementations may become more complicated. To increase its robustness, variations on the fundamental deadbeat control can also get highly complicated and challenging to comprehend. By avoiding the cascaded structure that is often employed in a linear control system, predictive control can be used to generate extremely quick transient reactions. Trajectory-based predictive control in speed control is one instance of this. By incorporating nonlinearities into the model, one can enhance the system's performance under all circumstances and avoid the need to linearize the model for a specific operating point. When creating the controller, limitations on certain variables are also an option. Some control schemes, like MPC, make it very easy to implement these advantages; however, other schemes, like deadbeat control, are very difficult to achieve.

III.2.2 : Basic Principles of Model Predictive Control

MPC is one of the advanced control methods—that is, more sophisticated than conventional PID control—that has been effectively applied in industrial settings [27-28]. While MPC originated as an application of optimal control theory in the 1960s, industrial interest in these concepts dates back to the late 1970s [29]. Since then, the chemical process industry has successfully used MPC because time constants there are long enough to complete all necessary calculations. In the 1980s, high-power systems with low switching frequencies were the focus of early MPC Power Electronics applications [23]. At that time, the control algorithm's lengthy calculation time prevented the use of higher switching frequencies. Nonetheless, during the past ten years, interest in the use of MPC in power electronics has grown significantly due to the advancement of quick and potent microprocessors.

Rather than focusing on a single control approach, MPC describes a broad family of controllers [27]. This type of controller shares two common features: it selects the best actuations by minimizing a cost function and employs a system model to forecast the future behavior of the variables until a predetermined time horizon. This structure has several important advantages:

- Dead times can be compensated.
- Simple treatment of constraints.
- Concepts are very intuitive and easy to understand.
- The resulting controller is easy to implement.
- Easy inclusion of non-linearities in the model.
- The multivariable case can be easily considered.

- This methodology is suitable for the inclusion of modifications and extensions depending on specific applications.

However, there are a few drawbacks that must be addressed, such as the increased computation load in comparison to traditional controllers. The resulting controller's quality is directly impacted by the model's quality, and if the system's parameters change over time, It is necessary to take into account an estimation or adaptation algorithm. The fundamental concepts found in MPC are:

- A cost function that represents the desired behavior of the system.
- The optimal actuation is obtained by minimizing the cost function.
- The use of a model to predict the future behavior of the variables until a horizon in time.

The model used for prediction is a discrete-time model which can be expressed as a state space model as follows:

$$\mathbf{x}(k+1) = A\mathbf{x}(k) + B\mathbf{u}(k) \tag{3.1}$$

$$\mathbf{y}(k) = C\mathbf{x}(k) + D\mathbf{u}(k) \tag{3.2}$$

A cost function that represents the desired behavior of the system needs to be defined. This function considers the references, future states, and future actuations:

$$J = f(\mathbf{x}(k), \mathbf{u}(k), \dots\dots, \mathbf{u}(k+N)) \tag{3.3}$$

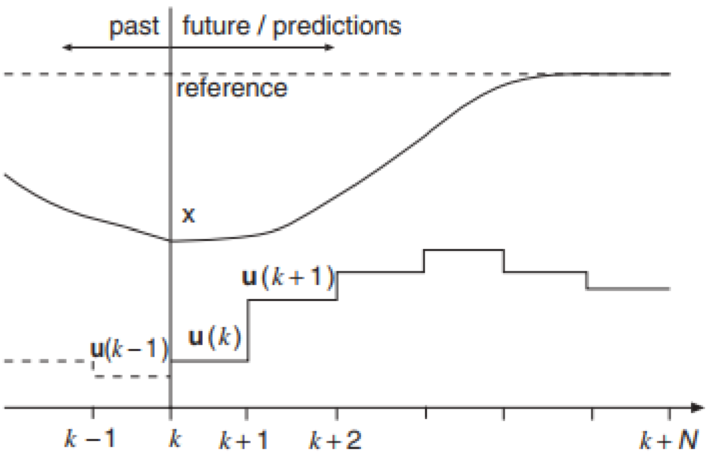


Figure III.2 Working principle of MPC

MPC is an optimization problem that consists of minimizing the cost function J, given the constraints and system model, for a predetermined time horizon in time N. A series of N ideal actuations is the end result. Only the initial element of the sequence will be applied by the controller.

$$\mathbf{u}(k) = [1\ 0 \ldots.0]\arg min_{u}.J \qquad (3.4)$$

where the optimization problem is solved again each sampling instant, using the new measured data and obtaining a new sequence of optimal actuations each time. This is called a *receding horizon* strategy.

A summary of the MPC operating principle can be found in Figure (III.2). Using the system model and the information (measurements) available up to time k, the future values of the system's states are predicted until a predetermined horizon in time k + N. By minimizing the cost function, the sequence of optimal actuations is determined, and the first element of this sequence is applied. Every sampling instant, this entire process is repeated while taking the most recent measured data into account.

III.2.3.1 : Controller Design

In the design stage of finite control set MPC for the control of a power converter, the following steps are identified:

- Modeling of the power converter identifying all possible switching states and its relation to the input or output voltages or currents.
- Defining a cost function that represents the desired behavior of the system.
- Obtaining discrete-time models that allow one to predict the future behavior of the variables to be controlled.

The power switch is the fundamental component of a converter model. It can be an IGBT, a thyristor, a gate turn-off thyristor (GTO), or another type of switch. This power switch's most basic model considers an ideal switch that has just two states: on and off. As a result, the number of possible pairings between each switch's two switching states equals the total number of switching states in a power converter. However, some combinations are not possible, for example, those combinations that short-circuit the DC link.

As a general rule, the number of possible switching states *N* is

$$N = x^{y} \qquad (3.5)$$

where *x* is the number of possible states of each leg of the converter, and *y* is the number of phases (or legs) of the converter. In this way a three-phase, two-level converter has *N* = 23 = 8 possible switching states, a three-phase, three-level converter has *N* = 33 = 27 switching states, and a five-phase, two-level converter has N = 25 = 32 switching states. In some multilevel topologies the number of switching states of the converter can be very high, as in a three-phase, nine-level cascaded H-bridge inverter, where the number of switching states is more than 16 million.

The relationship between the switching states and the voltage levels (for single-phase converters) or voltage vectors (for three-phase or multi-phase converters) is another component of the converter model. As opposed to voltage vectors, current vectors are related to potential switching states for current source converters. It is discovered that multiple switching states can produce the same voltage vector in multiple instances.

Eight switching states, for instance, produce seven distinct voltage vectors in a three-phase, two-level converter, with two switching states producing the zero vector. With 27 switching states, a three-phase, three-level converter has significant redundancy, with 19 distinct voltage vectors produced by 27 switching states.

III.2.3.2 : Implementation

The controller has to take into account the following tasks when it is implemented:

- Predict the behavior of the controlled variables for all possible switching states.
- Select the switching state that minimizes the cost function.
- Evaluate the cost function for each prediction.

Depending on the platform being used, different challenges may arise when implementing predictive models and a predictive control strategy. Programming requires extra care when utilizing a fixed-point processor to achieve the highest level of accuracy in the fixed-point representation of the variables. On the other hand, nearly identical simulation-based programming can be applied in the lab when implemented with a floating-point processor.

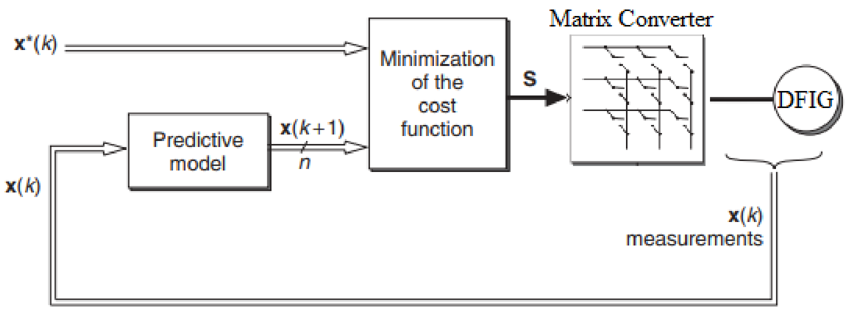


Figure III.3 General MPC scheme for power converters

The minimum sampling time will be limited by the number of calculations, which can be significant depending on the complexity of the controlled system. The calculation time is small for the simplest case, predictive current control; however, for other schemes, like torque and flux control, it is the parameter that establishes the permitted sampling time.

All feasible states are assessed in order to determine the switching state that minimizes the cost function, and the best result is saved for later use. The number of possible switching states is directly proportional to the number of calculations. Regarding the three-phase, It is not difficult to calculate predictions for the eight possible switching states in a two-level inverter; however, a different optimization strategy needs to be taken into account for multi-level and multi-phase systems in order to minimize the number of calculations.

III.2.3.3 : General Control Scheme

Figure (III.3) shows a general MPC control scheme applied to drives and power converters. The generic load in the figure can represent an electrical machine, the grid, or any other type of load, while the power converter can have any topology or number of phases. or any additional load, active or passive. In this scheme, the model uses the measured variables $x(k)$ to compute predictions $x(k+1)$ of the controlled variables, or switching states, voltages, or currents, for each of the n possible actuations. The best actuation S is then chosen and used in the converter after these predictions are assessed using a cost function that takes constraints and reference values $x^{*}(k)$ into account.

III.3:Predictive Current Control of the Matrix Converter

III.3.1 :Model of the Matrix Converter for Predictive Control

III.3.1.1: Input Filter Model

The input filter model can be represented by the following continuous-time equations, which are based on the circuit depicted in Figure (II. 4):

$$\mathbf{v}_s(t) = R_f \mathbf{i}_s(t) + L_f \frac{di_s(t)}{dt} + \mathbf{v}_i(t) \tag{3.6}$$

$$\mathbf{i_s}(t) = \mathbf{i_i} + C_f \frac{d\mathbf{v_i}(t)}{dt} \tag{3.7}$$

This continuous-time system can be rewritten as

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} \end{bmatrix} \mathbf{x}(t) + \begin{bmatrix} 0 & -\frac{1}{C_f} \\ \frac{1}{L_f} & 0 \end{bmatrix} \mathbf{u}(t) \tag{3.8}$$

—

with $\mathbf{A}_c = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} \end{bmatrix}$ $\mathbf{B}_c = \begin{bmatrix} 0 & -\frac{1}{C_f} \\ \frac{1}{L_f} & 0 \end{bmatrix}$

with

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{v_i}(t) \\ \mathbf{i}_s(t) \end{bmatrix} \quad \text{and} \quad \mathbf{u}(t) = \begin{bmatrix} \mathbf{v_s}(t) \\ \mathbf{i}_i(t) \end{bmatrix} \tag{3.9}$$

When a zero-order hold input is applied to a continuous-time system represented in state space form as in (3.8), a discrete state space model can be derived. Considering a sampling period Ts, the discrete-time system derived from (3.8) is

$$\mathbf{x}(k+1) = \mathbf{A}_q\mathbf{x}(k) + \mathbf{B}_q\mathbf{u}(k) \tag{3.10}$$

$$\mathbf{A}_q = e^{A_c T_s} \quad \text{and } B_q = \int_0^{T_s} e^{A_c(T_s-\tau)}\mathbf{B}_c d\tau \tag{3.11}$$

See [30] for further information on sampled-data systems and the theory used in this analysis. At sampling intervals, the continuous and discrete time variables will coincide. The discrete model can be easily obtained by using the MATLAB® function $c2d()$, which converts continuous-time models to discrete time. The mains current can be predicted by just solving is (k + 1) from (3.10):

$$\boldsymbol{i_s}(k+1) = \mathbf{A}_q(2,1)\boldsymbol{v_e}(k) + \mathbf{A}_q(2,2)\mathrm{i_s(k)} + \mathbf{B}_q(2,1)\mathbf{v}_s(k) + \mathbf{B}_q(2,2)i_e(k) \tag{3.12}$$

At this point, the method can use this model to predict the value of **i**s depending on $\boldsymbol{ii}$. Then (2.26) must be used to calculate $\boldsymbol{i_i}$ for each switching state.

III.3.1.2: The Instantaneous Active and Reactive Power

By taking into account the three-phase grid's instantaneous active power P reactive power Q, the MC's behavior can be enhanced. The active and reactive power is determined using the following equation [31]:

$$\begin{cases} Q = Im\{v_s(t).\bar{I}_s(t)\} \\ P = Re\{v_s(t).\bar{I}_s(t)\} \end{cases} \tag{3.13}$$

—

where $Im\{\}$ corresponds to the imaginary part of the product of the vectors and $\bar{I_s}\ (t)$ isthe complex conjugate of $\boldsymbol{i_s}(t)$.

where $Re\{\}$ corresponds to the real part of the product of the vectors and $\bar{I_s}\ (t)$ is the complex conjugate of $\boldsymbol{i_s}(t)$.

The instantaneous active and reactive power can be predicted by using

$$Q(k+1) = Im\{v_s(k+1).\bar{I}_s(k+1)\} \tag{3.14}$$

$$= v_{s\beta}(k+1).\bar{\iota}_{s\alpha}(k+1) - v_{s\alpha}(k+1).\bar{\iota}_{s\beta}(k+1)$$

$$P(k+1) = Re\{v_s(k+1).\bar{I}_s(k+1)\} \tag{3.15}$$

$$= v_{s\alpha}(k+1).\bar{\iota}_{s\alpha}(k+1) - v_{s\beta}(k+1).\bar{\iota}_{s\beta}(k+1)$$

where the real and imaginary components of the corresponding vector are denoted by the subscripts α and β. From (3.12), the anticipated value of the input current is $(k+1)$. Line voltages can be thought of as low-frequency signals, where $vs(k+1) \approx vs(k)$.

III.3.2: Output Current Control

Block diagram of the MC's predictive current control scheme with an induction machine (IM) as the load is displayed in Figure (II.4) . For each of the 27 switching states of the MC, future output current values are predicted using the load model and the filter model. The best switching state to apply in the converter is chosen using a cost function based on these predictions.

The evaluation criterion by which the control method chooses the best switching state to use during the subsequent sampling time is represented by the cost function g. Every legitimate switching state's g is evaluated as part of the optimization process. However, it is first necessary to define the goals that the converter must accomplish in order to come up with the equation that will represent the cost function. The load must be fed by the MC with currents that are nearly equal to the reference value while also, permit control over the input current to achieve regulated power factor (PF) and low harmonic distortion. Several other objectives can be included in the cost function due to the versatility of the presented approach, opening up a wide range of possibilities for further research.

Monitoring the reference current to the load is one of the goals that is represented in the cost function. It is better to switch in states where the output current values are closer to the reference. That goal is achieved by assigning cost or penalizing differences from the reference value, as expressed in the following cost function:

$$g_1 = \left|p^*{}_s(k+1) - P^p{}_s(k+1)\right| + \left|Q^*{}_s(k+1) - Q^p{}_s(k+1)\right| \qquad (3.16)$$

where the real and imaginary components of the reference active and reactive power $P^*$and Q^* are represented by the power $P^*{}_s$ and $Q^*{}_s$.For a given switching state, the real and imaginary components of the predicted active and reactive power $P^p(k+1)$ and $Q^p(k+1)$, are the powers $P^p{}_s$and $Q^p{}_s$.

the predictive control scheme with no reactive power control offers good reference tracking for the output currents. Nevertheless, there is no control over the input power factor and the input currents are highly distorted.

The ability of the MC topology to allow power to flow from the load to the grid, or regeneration, is one of its advantages. the MC's operation under regeneration conditions for current control in the absence of input power factor regulation. It is evident that even in the presence of distorted input currents, the output current control continues to function well.

III.3.3: Output Current Control with Minimization of the Input Reactive Power

The amplitude is determined by the active power flow, since the MC does not store energy; in addition to the output currents, it can also control the phase of the input current from the mains. Most modulation methods reach the objective of working with unity power factor by means of relatively complex strategies [32, 33]. The complexity rises significantly when dealing with inductive or capacitive power factor [13–34]. By penalizing switching states that generate predictions of Q that deviate from the reference value, the predictive control approach makes it easy to achieve the goal of controlling reactive power Q [21, 35].That is

$$g_2 = |Q^* - Q^p(k+1)| \qquad (3.17)$$

For every feasible switching state, the predicted reactive power Q^p value is derived from (3.14).As illustrated in Figure (II.4), its reference value Q^* is provided externally to operate with capacitive, inductive, or unity power factor (PF). Compared to other modulation strategies, this method offers the alternative of controlling that variable with a very simple approach, as most applications require unity PF, which is why $Q* = 0$ and $g_2 = |Q^p|$ [13–34].

The resulting cost function that reflects both objectives, output current and reactive input power control, is obtained simply by adding $g1$ and $g2$, thus

$$g = |p^*_s - P^p{}_s| + |Q^*_s - Q^p{}_s| + A|Q^* - Q^p| \tag{3.18}$$

where the weighing factor A handles the relevance of each objective. In order to deal with the different units of the terms present in g, A must have V^{-1} as unit.

A block diagram for the predictive control of the MC considering the input reactive power minimization is shown in Figure (III.4). Compared to the control scheme from Figure(II.4) the model of the input filter has been added and the cost function is the one presented in (3.18).

Controlling the reactive input power (PF) over the output current reference tracking is more relevant when the value of A is higher. The selection criteria for the value of A are discussed in brief next.

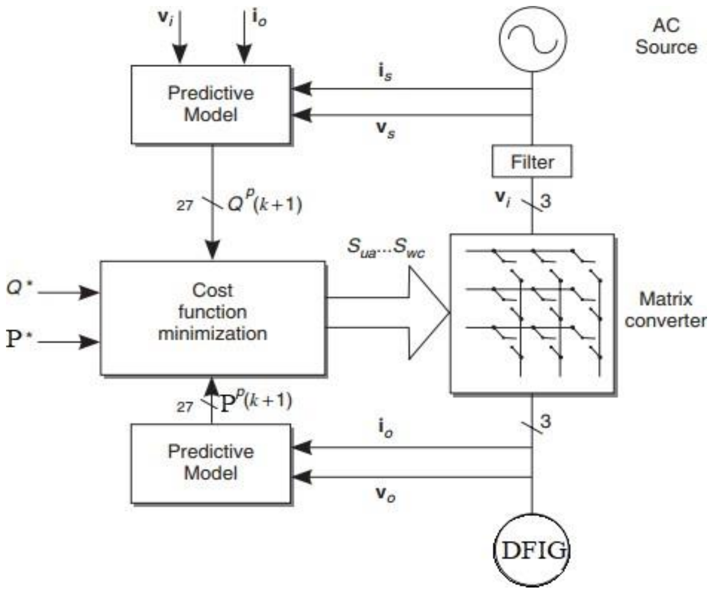
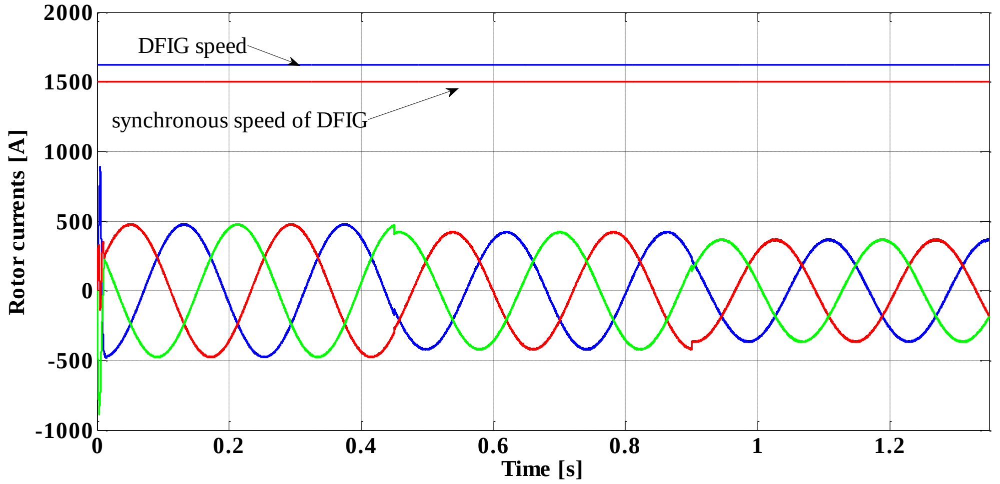


Figure III.4 Block diagram of the predictive current control strategy with minimization of the input active and reactive power

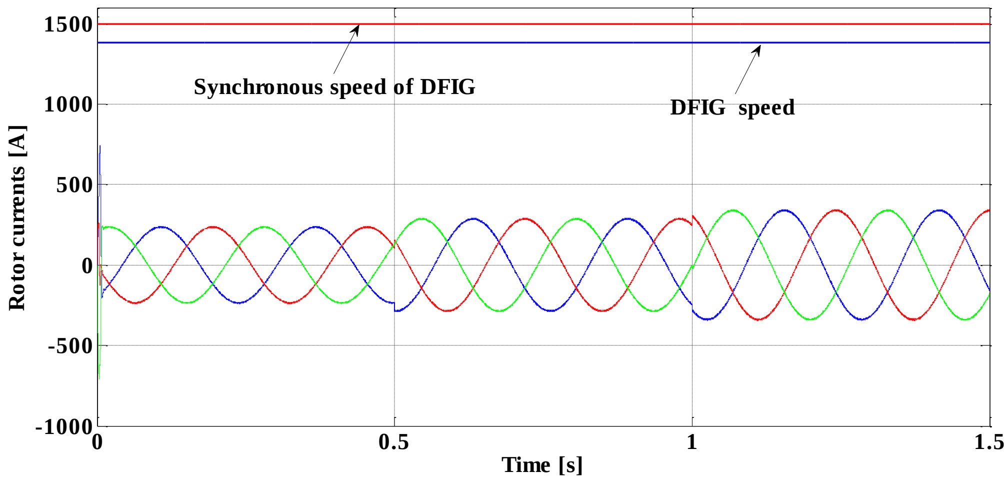
III.3.1 : Input Reactive Power Control

Reactive power production and consumption by generators allows the network operator to control voltages throughout their system, as we know that reactive power control plays a significant role in maintaining system stability efficiency, and reliable power transfer.

III.4: Simulation results:



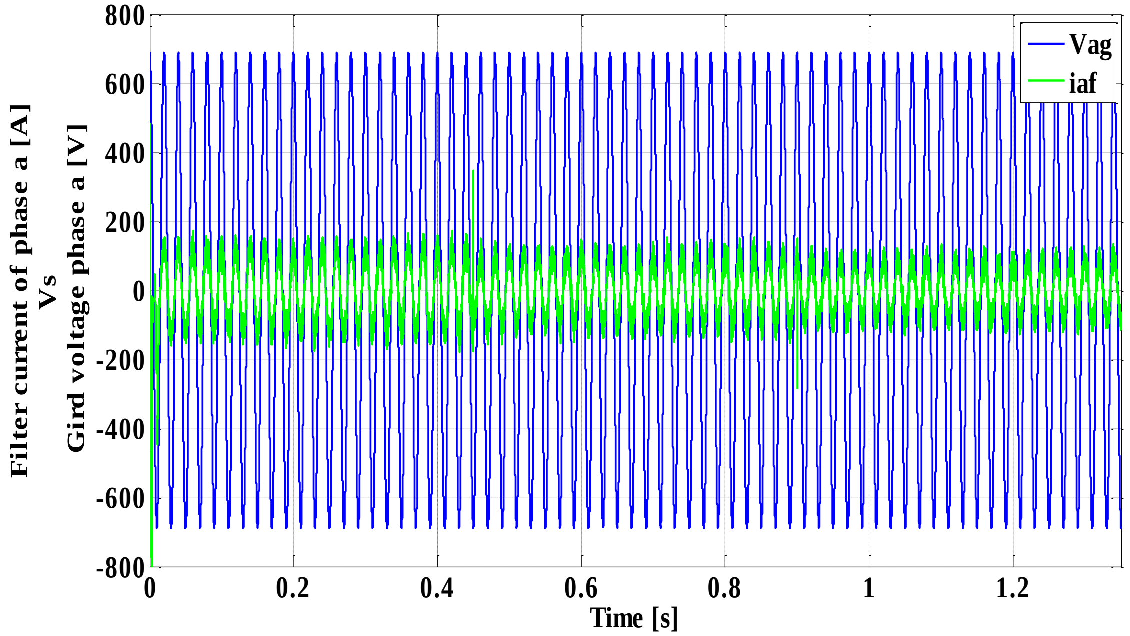
(a)



(b)

Figure III .5: Rotor currents. (a) speed more than 1500 tr/min .(b) less than 1500tr/min.

In view of what we discussed in the first chapter, we said that a doubly fed induction generator affects the synchronous speed by ±30%. In picture (a), we notice that when the speed is greater than 30% of the synchronous speed of the DFIG (hyper synchronous mode), the three rotor sinusoidal currents (I_{ra} ,I_{rb} *and* I_{rc}) varied in function of the variation in active power.



(a)

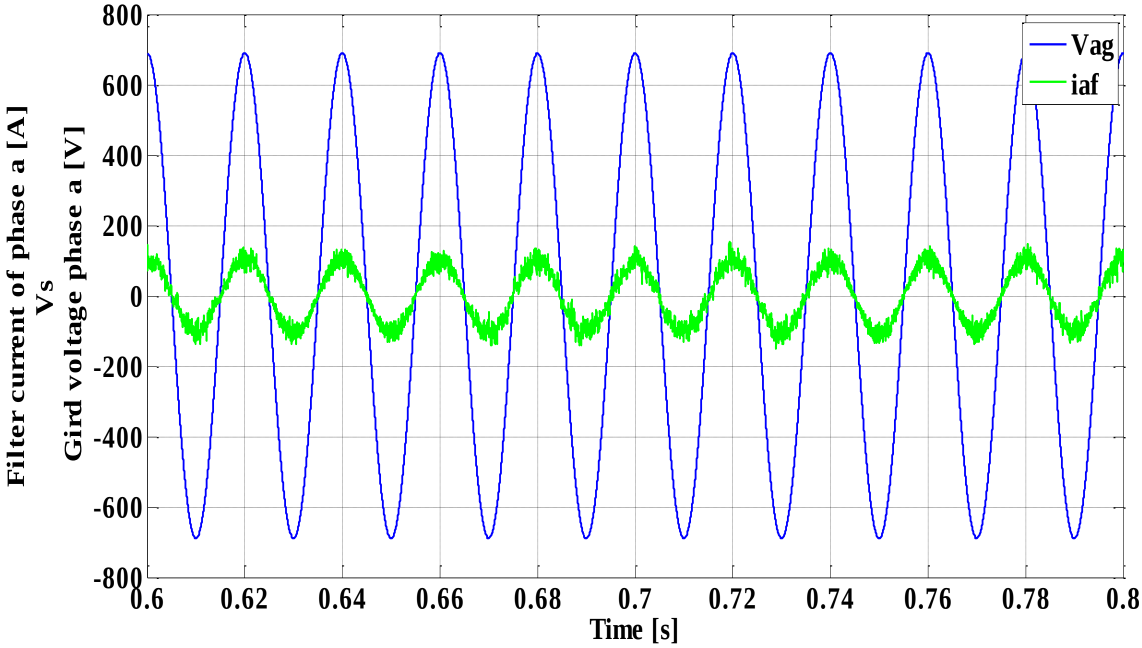


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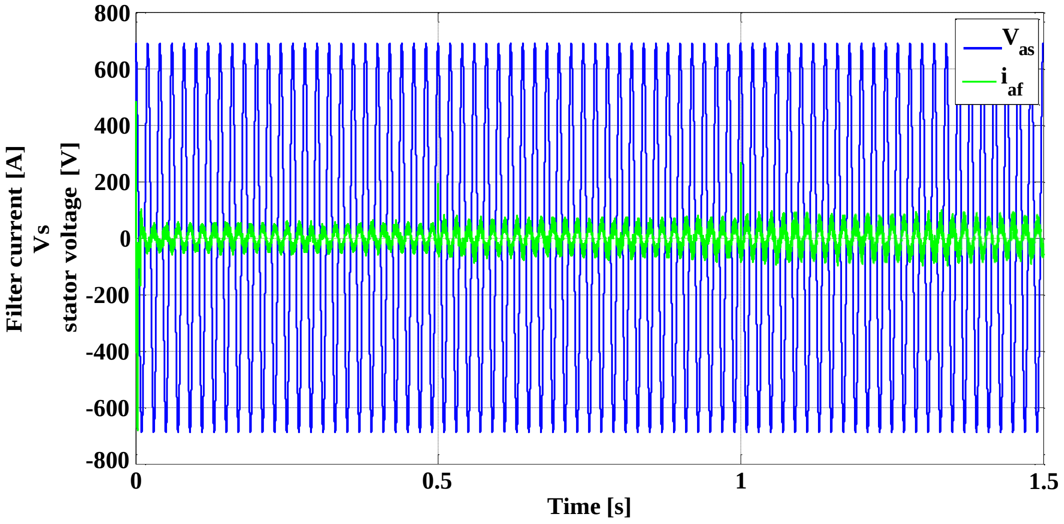
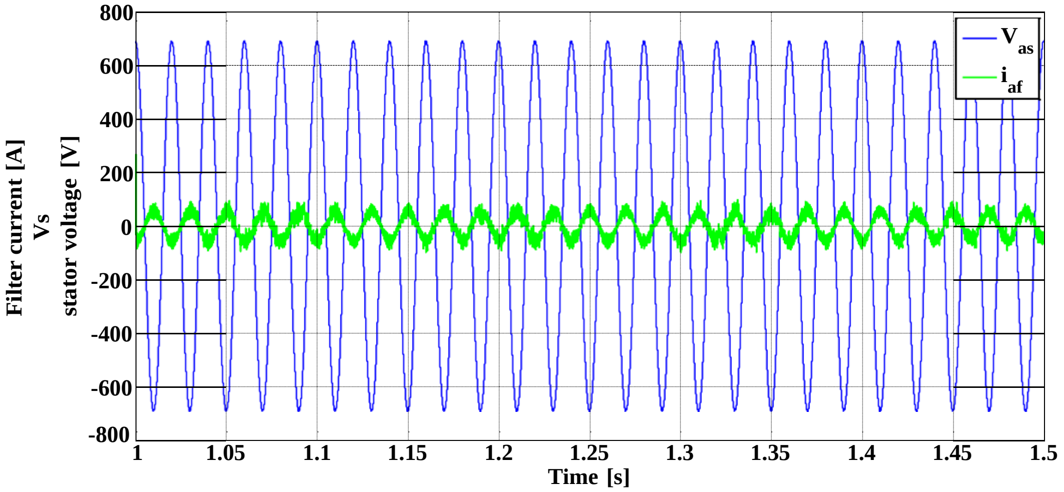
Figure III .6: Filter current and grid voltage phase

In picture (b), we notice that when the speed is less than 30% of the synchronous speed of the DFIG (sub synchronous speed mode), the three rotor sinusoidal currents (I_{ra} ,I_{rb} *and* I_{rc}) also varied in function with variation in the active power reference. But in this case we see the oscillation ripple in the rotor currents is large compared to the previous case in hyper synchronous mode.



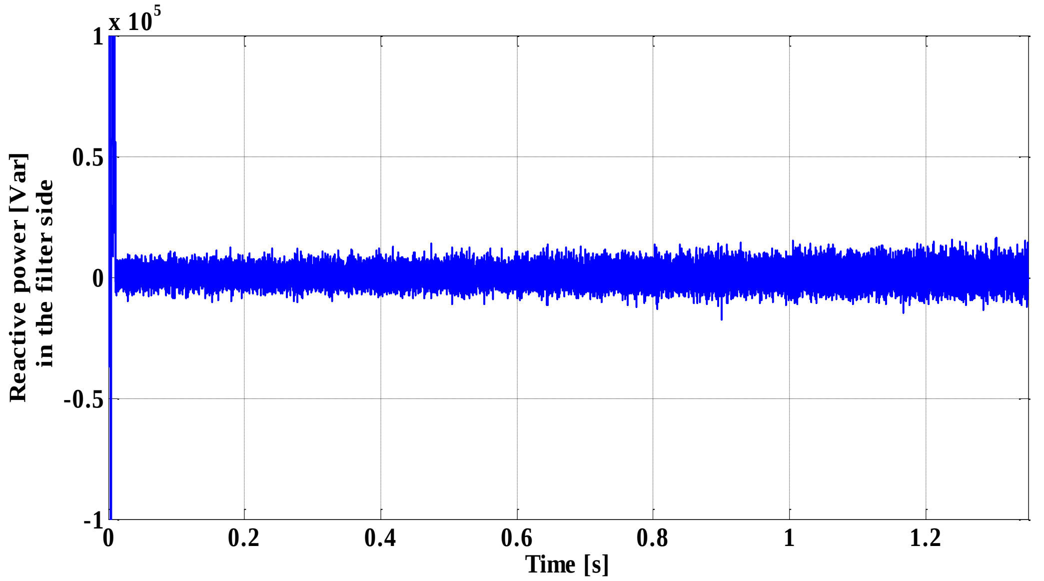
a



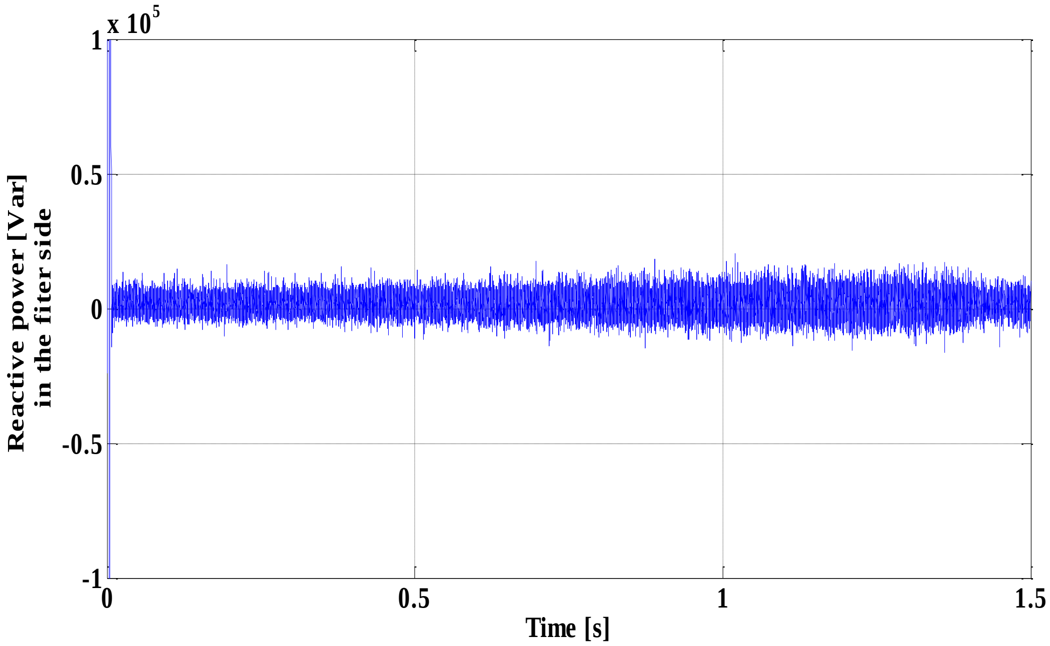
b

Figure III .7: Filter current and stator voltage phase.

The filter current injected into the network is in turn presented in Figure III.7 appearing sinusoidal with a frequency of 50Hz and is either in phase with the network voltage when operating in hypo synchronism or in phase opposition with the voltage of the network when operating in hyper synchronism. A zoom of the area changing the operating mode is illustrated by Figures III.6.b and Figure III.7.b, which results in almost zero consumptionof reactive power on the filter side. As for the stator currents in Figure (III.11), they are in their turns of form sinusoidal frequency 50Hz.

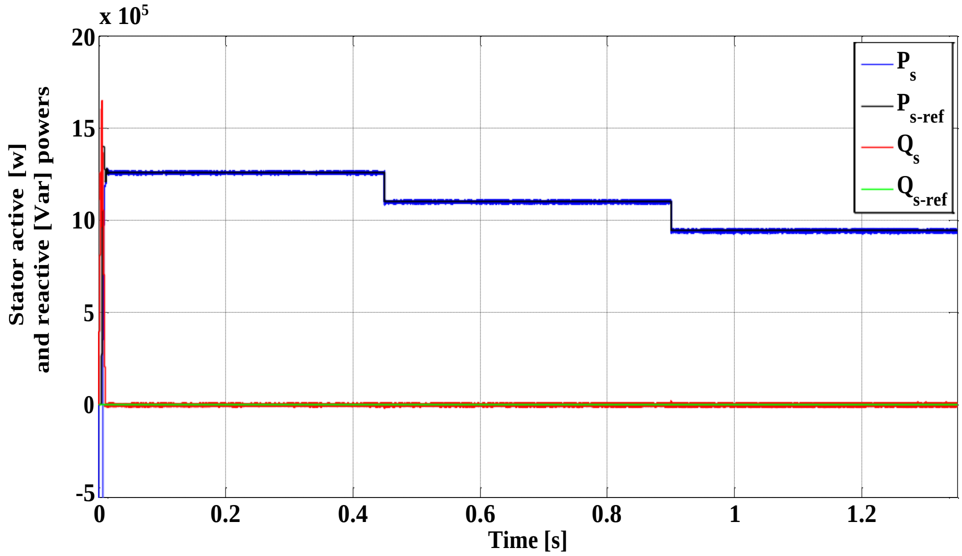


(a)

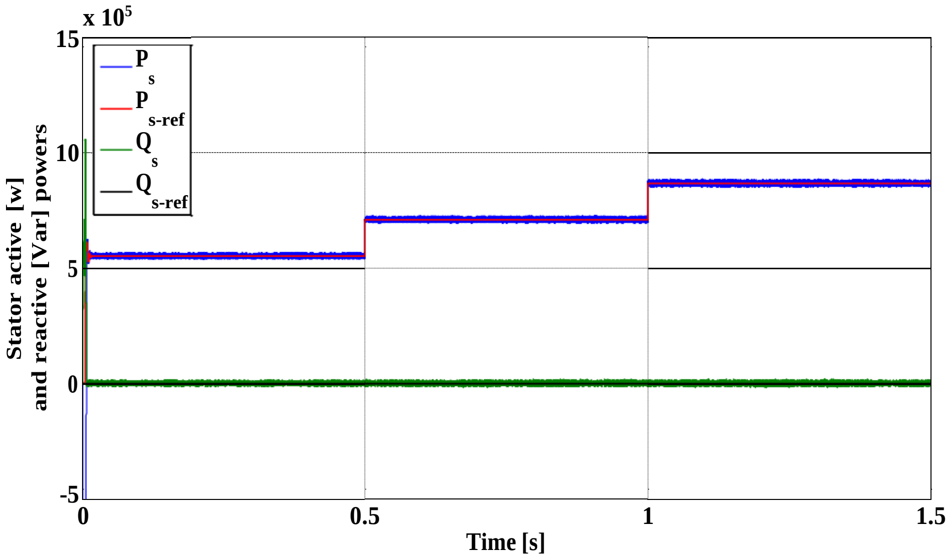


(b)

Figure III .8 : Reactive power in the filter side (a) speed more than 1500 tr/min .(b) less than 1500tr/min.



(a)

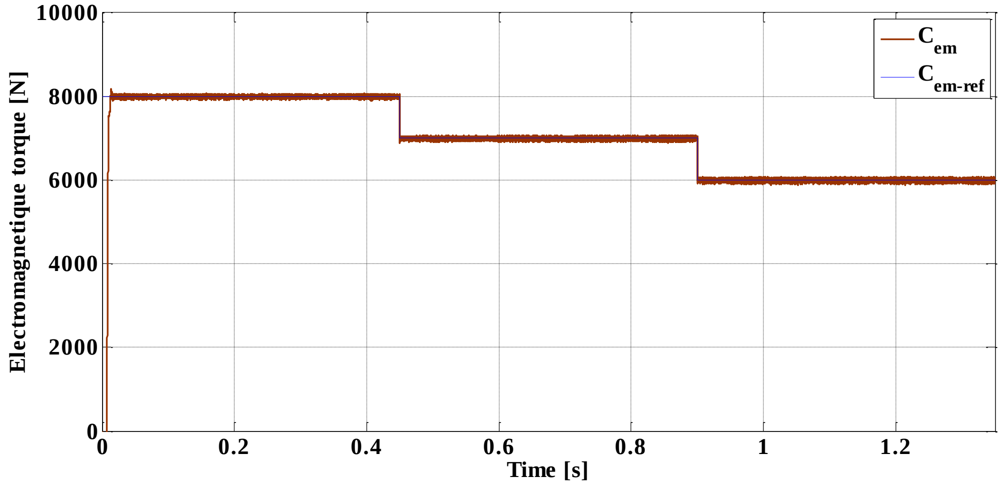


(b)

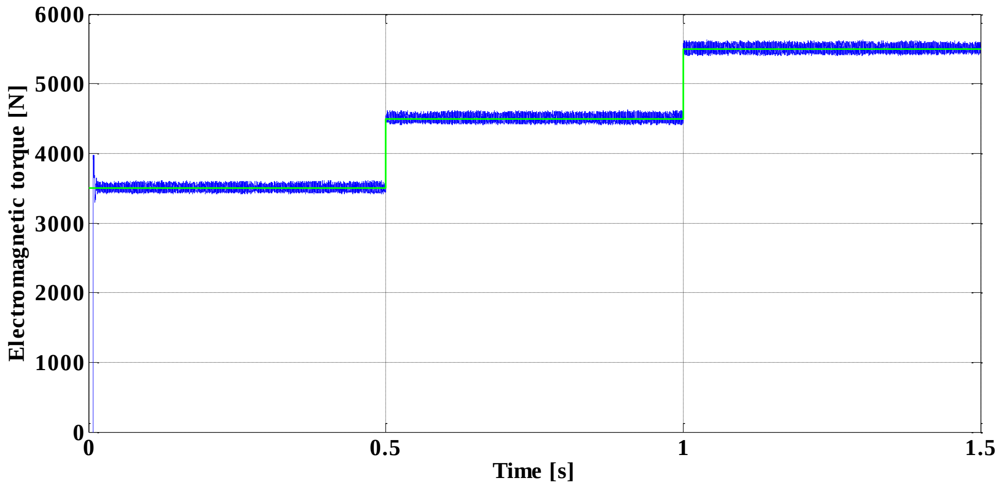
Figure III .9: Active and reactive stator power. (a) speed more than 1500 tr/min.(b) less

The generated stator active and reactive powers are illustrated by Figures III.9.a and b for a stator reactive power reference settled to 0 VAR. The tracking performance shows high dynamic performance for both stator powers and electromagnetic torque (Figure III.10.a and b) since the powers are perfectly decoupled and track their references accurately and precisely

The second term of the cost function depends on the minimization of the stator reactive power. By observing Figure III.9.a and Figure III.9.b, we see that the regulation performance is ensured since the reactive power of the stator is almost zero, which results in an operation with zero phase shift between the stator currents and the network voltages.



(a)



(b)

Figure III .10 : Electromagnetic torque. (a) speed more than 1500 tr/min .(b) less than 1500tr/min**.**

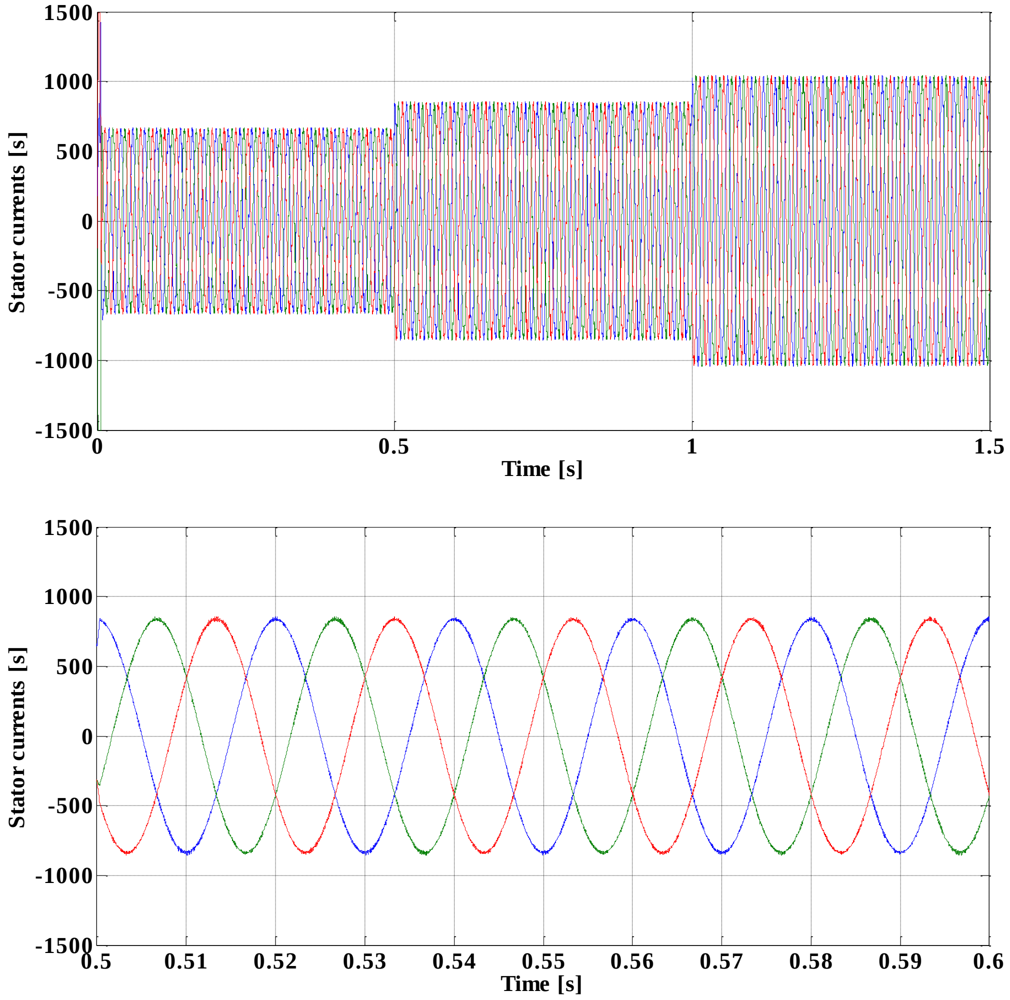


Figure III .11: Stator currents.

The stator currents in Figure (III .11) are in their turning form Sinusoidal with a frequency of 50 Hz and compatible with the grid voltage. Can see the amplitude of the stator currents is varied in function with the value of the active power reference.

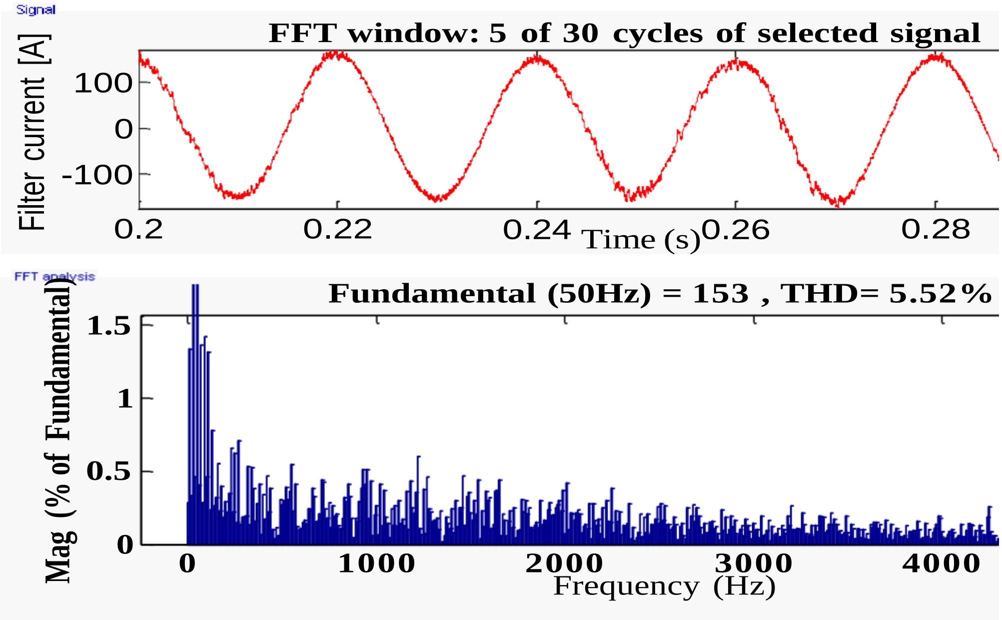


Figure III .12 : The analysis of electrical current using the Fast Fourier Transform (FFT).

Figure (III.12**)** displays the harmonic spectra of the filter currents. The THD current around 5.52% and is sinusoidal. The filter current is quasi-sinusoidal and less susceptible to harmonic content ripples. These findings demonstrate that, even with varying switching frequencies, the FS-MPC control maintains high power quality; THD is computed up to 4000 Hz.

III.6: Conclusion

This chapter allowed us to discover the application of the FS-MPC to control the active and reactive powers of the DFIG feed by a matrix converter.

The control scheme is very simple and uses the discrete model of the converter to predict the behavior of the drive system and to obtain the most suitable converter switching state considering the active and reactive powers errors by evaluating twenty-seven (27) combinations possible of the topology. The simplicity of the FS-MPC control being its major advantage, in fact its structure rejects any use of conventional linear regulators in the internal regulation loops. It is enough to add regulation terms in the cost function. Its flexibility also gives it a major advantage in taking into consideration the constraints arising from the operation of the system and this by a simple addition of several terms in its cost function (for example minimization of reactive power).

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General conclusion

Conclusion

Direct predictive control of active and reactive powers to the doubly fed induction generator (DFIG) is presented in our work. A matrix converter controlling the DFIG were presented throughout this wok under the concept of the MPC technique control. A cost function firstly minimizing the error between the reference quantities and those measured or estimated for the powers of the machine is given for each control structure. Then, other terms are added to the formulated cost function initially to take into account other constraints and objectives that we see as essential for the proper functioning of the electromechanical conversion chain, The chapters covered in this thesis show a remarkable richness of the order

- predictive MPC, in particular:
- Flexibility: It can be applied to a wide variety of systems, including those that are nonlinear, multivariable, or have significant delays.
- The method does not need internal control loops.
- It is a completely different control technique from other modulation techniques.
- Easy to use, adaptable, and capable of being embedded by digital computers.

In the first chapter, we gave a general overview of DFIG fed by a Matrix Converter. At second chapter, we presented the modeling of DFIG fed by direct matrix converter (DMC). at the final chapter an application of Predictive Control on DFIG powered by Matrix Converter, firstly the philosophy of the command is given in detail, then its application on the DFIG for powers control. The simulation results show better performance in terms fast dynamics, with better results in terms of reducing oscillations which gives an advantage to classic techniques. DFIG overcurrent protection is taken into consideration by the addition of term in the cost function to be minimized.

The simulation results are even better and better with the application of MPC on matrix topologies. Indeed, the ripples of the torque and the flux are largely reduced with these topologies, the waveforms of the currents are clearly increasingly better as the topology of the converter presents more voltage sources at the input and with a significantly reduced harmonic content too. To remedy the problem of balancing source voltages, the MPC control once again offers, thanks to its flexibility, a solution interesting by adding other terms in the formulated cost function thus making the voltages of the input capacitors balanced.