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CONTROL OF WIND TURBINE BASED ON PERMANENT MAGNET SYNCHRONOUS MACHINE (PMSG)

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أَعُوذُ بِاللَّهِ مِنَ الشَّيْطَانِ الرَّجِيمِ

﴿وَأَن لَّيْسَ لِلْإِنسَانِ إِلَّا مَا سَعَىٰ

* وَأَن سَعْيُهُ سَوْفَ يُرَىٰ﴾

(سورة النجم: 39-40)

"And that there is not for man except that [good] for which he strives, And that his effort is going to be seen."

(Surah An-Najm: 39-40)

DEDICATIONS

I dedicate this dissertation to the people who have meant and continue to mean so much to me.

To my beloved Mother,

For her endless love, continuous prayers, and countless sacrifices. You have always been my source of strength and inspiration. This is the fruit of your sleepless nights and unconditional support.

To my dear Father,

For his guidance, patience, and for instilling in me the value of hard work and education. You have always believed in me, even when I doubted myself.

To my brothers, sisters, and extended family,

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For the great teamwork, patience, late-night studies, and shared dedication to bringing this work to life. It was a great journey working together.

To all my friends and those who supported me along the way, I

dedicate this work.

Hamda Saif eddine

DEDICATIONS

To those whose names I proudly bear, to the wellspring of boundless generosity and support... my dear father and beloved mother, you are the light that illuminated my path, and the fruit of this endeavor is a result of your prayers and blessings.

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SUMMARY

This thesis investigates the modeling and advanced control of a grid-connected Wind Energy Conversion System (WECS) based on a direct-drive Permanent Magnet Synchronous Generator (PMSG). To overcome the dynamic limitations and parameter sensitivity of classical Proportional-Integral (PI) controllers, an advanced predictive control framework is proposed. First, the aerodynamic, mechanical, and electrical state-space models of the system are established. Then, an Optimal Torque Control (OTC) strategy is implemented to achieve Maximum Power Point Tracking (MPPT) and maximize aerodynamic energy extraction. For the Machine-Side Converter (MSC), a Finite-Set Model Predictive Control (FS-MPC) algorithm is developed, offering exceptional dynamic response and multivariable constraint handling without the need for a traditional PWM modulator. Concurrently, Voltage Oriented Control (VOC) is applied to the Grid-Side Converter (GSC) to regulate the DC-link voltage and inject high-quality active power into the grid at a unity power factor. The proposed control strategies are validated through MATLAB/Simulink simulations, demonstrating superior robustness, high tracking accuracy, and significantly reduced current ripple under highly variable wind speed conditions.

Keywords: Wind Energy, PMSG, MPPT, Optimal Torque Control (OTC), Finite-Set Model Predictive Control (FS-MPC), Voltage Oriented Control (VOC), Grid-Connected System.

Résumé

Ce mémoire étudie la modélisation et la commande avancée d'un système de conversion d'énergie éolienne (WECS) connecté au réseau, basé sur un générateur synchrone à aimants permanents (PMSG) à entraînement direct. Afin de surmonter les limitations dynamiques et la sensibilité aux paramètres des régulateurs classiques Proportionnel-Intégral (PI), une structure de commande prédictive avancée est proposée. Dans un premier temps, les modèles d'état aérodynamiques, mécaniques et électriques du système sont établis. Ensuite, une stratégie de commande par couple optimal (OTC) est mise en œuvre pour assurer la poursuite du point de puissance maximale (MPPT) et maximiser l'extraction d'énergie. Pour le convertisseur côté machine (MSC), un algorithme de commande prédictive à ensemble fini (FS-MPC) est développé, offrant une réponse dynamique exceptionnelle et une gestion multivariable des contraintes sans nécessiter de modulateur MLI (PWM) traditionnel. Parallèlement, la commande par orientation de tension (VOC) est appliquée au convertisseur côté réseau (GSC) pour réguler la tension du bus continu et injecter une puissance active de haute qualité dans le réseau avec un facteur de puissance unitaire. Les stratégies de commande proposées sont validées par des simulations sur MATLAB/Simulink, démontrant une robustesse supérieure, une grande précision de poursuite et une réduction des ondulations de courant sous des conditions de vitesse de vent très variables.

Mots-clés : Énergie éolienne, PMSG, MPPT, Commande par couple optimal (OTC), Commande prédictive à ensemble fini (FS-MPC), Système connecté au réseau.

الملخص

تبحث هذه المذكرة في نمذجة والتحكم المتقدم لنظام تحويل طاقة الرياح (WECS) المتصل بالشبكة والمبني على المولد التزامني ذو المغناطيس الدائم (PMSG) بالدفع المباشر. للتغلب على القيود الديناميكية والحساسية لتغيرات المعلمات في أجهزة التحكم الكلاسيكية التناسبية-التكاملية (PI)، تم اقتراح هيكل تحكم تنبئي متطور. في البداية، تم تأسيس النماذج الأيروديناميكية، الميكانيكية، والكهربائية (في فضاء الحالة) للنظام. بعد ذلك، تم تطبيق استراتيجية التحكم الأمثل في العزم (OTC) لتحقيق تتبع نقطة الاستطاعة القصوى (MPPT) وتعظيم استخراج الطاقة.

بالنسبة للمحول من جهة الآلة (MSC)، تم تطوير خوارزمية التحكم التنبئي ذو المجموعة المنتهية (FS-MPC)، والتي توفر استجابة ديناميكية استثنائية وقدرة على التعامل مع القيود متعددة المتغيرات دون الحاجة إلى معدل النبضات التقليدي (PWM).

بالتوازي مع ذلك، تم تطبيق التحكم الموجه بالجهد (VOC) على المحول من جهة الشبكة (GSC) لتنظيم جهد الحلقة المستمرة (DC-link) وحقن طاقة فعالة عالية الجودة في الشبكة بمعامل استطاعة أحادي. تم التحقق من صحة استراتيجيات التحكم المقترحة من خلال المحاكاة باستخدام برنامج MATLAB/Simulink، حيث أثبتت النتائج متانة عالية، دقة تتبع فائقة، وتقليلاً واضحاً لمتوجات التيار تحت ظروف سرعة رياح شديدة التغير.

الكلمات المفتاحية: طاقة الرياح، المولد التزامني ذو المغناطيس الدائم (PMSG)، تتبع نقطة الاستطاعة القصوى (MPPT)، التحكم الأمثل في العزم (OTC)، التحكم التنبئي (FS-MPC)، النظام المتصل بالشبكة

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LIST OF SYMBOLS

Aerodynamic & Mechanical Symbols

- C_p : Power coefficient
- $C_{p,max}$: Maximum power coefficient
- F : Viscous friction coefficient
- J : Total rotational inertia ($kg.m^2$)
- K_{opt} : Optimal torque coefficient
- P_m : Aerodynamic mechanical power (W)
- R : Turbine blade radius (m)
- T_e : Electromagnetic torque ($N.m$)
- T_m : Aerodynamic mechanical torque ($N.m$)
- T_{opt} : Optimal mechanical reference torque ($N.m$)
- v : Wind speed (m/s)
- β : Blade pitch angle ($degree$)
- λ : Tip-speed ratio
- λ_{opt} : Optimal tip-speed ratio
- ρ : Air density (kg/m^3)
- ω_m : Mechanical rotor speed (rad/s)
- $\omega_{m,opt}$: Optimal mechanical rotor speed (rad/s)

Electrical & Control Symbols

- g : Predictive cost function
- i_d, i_q : d -axis and q -axis stator currents (A)
- $i_{d,ref}, i_{q,ref}$: d -axis and q -axis reference stator currents (A)
- $i_{g,d}, i_{g,q}$: d -axis and q -axis grid currents (A)
- i_{max} : Maximum allowable stator current limit (A)
- L_d, L_q : d -axis and q -axis stator inductances (H)
- L_s : Stator synchronous inductance (H)
- L_g : Grid filter inductance (H)
- p : Number of pole pairs
- R_s : Stator resistance (Ω)
- R_g : Grid filter resistance (Ω)
- T_s : Sampling time (s)
- V_d, V_q : d -axis and q -axis stator voltages (V)
- $V_{g,d}, V_{g,q}$: d -axis and q -axis grid voltages (V)
- $V_{GSC,d}, V_{GSC,q}$: Grid-Side Converter output voltages (V)
- V_{dc} : DC-link voltage (V)
- Ψ_d, Ψ_q : d -axis and q -axis stator flux linkages (Wb)
- Ψ_m : Permanent magnet flux linkage (Wb)
- ω_e : Electrical angular velocity (rad/s)
- ω_g : Grid electrical angular frequency (rad/s)
- θ_e : Electrical rotor position (rad)

LIST OF ABBREVIATIONS

A

- **AC:** Alternating Current

D

- **DC:** Direct Current
- **DFIG:** Doubly Fed Induction Generator

F

- **FOC:** Field-Oriented Control
- **FS-MPC:** Finite-Set Model Predictive Control

G

- **GSC:** Grid-Side Converter

H

- **HIL:** Hardware-In-the-Loop

M

- **MPC:** Model Predictive Control
- **MPPT:** Maximum Power Point Tracking
- **MRAS:** Model Reference Adaptive System
- **MSC:** Machine-Side Converter

O

- **OTC:** Optimal Torque Control

P

- **PI:** Proportional-Integral
- **PMSG:** Permanent Magnet Synchronous Generator

- **PWM:** Pulse Width Modulation

S

- **SPMSG:** Surface-Mounted Permanent Magnet Synchronous Generator
- **SVPWM:** Space Vector Pulse Width Modulation

T

- **THD:** Total Harmonic Distortion

V

- **VOC:** Voltage Oriented Control

W

- **WECS:** Wind Energy Conversion System

LIST OF EQUATION

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GENERAL

INTRODUCTION

The continuous advancement of global industrialization and rapid population growth have led to an unprecedented and accelerating demand for energy. Historically, this escalating demand has been met through the extensive extraction and combustion of fossil fuels. However, the severe environmental repercussions of this reliance—most notably the emission of greenhouse gases and the accelerating crisis of global warming—have necessitated an urgent and structural transition toward cleaner, sustainable alternatives. Within this context, renewable energy sources have shifted from being optional supplements to fundamental pillars of the modern electrical grid. Among these alternatives, wind energy has experienced exponential global growth. It has emerged as a highly viable solution primarily because it harnesses a naturally occurring, inexhaustible resource and operates with zero direct carbon emissions.

As wind power systems scale up to meet modern grid demands, the electromechanical technology driving them must simultaneously become more efficient and reliable. Within modern Wind Energy Conversion Systems (WECS), the direct-drive Permanent Magnet Synchronous Generator (PMSG) has become increasingly prominent. Compared to traditional generators, the gearless PMSG architecture is highly favored for its superior operational efficiency, minimal maintenance requirements, and excellent performance across variable wind speeds.

However, harnessing the maximum potential of a PMSG-based wind turbine presents complex dynamic challenges. The aerodynamic nature of wind is inherently volatile and non-linear. While classical Field-Oriented Control (FOC) utilizing Proportional-Integral (PI) regulators is widely used in the industry, it often struggles to maintain optimal performance due to delayed dynamic responses, parameter sensitivity, and linearization constraints. To overcome these limitations, advanced control methodologies have become a focal point of recent electrical engineering research. Finite-Set Model Predictive Control (FS-MPC) has emerged as a highly promising approach, offering exceptional dynamic response, inherent robustness, and the unique ability to handle multiple system constraints seamlessly without the need for traditional modulation stages.

Accordingly, the primary objective of this thesis is to model, design, and configure an advanced predictive control framework for a grid-connected PMSG wind energy

system. The study focuses on maximizing aerodynamic energy extraction while ensuring highly dynamic and stable electrical performance.

To achieve these objectives, this thesis is organized into three main chapters:

- **Chapter 1: Introduction to Wind Energy Systems:** This chapter establishes the fundamental context of wind energy and references the wind potential in Algeria as a motivating geographical context. It presents the general architecture of wind energy conversion systems, provides a comparative analysis between PMSG and DFIG technologies, and outlines the limitations of classical PI-based control to justify the need for predictive strategies.
- **Chapter 2: Modeling of the PMSG-Based Wind Energy System:** This chapter is dedicated to formulating the rigorous mathematical foundation of the system. It details the aerodynamic model of the turbine, the mechanical drivetrain, and the dynamic state-space modeling of the PMSG in the synchronous $d - q$ reference frame. Finally, it establishes the grid-side modeling required for complete system integration.
- **Chapter 3: Control Strategies for the WECS:** The final chapter details the proposed control framework. It introduces the Optimal Torque Control (OTC) strategy for Maximum Power Point Tracking (MPPT). Subsequently, it formulates the discrete-time Finite-Set Model Predictive Control (FS-MPC) algorithm for the machine-side converter. It also outlines the Voltage Oriented Control (VOC) for grid synchronization and concludes with the specific system parameters configured for practical implementation, alongside a comprehensive presentation and discussion of the simulation results.

CHAPTER 1

CHAPTER 1

1.1 Introduction to Wind Energy

In the last decade The world is using more energy caused by growing industries and population. In the past we met this growing demand by extracting and burning fossil fuels.. This has caused big environmental problems like global warming and greenhouse gas emissions. So we need to shift to cleaner energy sources.

Wind energy is a solution because it uses a free and natural resource and doesn't emit carbon directly. This makes it crucial for reducing carbon emissions in the energy sector. As wind power systems get bigger to meet today's grid demands the technology driving them must become more efficient and reliable.

In Wind Energy Conversion Systems the Permanent Magnet Synchronous Generator (PMSG) is becoming more popular. It's liked for its power density, high efficiency and good performance in varying wind speeds. Also it can operate directly without gearboxes making the turbine last longer and be more reliable.

Getting the most out of a PMSG-based wind turbine is complex. Wind is unpredictable and non-linear so we need control strategies to get the most power while ensuring stable power delivery to the grid. Traditional control methods often struggle with the changing conditions of wind systems.

To solve these problems and make turbines more efficient advanced control methods are being researched. Model Predictive Control (MPC) is an approach for managing PMSG wind turbines. It uses a model to predict the turbines behavior and minimize a cost function. This offers a dynamic response, high robustness and the ability to handle multiple system constraints.

This thesis focuses on developing, applying and analyzing predictive control strategies for a wind turbine driven by a Permanent Magnet Synchronous Generator. By using this control framework this work aims to demonstrate :

- The development of predictive control strategies for PMSG wind turbines.
- The application of Model Predictive Control for wind turbines.
- The performance analysis of control strategies, for PMSG wind turbines.

The goal is to show how predictive control can improve the efficiency and reliability of wind turbines.

1.2 Wind Energy Potential in Algeria

Algeria occupies a unique geographical position that grants it an exceptional, yet historically underutilized, wind energy potential. As part of a broader national strategy to diversify its electrical grid and ensure long-term energy security, the government has initiated an ambitious transition framework. A central objective of this roadmap is the installation of at least 1000 MW of commercial wind power capacity by the year 2030 [1].

Achieving this target relies heavily on the distinct meteorological profiles of the High Plateaus and the expansive southern Saharan territories. Recent techno-economic assessments consistently demonstrate that these regions possess highly favorable conditions for large-scale wind farm integration [2]. Locations such as Adrar, In Salah, and the El Oued province feature vast, unobstructed landscapes where average wind velocities frequently range between 7 and 9 meters per second. This specific aerodynamic profile is highly optimal for modern wind energy conversion systems. At these speeds, turbines equipped with direct-drive Permanent Magnet Synchronous Generators (PMSGs) can operate near their peak efficiency, capturing maximum aerodynamic power while delivering a stable and reliable electrical output to the grid.

The feasibility of exploiting these southern wind corridors is not merely theoretical. It has been practically validated by the successful commissioning of the Kaberten wind farm in the Adrar province, which operates with an installed capacity of 10 MW [3]. This pioneering installation serves as a foundational proof of concept, highlighting the

technical viability of scaling up wind infrastructure across the Algerian south and paving the way for more advanced generation and control technologies.

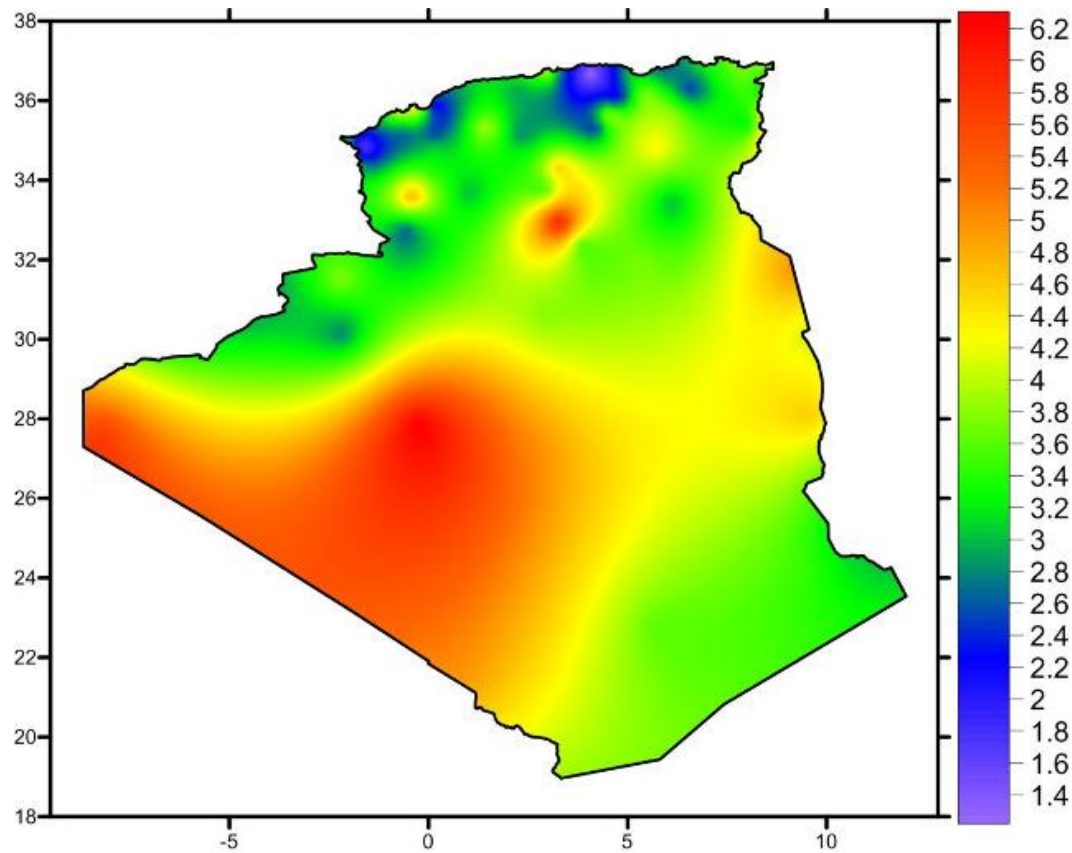


Figure 1-1 Wind potential map of Algeria [4]

1.3 Architecture of a Wind Energy Conversion System (WECS)

The fundamental objective of a Wind Energy Conversion System (WECS) is to transform the kinetic energy of the wind into high-quality electrical energy suitable for the power grid. To achieve this conversion with high efficiency, the system architecture is generally composed of four primary functional stages: the aerodynamic rotor, the drive train, the electrical generator, and the power electronic interface [2], [5].

The Rotor: This is the primary stage of energy capture, consisting of the blades and the hub. Its function is to intercept the wind flow and convert its kinetic energy into mechanical torque, which rotates the main shaft.

The Drive Train: This subsystem is responsible for transmitting the mechanical power

from the rotor to the generator. It typically includes the main shaft, bearings, and, in conventional designs, a speed-increasing gearbox.

The Electrical Generator: Acting as the electromechanical heart of the system, the generator converts the rotational mechanical energy into electrical power. In modern high-performance turbines, the Permanent Magnet Synchronous Generator (PMSG) is frequently employed due to its superior efficiency.

The Power Converters: Since the wind speed is variable, the frequency and voltage produced by the generator are also variable. Power electronic converters are essential to rectify, modulate, and synchronize this power with the constant requirements of the electrical grid [2].

A significant evolution in modern WECS design is the shift toward "Direct-Drive" architectures. Traditional turbines rely on a gearbox to match the slow rotation of the blades with the high speed required by standard generators. However, the gearbox is often the most maintenance-intensive and failure-prone component due to mechanical stress and lubrication requirements. To enhance system reliability and reduce operational downtime, modern industry trends are increasingly moving toward eliminating the gearbox entirely [5]. By coupling a low-speed PMSG directly to the rotor hub, the system achieves a more robust, compact, and efficient design, which is particularly advantageous for the harsh environments of the Algerian Sahara.

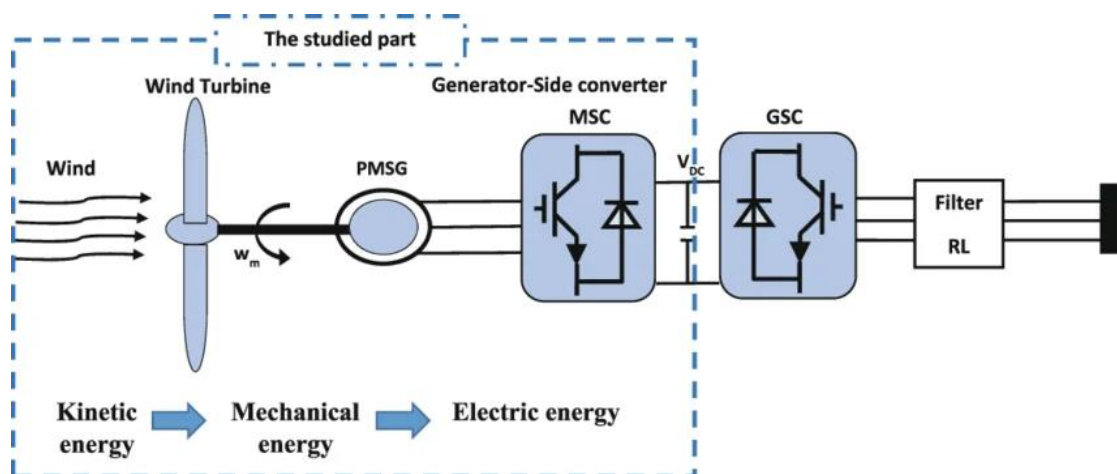


Figure 1-2 General architecture of a direct-drive PMSG-based wind energy conversion system [6]

1.4 Generator Technologies: DFIG vs PMSG

The modern wind energy sector is predominantly driven by a technological competition between two major electrical machines: the Doubly Fed Induction Generator (DFIG) and the Permanent Magnet Synchronous Generator (PMSG) . While both technologies have been successfully commercialized worldwide to meet growing energy demands, they rely on fundamentally different electromechanical architectures.

Historically, the DFIG has maintained a strong market presence, largely because it requires a power converter rated at only a fraction of the total system power. However, its operational architecture strictly necessitates the use of a multi-stage gearbox to mechanically couple the low-speed aerodynamic rotor to the high-speed induction generator. This mechanical complexity introduces significant rotational friction and structural stress. Consequently, the gearbox becomes a highly vulnerable component that requires continuous lubrication and intensive, costly maintenance, frequently leading to increased system downtime .

In stark contrast, the PMSG is rapidly becoming the preferred choice for modern, high-performance wind energy conversion systems. The primary advantage of the PMSG lies in its ability to operate in a "Direct-Drive" configuration. By utilizing permanent magnets to generate the necessary constant excitation field, the PMSG can operate efficiently at low rotational speeds. This completely eliminates the need for both the gearbox and the mechanical slip rings. This gearless architecture inherently minimizes mechanical power losses, drastically reduces routine maintenance requirements, and yields a significantly higher overall system efficiency and reliability . Furthermore, this robust and highly responsive nature makes the PMSG an ideal candidate for implementing advanced, highly dynamic electrical optimization strategies, such as predictive control frameworks.

The key technical and operational differences between the two generator technologies are summarized in Table 1.1 below.

Feature	Doubly Fed Induction Generator (DFIG)	Permanent Magnet Synchronous Generator (PMSG)
Gearbox Requirement	Requires a multi-stage gearbox	No gearbox needed (Direct-Drive)
Maintenance Cost	High (due to gearbox and slip rings)	Low (brushless and gearless)
Efficiency	Moderate	High (no excitation losses)
Size and Weight	Relatively compact	Larger and heavier
Converter Size	Partial scale (~30% of rated power)	Full scale (100% of rated power)
Control Complexity	Complex (stator and rotor dynamics)	Simplified (controlled via stator only)

Table 1-1 Comparative analysis between DFIG and PMSG technologies [5]

1.5 Classical Control: Field-Oriented Control (FOC)

The conventional approach for PMSG regulation is Field-Oriented Control (FOC), which relies on the decoupling of stator currents into d and q components [14]. In a standard FOC architecture, a cascaded control structure is employed. An outer speed loop generates the torque command, while inner loops utilize Proportional-Integral (PI) controllers to regulate the currents. The output of the PI controllers defines the required continuous voltage vectors, which are subsequently processed by a Space Vector Pulse Width Modulation (SVPWM) or Sinusoidal PWM generator to produce the discrete switching signals for the power inverter.

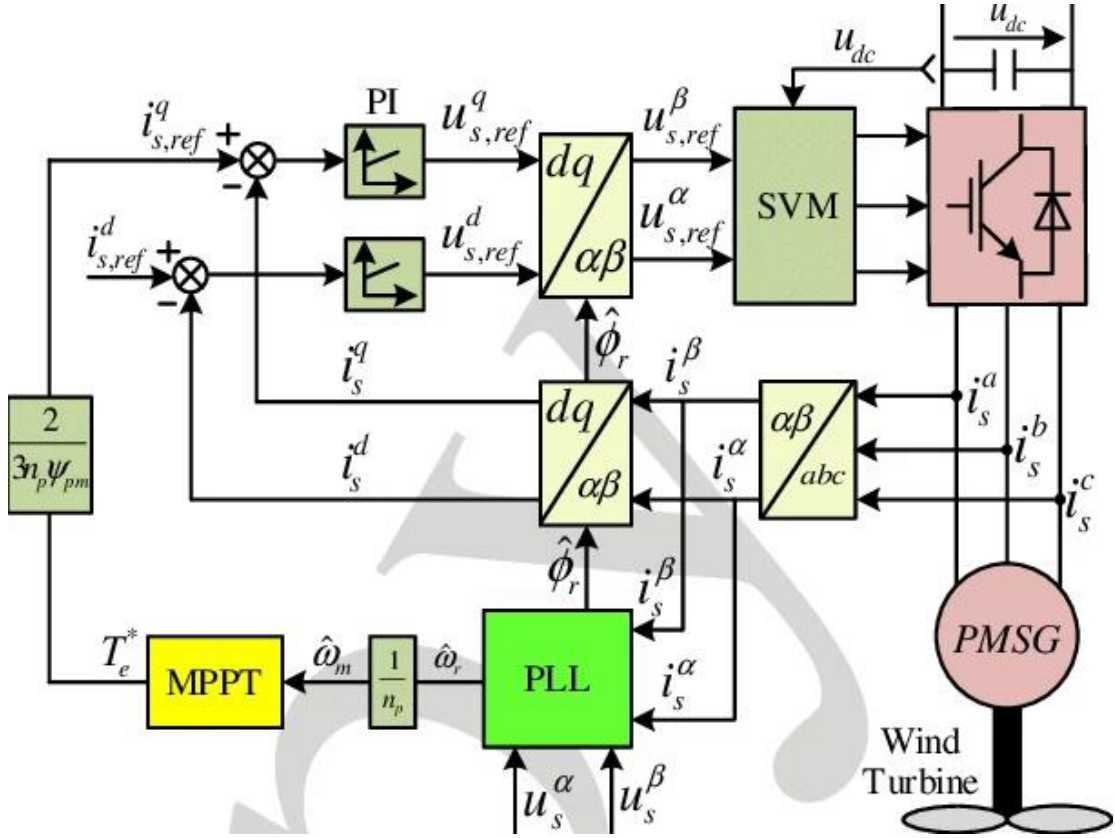


Figure 1-3 Block diagram of the classical Field-Oriented Control (FOC) scheme for PMSG [14].

1.6 Limitations of PI-Based Control in WECS

Despite its widespread industrial use, PI-based FOC exhibits significant drawbacks when applied to highly dynamic wind energy systems:

1. **Dynamic Response:** The bandwidth of PI controllers is limited by the requirement for a separate PWM stage, leading to delays in tracking rapid wind speed fluctuations.
2. **Parameter Sensitivity:** The performance of PI controllers is heavily dependent on precise gain tuning (K_p, K_i). Variations in machine parameters, such as stator resistance due to thermal effects, can compromise system stability [11].
3. **Linearization Constraints:** PI controllers are designed based on linearized models, which may not adequately capture the non-linearities inherent in power converters and wind turbine dynamics.

1.7 Conclusion

In summary, this chapter has established the fundamental context for the global transition towards renewable energy, highlighting the significant, yet underutilized, wind energy potential within the Algerian landscape. Through a detailed examination of Wind Energy Conversion Systems (WECS), the direct-drive Permanent Magnet Synchronous Generator (PMSG) was identified as the optimal technological architecture due to its gearless reliability, high efficiency, and operational robustness.

However, extracting maximum power from such systems under highly variable wind conditions presents a significant control challenge. While classical Field-Oriented Control (FOC) utilizing Proportional-Integral (PI) regulators has been the industry standard, its limitations—such as delayed dynamic response, parameter sensitivity, and an inability to efficiently handle system non-linearities—hinder the optimal performance of modern PMSG wind turbines. This necessitates the adoption of more advanced and robust optimization frameworks, specifically Model Predictive Control (MPC), to overcome these dynamic constraints.

Building upon this foundational understanding, developing a high-performance predictive controller first requires an accurate representation of the system's electromechanical dynamics. Consequently, the next chapter will be dedicated to the comprehensive mathematical modeling of the PMSG-based wind turbine, which will serve as the essential mathematical framework for designing and implementing the predictive control strategies proposed in this work.

CHAPTER 2

CHAPTER 2 Modeling of the PMSG-Based Wind Energy System

2.1 Introduction

The effective control of a wind energy conversion system (WECS) necessitates a rigorous mathematical model of its underlying dynamics. Formulating an accurate representation of the physical system is a fundamental prerequisite for the implementation of advanced control strategies. A direct-drive WECS encompasses three interdependent physical domains: aerodynamic power extraction, mechanical drivetrain dynamics, and the electromagnetic behavior of the generator. Consequently, this chapter is dedicated to the mathematical modeling of these interconnected subsystems. The modeling process addresses the aerodynamic characteristics of the wind turbine rotor, the mechanical dynamics represented by a simplified one-mass drivetrain model, and the electrical modeling of the Permanent Magnet Synchronous Generator (PMSG) expressed in the synchronous d-q reference frame. These established mathematical models serve not merely as a theoretical foundation, but constitute the core predictive equations required for the formulation of the Finite-Set Model Predictive Control (FS-MPC) algorithm detailed in the subsequent chapter.

2.2 Aerodynamic Model of the Wind Turbine

The kinetic energy of the wind is converted into mechanical rotational power by the turbine blades. This mechanical power P_m is calculated using the standard aerodynamic equation [7]:

$$P_m = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \quad 2.1$$

where ρ is the air density, R represents the blade radius, and v is the wind speed. The term $C_p(\lambda, \beta)$ denotes the power coefficient, which quantifies the aerodynamic

efficiency of the turbine in extracting power from the wind. According to the Betz limit, the theoretical maximum value for C_p is approximately 0.593 [7].

In practical applications, this coefficient varies as a function of the blade pitch angle β and the tip-speed ratio λ . The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_m R}{v} \quad 2.2$$

where ω_m is the mechanical rotor speed. To achieve maximum power extraction below the rated wind speed, the pitch angle is typically maintained at zero ($\beta = 0^\circ$), and the rotor speed is regulated to operate at the optimal tip-speed ratio, λ_{opt} .

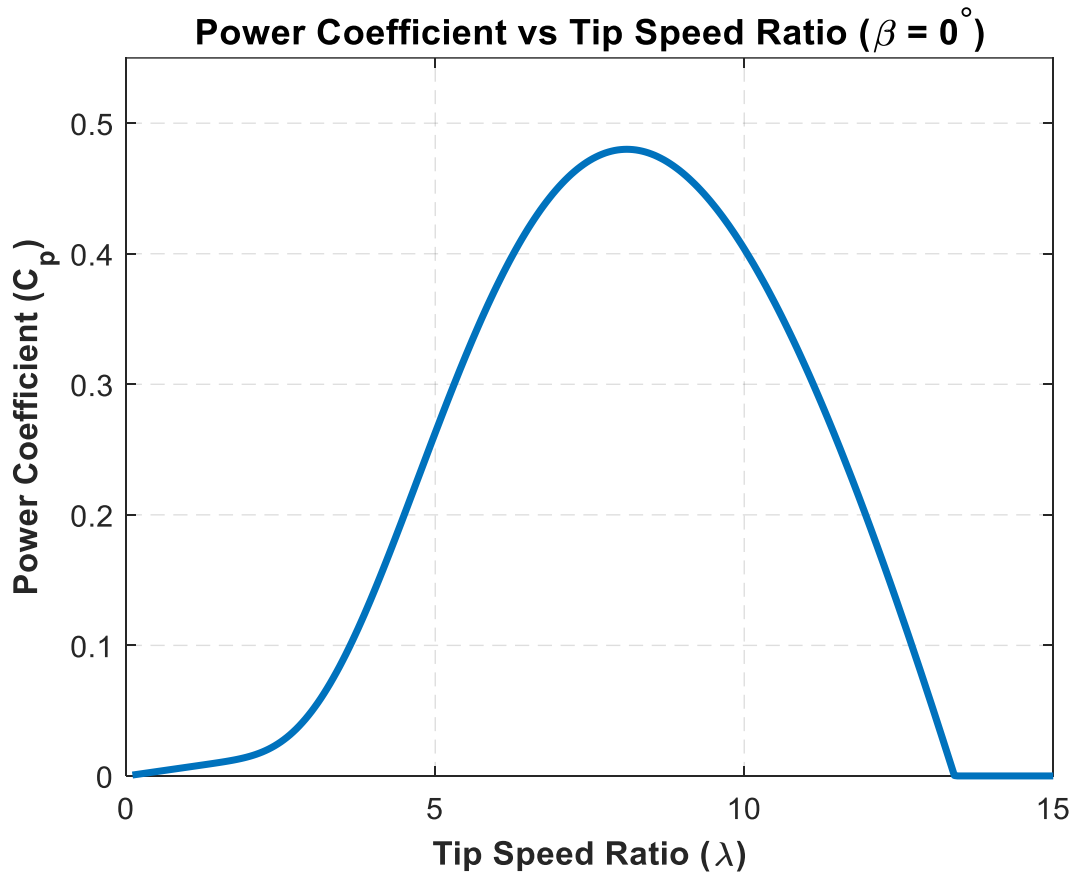


Figure 2-1 Power coefficient curve as a function of tip speed ratio plotted in MATLAB.

2.3 Mechanical Drive Train Model

The drivetrain couples the wind turbine rotor to the electrical generator. Traditional wind energy conversion systems employ a multi-stage gearbox between a low-speed rotor shaft and a high-speed generator shaft, which necessitates complex multi-mass modeling to account for torsional dynamics [5].

However, in a direct-drive PMSG configuration, the gearbox is eliminated. The turbine rotor is directly coupled to the generator rotor, ensuring both rotate at an identical mechanical speed. This structural simplification allows the entire rotational system to be accurately represented by a one-mass equivalent model [8]. The rotational dynamics of this single-mass system are governed by Newton's second law of motion:

$$J \frac{d\omega_m}{dt} = T_m - T_e - F \omega_m \quad 2.3$$

In this equation, J is the equivalent total rotational inertia, T_m is the mechanical aerodynamic torque, T_e is the electromagnetic torque of the generator, and F represents the viscous friction coefficient. This equation forms the critical dynamic link between the mechanical input power and the electrical generator control system.

2.4 Dynamic Modeling of the PMSG

The implementation of a predictive control strategy necessitates a precise electrical model of the PMSG. Analyzing the generator in the standard three-phase ($a - b - c$) reference frame yields time-varying differential equations due to the continuous rotation of the magnetic field. To circumvent this complexity, the Clarke and Park transformations are applied [9].

The Clarke transformation converts the three-phase variables into a two-phase stationary reference frame ($\alpha - \beta$). Subsequently, the Park transformation projects these stationary variables onto a synchronous reference frame ($d - q$) rotating at the electrical angular velocity ω_e .

The transformation matrix from the $\alpha - \beta$ to the $d - q$ frame is expressed as:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & \sin(\theta_e) \\ -\sin(\theta_e) & \cos(\theta_e) \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \quad 2.4$$

This transformation converts alternating sinusoidal signals into equivalent direct current (DC) quantities, significantly facilitating the control process. To derive the formal state-space mathematical model of the PMSG, which is essential for designing advanced control strategies like Model Predictive Control (MPC), the stator flux linkages in the synchronous rotating reference frame must first be established. The flux linkages ψ_d and ψ_q are given by [10]:

$$\psi_d = L_d i_d + \psi_m \quad 2.5$$

$$\psi_q = L_q i_q \quad 2.6$$

According to Faraday's law of induction, the stator voltage equations are derived by differentiating the flux linkages with respect to time, while accounting for the cross-coupling effects induced by the rotational speed ω_e of the synchronous frame:

$$V_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad 2.7$$

$$V_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \quad 2.8$$

Substituting the flux linkage expressions into the voltage equations yields the dynamic differential equations of the PMSG [9]:

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad 2.9$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_m \quad 2.10$$

From a modern control engineering perspective, these non-linear coupled differential equations are best represented in a state-space formulation. By isolating the current derivatives $\frac{di_d}{dt}$ and $\frac{di_q}{dt}$ (which represent the state variables of the system), the following is obtained:

$$\left\{ \begin{array}{l} \frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{\omega_e L_q}{L_d} i_q + \frac{1}{L_d} V_d \end{array} \right. \quad 2.11$$

$$\left\{ \begin{array}{l} \frac{di_q}{dt} = -\frac{\omega_e L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{\omega_e \psi_m}{L_q} + \frac{1}{L_q} V_q \end{array} \right. \quad 2.12$$

This can be formulated in the standard continuous-time state-space matrix form

$$(\dot{x} = Ax + Bu + D)$$

which serves as the foundational architecture for the predictive controller. For a Surface-Mounted PMSG (SPMSG), the absence of rotor saliency implies that the inductances are equal ($L_d = L_q = L_s$). Therefore, the state-space matrix model simplifies to [10], [15]:

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_e \\ -\omega_e & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} V_d \\ V_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_e \psi_m}{L_s} \end{bmatrix} \quad 2.13$$

The electromagnetic torque T_e of a general permanent magnet synchronous machine is derived from the power balance equations in the $d - q$ reference frame.

Operating in the generator convention, the electromagnetic torque acts as a braking force that opposes the mechanical rotation. The general expression for this torque is given by [10]:

$$T_e = -\frac{3}{2} p (\psi_m i_q + (L_d - L_q) i_d i_q) \quad 2.14$$

where p represents the number of pole pairs. This general equation consists of two distinct components: the excitation torque and the reluctance torque resulting from the rotor's magnetic saliency. However, for the specific case of a Surface-Mounted PMSG (SPMSG) considered in this study, the permanent magnets are symmetrically mounted on the rotor surface.

This configuration creates a uniform air gap, ensuring that the d -axis and q -axis inductances are virtually identical ($L_d = L_q = L_s$).

Consequently, the reluctance torque component is completely eliminated, and the electromagnetic torque equation simplifies significantly to [9]:

$$T_e = -\frac{3}{2}p\psi_m i_q \quad 2.15$$

This simplified linear relationship demonstrates that the opposing electromagnetic torque is directly proportional to the q -axis current i_q . To extract maximum power from the wind turbine, the predictive controller must regulate i_q to track a highly dynamic reference, while the d -axis current reference is set to zero ($i_{d,ref} = 0$) to minimize resistive losses and optimize the generator's operational efficiency.

2.5 Grid-Side

Modeling To complete the mathematical framework of the grid-connected Wind Energy Conversion System, the electrical dynamics of the grid-side filter (typically an RL or LCL filter) connected to the Grid-Side Converter (GSC) must be modeled.

In the synchronous $d - q$ reference frame, oriented according to the grid voltage vector, the dynamic equations are formulated as follows [9]:

$$\left\{ \begin{array}{l} V_{g,d} = R_g i_{g,d} + L_g \frac{di_{g,d}}{dt} - \omega_g L_g i_{g,q} + V_{GSC,d} \\ V_{g,q} = R_g i_{g,q} + L_g \frac{di_{g,q}}{dt} + \omega_g L_g i_{g,d} + V_{GSC,q} \end{array} \right. \quad \begin{array}{l} 2-16 \\ 2.17 \end{array}$$

Where $V_{g,d}$ and $V_{g,q}$ represent the grid voltages, $i_{g,d}$ and $i_{g,q}$ are the grid currents, R_g and L_g denote the resistance and inductance of the filter, ω_g is the grid electrical angular frequency, and $V_{GSC,d}$, $V_{GSC,q}$ are the output voltages of the GSC. Establishing this grid-side model is crucial for implementing synchronization and power injection control strategies in the subsequent stages.

2.6 Conclusion

In conclusion, this chapter has established a comprehensive mathematical framework for the complete grid-connected Wind Energy Conversion System (WECS). The derivation of the aerodynamic model and the single-mass drivetrain provides a clear understanding of the mechanical power extraction process. Furthermore, the dynamic state-space modeling of the PMSG in the synchronous $d - q$ reference frame offers a precise and simplified representation of the generator's electromechanical behavior, which is critical for advanced optimization.

By completing the system architecture with the mathematical modeling of the grid-side filter, the entire power conversion chain has been accurately defined.

These formulated differential equations transcend theoretical representation; they form the essential predictive foundation required for the implementation of the Finite-Set Model Predictive Control (FS-MPC) algorithm for the machine-side converter, as well as the synchronization and power injection strategies for the grid-side converter. Consequently, the next chapter will be dedicated to designing and detailing these comprehensive control strategies.

CHAPTER 3

CHAPTER 3 Control Strategies for the WECS

3.1 Introduction

The intermittent and stochastic nature of wind speed necessitates the implementation of sophisticated control strategies to ensure optimal energy harvesting and system stability. This chapter details the control framework designed for the PMSG-based wind energy conversion system (WECS). First, the Maximum Power Point Tracking (MPPT) strategy is formulated to determine the optimal reference trajectories. Subsequently, the proposed Finite-Set Model Predictive Control (FS-MPC) is developed, providing a high-bandwidth, multi-variable control solution that eliminates the inherent limitations of traditional proportional-integral (PI) controllers. Finally, the control scheme for the Grid-Side Converter is presented to ensure stable power injection into the grid.

3.2 Maximum Power Point Tracking (MPPT)

To maximize the aerodynamic efficiency of the wind turbine, the system must operate at the peak of the power coefficient curve (C_p). This study utilizes the Optimal Torque Control (OTC) strategy, an MPPT technique that facilitates maximum power extraction without the requirement for anemometers or wind speed sensors [13].

The OTC method is based on the principle that for a given wind speed, there exists a unique optimal mechanical speed ($\omega_{m,opt}$) that corresponds to the optimal tip-speed ratio (λ_{opt}). The target optimal mechanical torque T_{opt} is expressed as follows:

$$T_{opt} = K_{opt} \omega_m^2 \quad 3.1$$

The coefficient K_{opt} is a constant derived from the turbine's physical characteristics:

$$K_{opt} = \frac{1}{2} \rho \pi R^5 \frac{c_{p,max}}{\lambda_{opt}^3} \quad 3.2$$

By equating the generator's electromagnetic torque to the optimal aerodynamic torque, the reference current for the q -axis ($i_{q,ref}$) is derived. Utilizing the torque relationship established in Chapter 2, the reference current is formulated as:

$$i_{q,ref} = \frac{2T_{opt}}{3p\psi_m} \quad 3.3$$

This reference trajectory is dynamically updated and utilized as the primary input for the current control loop. For the d -axis, the reference current is maintained at zero ($i_{d,ref} = 0$) to optimize the torque-to-current ratio and minimize stator copper losses.

3.3 Finite-Set Model Predictive Control (FS-MPC)

To overcome the limitations of classical control, this thesis proposes the implementation of Finite-Set Model Predictive Control (FS-MPC). This strategy leverages the discrete nature of power converters to perform real-time optimization without the need for a PWM modulator.

3.3.1 Discrete-Time Predictive Model

The FS-MPC algorithm utilizes the mathematical model of the PMSG to predict the future behavior of the stator currents. By applying the Forward Euler approximation with a sampling time T_s , the continuous-time equations from Chapter 2 are discretized.

The predicted currents for the subsequent time step ($k + 1$) are formulated as [12]:

$$i_d(k + 1) = \left(1 - \frac{R_s T_s}{L_s}\right) i_d(k) + \omega_e T_s i_q(k) + \frac{T_s}{L_s} V_d(k) \quad 3.4$$

$$i_q(k + 1) = \left(1 - \frac{R_s T_s}{L_s}\right) i_q(k) - \omega_e T_s i_d(k) - \frac{\omega_e T_s \psi_m}{L_s} + \frac{T_s}{L_s} V_q(k) \quad 3.5$$

3.3.2 Cost Function Minimization

The core of the FS-MPC algorithm is the evaluation of a Cost Function (g). For each sampling period, the controller evaluates the cost function for the eight possible switching states of the two-level voltage source inverter. The primary objective is to minimize the absolute error between the reference trajectories and the predicted currents. To ensure operational safety and prevent overcurrent damage, a bounded nonlinear penalty function F is incorporated into the cost function [10]:

$$g = |i_{d,ref}(k) - i_d(k + 1)| + |i_{q,ref}(k) - i_q(k + 1)| + F \quad 3.6$$

Where the penalty function F is defined as:

$$F = \begin{cases} \infty, & \text{if } |i_d(k + 1)| > i_{max} \text{ or } |i_q(k + 1)| > i_{max} \\ 0, & \text{otherwise} \end{cases} \quad 3.7$$

The switching state that yields the minimum g value is selected and directly applied to the inverter at the next sampling instant. This approach ensures high-speed optimization, inherent robustness against system non-linearities, and strict adherence to physical current limits.

3.4 Grid-Side Converter (GSC) Control

Since the wind energy conversion system is connected to the grid, the power extracted by the MSC must be efficiently transferred to the electrical network. The Grid-Side Converter (GSC) plays a pivotal role in this process. The primary control objectives of the GSC are twofold:

1. To maintain the DC-link voltage (V_{dc}) at a constant reference value, ensuring a dynamic power balance between the generator and the grid.
2. To regulate the reactive power injected into the grid, typically maintaining a unity power factor by setting the grid quadrature current reference to zero ($i_{g,q,ref} = 0$). To achieve these objectives, Voltage Oriented Control (VOC) is widely adopted [9]. In the synchronous $d - q$ reference frame oriented with the grid voltage, a cascaded control structure is utilized. The outer control loop employs a Proportional-Integral (PI) regulator to maintain the DC-link voltage V_{dc} , generating the active current reference ($i_{g,d,ref}$). Subsequently, two inner PI controllers independently regulate the grid currents $i_{g,d}$ and $i_{g,q}$. The outputs of these current controllers determine the reference voltage vectors, which are then synthesized by a Space Vector Pulse Width Modulation (SVPWM) scheme to drive the GSC switches.

3.5 Simulation Results and Discussion

To validate the performance of the proposed control strategies (MPPT, FS-MPC, and VOC), the entire Wind Energy Conversion System (WECS) was modeled and simulated using MATLAB/Simulink.

The system parameters used for this simulation are detailed in Table 3.1.

System Component	Parameter	Symbol	Value	Unit
Wind Turbine	Air density	ρ	1.225	kg/m ³
	Blade radius	R	4.5	m
	Optimum tip-speed ratio	λ_{opt}	8.1	-
	Maximum power coefficient	$C_{p,max}$	0.48	-
PMSG	Rated active power	P_n	20	kW
	Stator resistance	R_s	0.18	Ω
	d-axis inductance	L_d	4.15	mH
	q-axis inductance	L_q	4.15	mH
	Permanent magnet flux	ψ_m	0.438	Wb
	Number of pole pairs	p	3	-
Converters & Grid	DC-link reference voltage	V_{dc-ref}	900	V
	DC-link capacitance	C_{dc}	2200	μF
	Grid voltage (Line-to-Line)	V_g	380	V
	Grid frequency	f	50	Hz
	Filter inductance	L_g	5	mH
	Sampling time	T_s	100	μs

Table 3-1 System and Simulation Parameters

3.5.1 Machine-Side Converter (MSC) Performance

This section evaluates the mechanical tracking and the electrical regulation of the PMSG using the FS-MPC strategy.

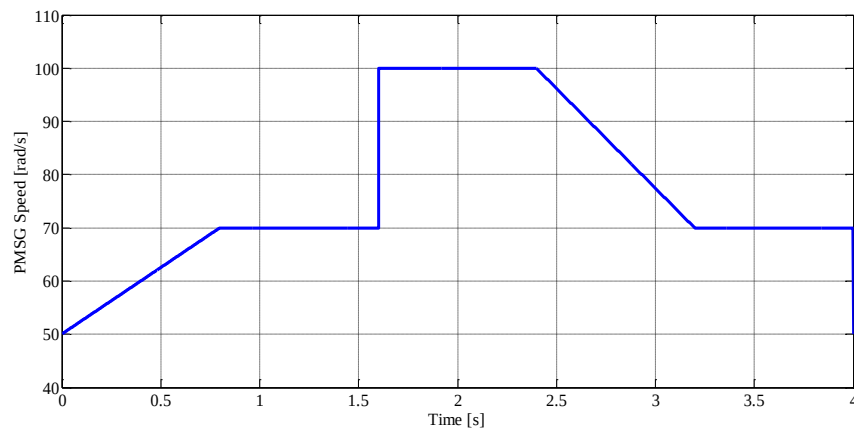


Figure 3-1 PMSG rotor speed dynamic response under variable wind conditions

This figure illustrates the mechanical speed trajectory of the permanent magnet synchronous generator. The tracked rotor speed demonstrates an exceptional capability to closely follow the sudden step variations of its optimal reference speed. This instantaneous tracking confirms the high efficiency and accuracy of the implemented Maximum Power Point Tracking (MPPT) loop under fast changing wind velocities.

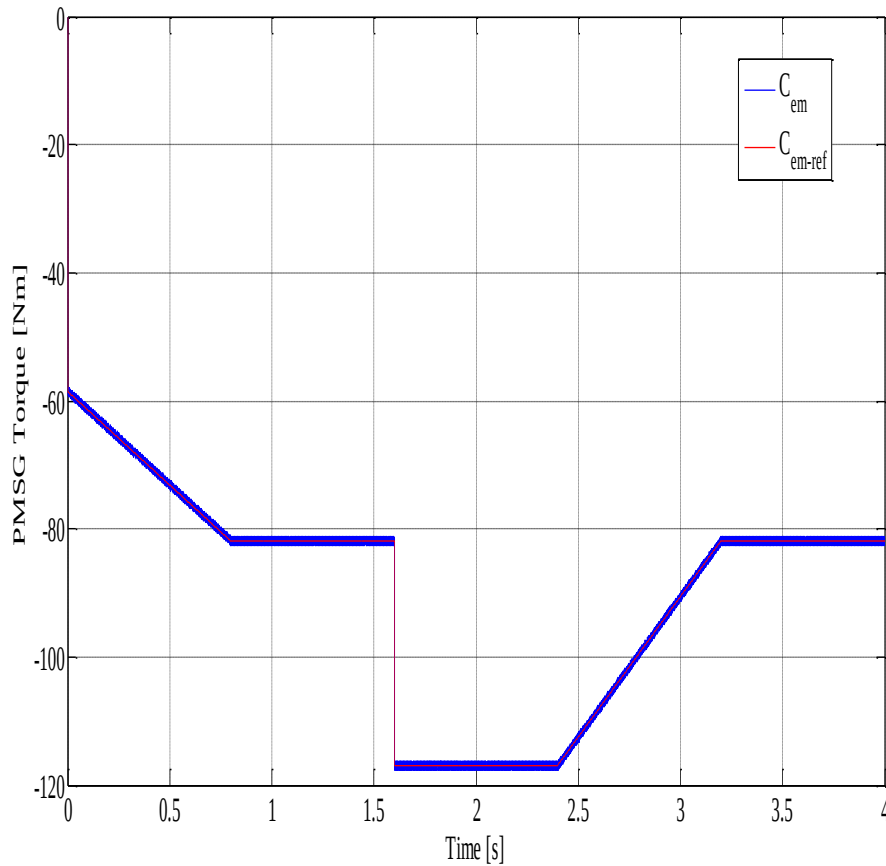


Figure 3-2 PMSG electromagnetic torque tracking under variable load operation

This figure displays the performance of the electromagnetic torque (C_{em}). The estimated machine torque tracks its reference signal (C_{em-ref}) generated by the Optimal Torque Control (OTC) with high speed and zero steady-state error.

The negative sign properly verifies that the electrical machine is operating in the generation mode, satisfying the wind turbine power extraction requirements.

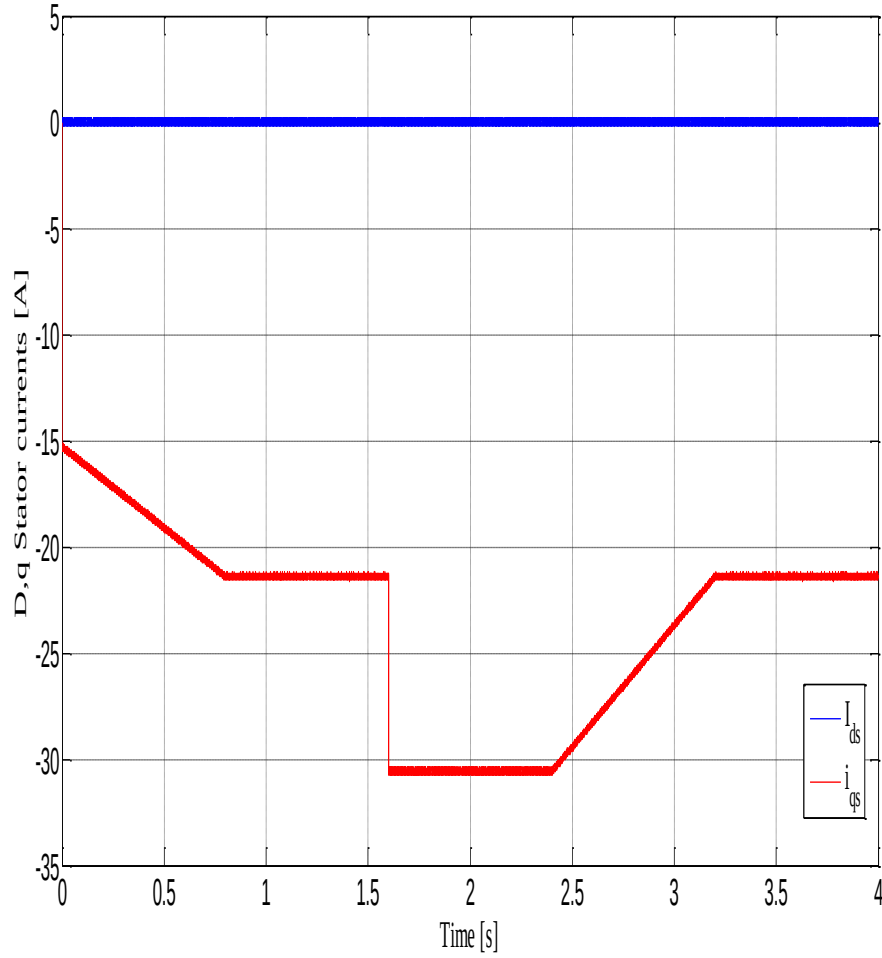


Figure 3-3 Stator d - q axis currents tracking performance using FS-MPC.

This figure validates the dynamic performance of the Finite-Set Model Predictive Control (FS-MPC) applied to the Machine-Side Converter. As observed, the direct-axis current (i_{ds}) is strictly regulated at exactly 0 A throughout the operation. This successfully implements the control objective to minimize stator copper losses and maximize the generator's electrical efficiency. Concurrently, the quadrature-axis current (i_{qs}) exhibits rapid and precise tracking of its highly dynamic trajectory, particularly during the abrupt step change at $t = 1.6$ s. The complete absence of transient overshoots highlights the fast execution and superior constraint-handling capabilities of the proposed predictive controller compared to classical linear regulators.

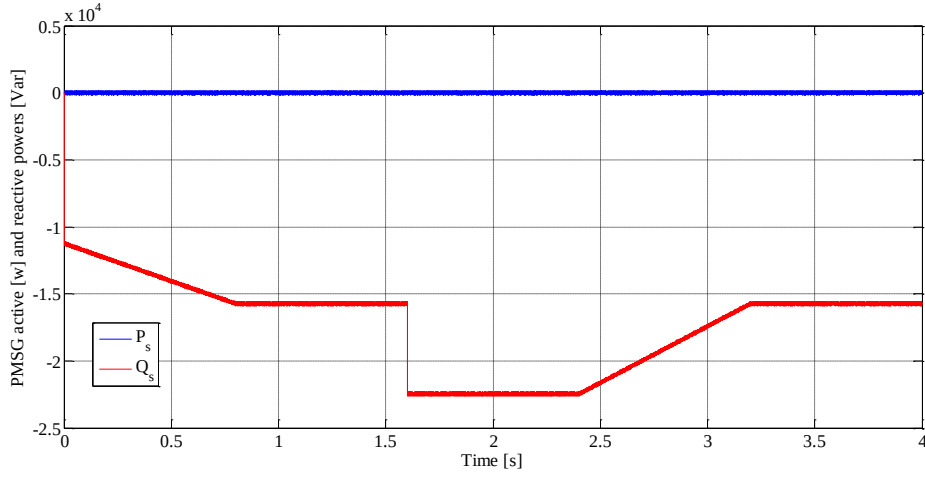


Figure 3-4 PMSG active and reactive powers under variable wind speed

This figure presents the electrical power output of the generator. Consistent with the $i_{ds} = 0$ control strategy, the reactive power (Q_s) is firmly regulated to zero, ensuring an optimal power factor within the machine and minimizing the required converter sizing. Simultaneously, the active power (P_s) smoothly and accurately mirrors the aerodynamic power extracted from the wind turbine. The stable and continuous profile of the generated power further demonstrates the reliable operation of the PMSG under the proposed FS-MPC algorithm.

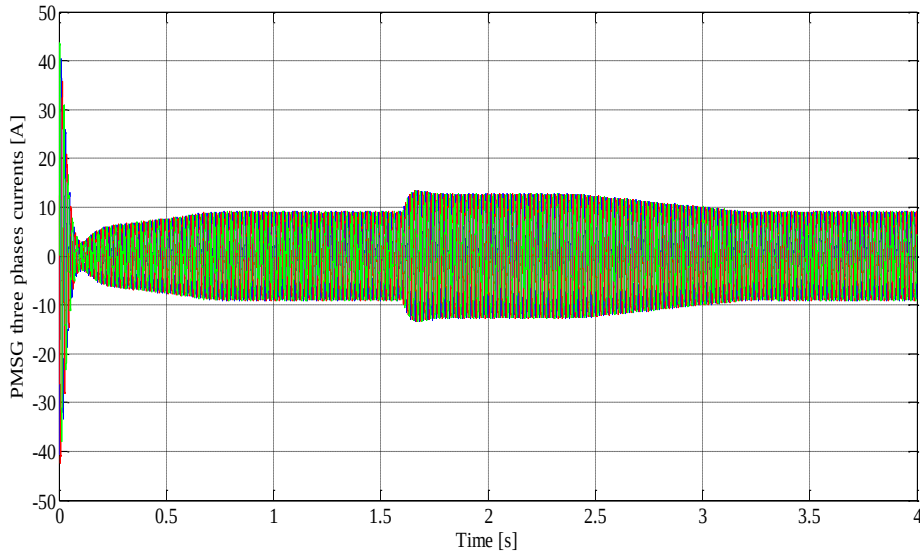


Figure 3-5 PMSG three-phase stator currents macroscopic profile.

This figure illustrates the overall behavior of the three-phase stator currents generated by the PMSG over the entire simulation period. The amplitude of these currents dynamically adjusts to reflect the variations in the required electromagnetic torque and active power. For instance, the current magnitude distinctly increases at $t = 1.6$ s in response to the higher wind speed step. Despite the continuous variations in the operating conditions, the currents maintain a highly symmetrical and balanced sinusoidal envelope. This demonstrates the stable, reliable, and high-quality electrical energy generation achieved by the proposed control scheme.

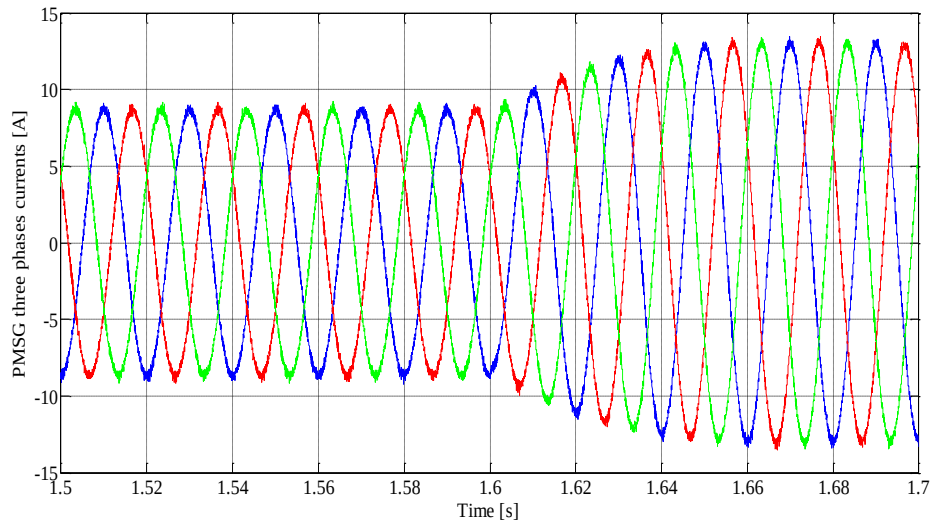


Figure 3-6 Zoomed-in view of the three-phase stator currents during a transient state

A magnified view of the stator currents between $t = 1.5$ s and $t = 1.7$ s is provided to deeply analyze the transient behavior of the generator. Exactly at $t = 1.6$ s, following the sudden variation in wind speed, the currents seamlessly and instantaneously adjust their amplitude and frequency to meet the new power demands. The transition is remarkably smooth, with a complete absence of harmful transient overshoots or severe harmonic distortions.

This exceptional performance firmly validates the ultra-fast dynamic response and the robustness of the implemented FS-MPC algorithm under sudden aerodynamic disturbances.

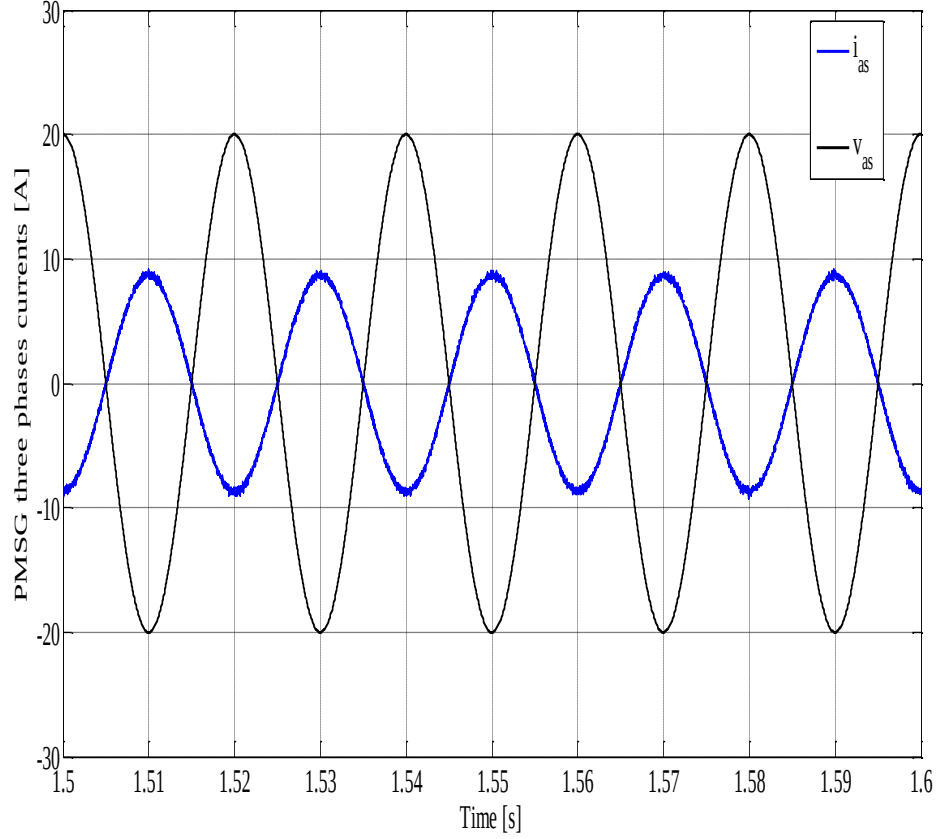


Figure 3-7 Phase A stator voltage and current waveforms

This figure depicts the steady-state stator voltage (v_{as}) and current (i_{as}) for phase A. As clearly observed, the voltage and current waveforms are exactly 180° out of phase (anti-phase). This specific relationship is the fundamental characteristic of a generator delivering pure active power to the converter. It physically confirms that the reactive power (Q_s) is strictly maintained at zero, which is the direct and successful outcome of the implemented $i_{ds} = 0$ control strategy. Consequently, the generator operates at an optimal unity power factor, minimizing internal losses and maximizing overall efficiency.

3.5.2 DC-Link Voltage Regulation

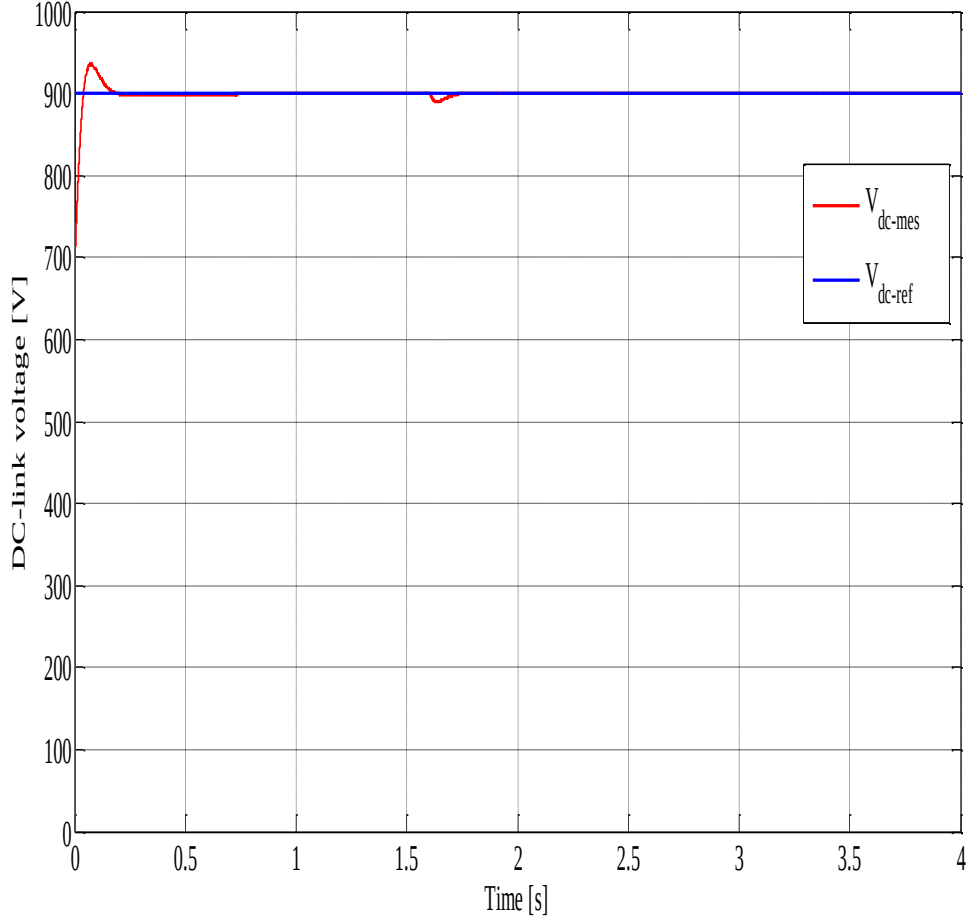


Figure 3-8 Macroscopic tracking performance of the DC-link voltage

This figure illustrates the overall dynamic behavior of the DC-link voltage (V_{dc}) throughout the entire simulation period. The Voltage Oriented Control (VOC) strategy, implemented on the Grid-Side Converter (GSC), successfully and robustly regulates the measured DC voltage (V_{dc-mes}) to track its predefined reference value of 900 V. Despite the continuous and sudden variations in the extracted wind active power, the voltage remains highly stable. This stability is crucial, as it confirms that the power flow between the Machine-Side Converter and the electrical grid is perfectly balanced at all times.

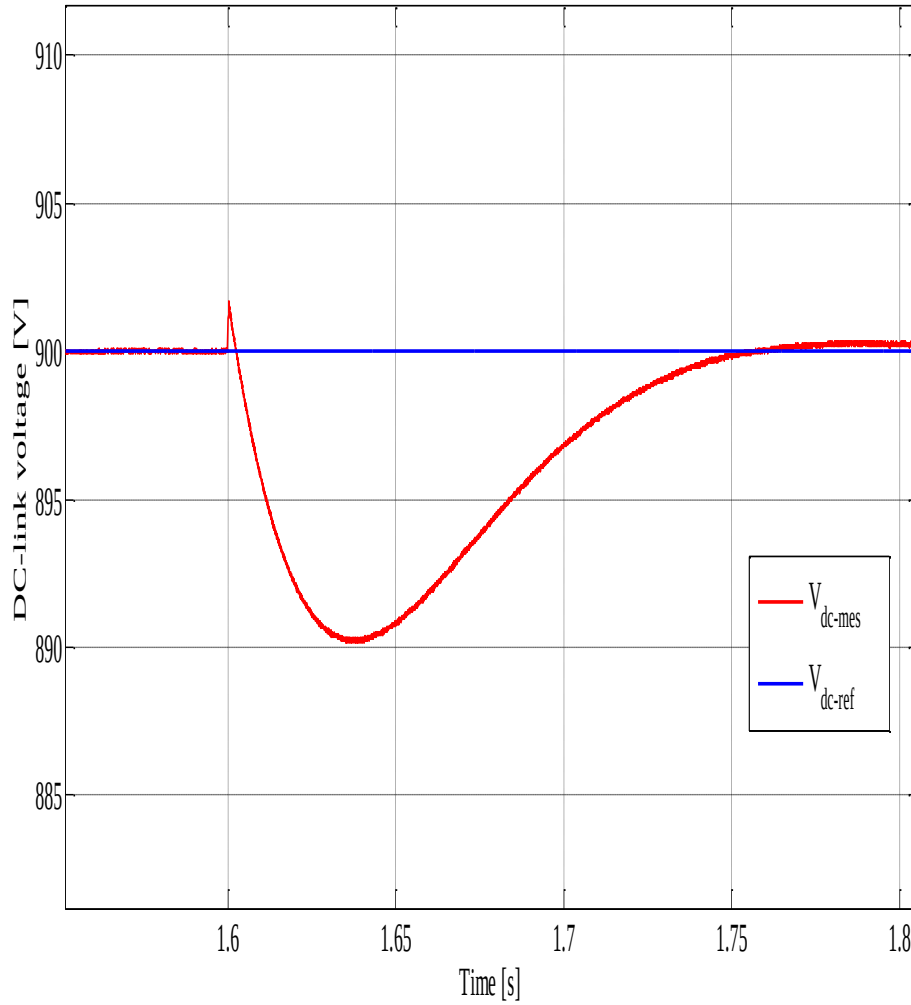


Figure 3-9 Zoomed-in view of the DC-link voltage during a step change in wind speed

A magnified view of the DC-link voltage transient response at $t = 1.6$ s is presented in this figure to evaluate the system's robustness. Following the abrupt increase in the injected wind power, a minor voltage undershoot of approximately 10 V (representing only 1.1\% of the nominal 900 V reference) is observed. The control system exhibits exceptional disturbance rejection, successfully recovering and stabilizing the voltage back to its reference in a remarkably short period of about 0.15 seconds. This minimal deviation and swift recovery time strongly validate the efficiency and high reliability of the implemented voltage regulation loop under severe aerodynamic disturbances.

3.5.3 Grid-Side Converter (GSC) Performance

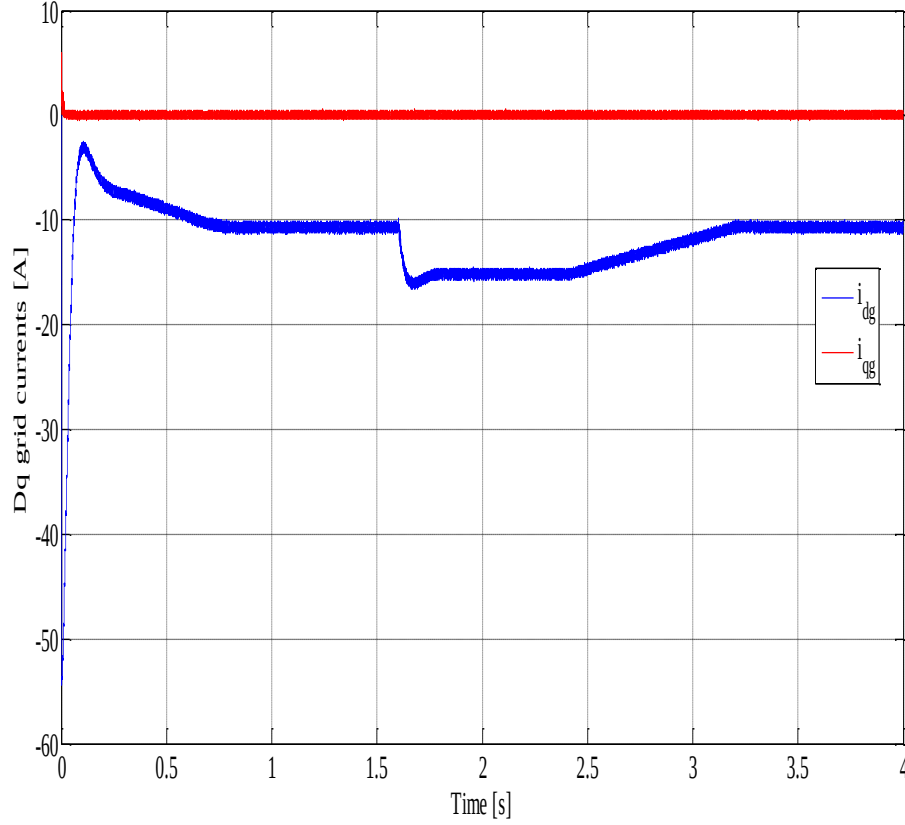


Figure 3-10 Grid-side d - q axis currents under variable wind conditions

This figure presents the dynamic behavior of the grid-side currents evaluated in the synchronous $d - q$ reference frame. To comply with strict grid integration codes and ensure a unity power factor, the quadrature-axis current (i_{qg}) is robustly regulated to zero throughout the entire operation. Concurrently, the direct-axis current (i_{dg}) actively dynamically responds to the variations in the extracted wind energy. The negative magnitude of i_{dg} fundamentally confirms the generation mode, demonstrating that active power is being successfully and continuously injected into the electrical network. The smooth tracking profile and the absence of significant steady-state ripples validate the high power quality managed by the Voltage Oriented Control (VOC) scheme.

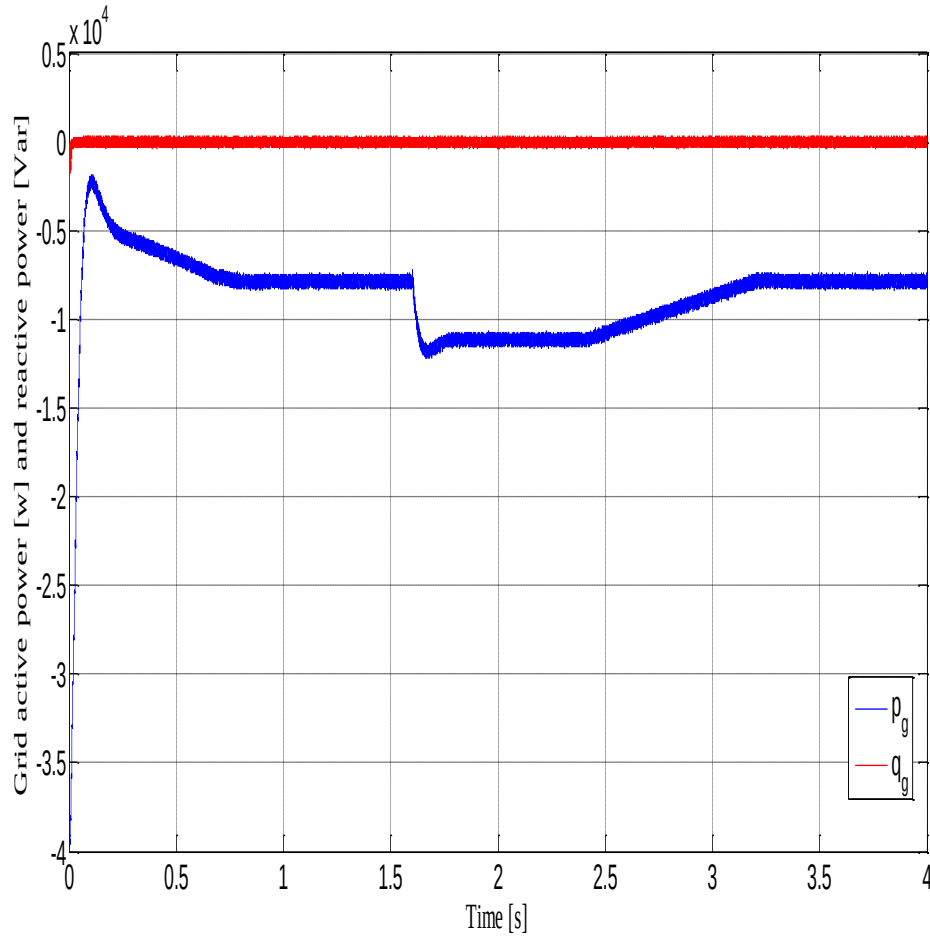


Figure 3-11 Active and reactive power injected into the electrical grid

This figure illustrates the profile of the active (P_g) and reactive (Q_g) power exchanged between the Wind Energy Conversion System (WECS) and the electrical grid. In compliance with the grid integration standards, the reactive power (Q_g) is strictly maintained at 0 VAR, ensuring a unity power factor operation. Consequently, the active power (P_g) perfectly mirrors the aerodynamic power extracted from the wind. The negative sign of P_g is a formal indication of the generation mode, confirming that the electrical energy is being efficiently and unidirectionally injected into the national grid. This finalizes the validation of the entire control scheme, demonstrating its capability to deliver high-quality, stable, and reliable wind energy to the utility network.

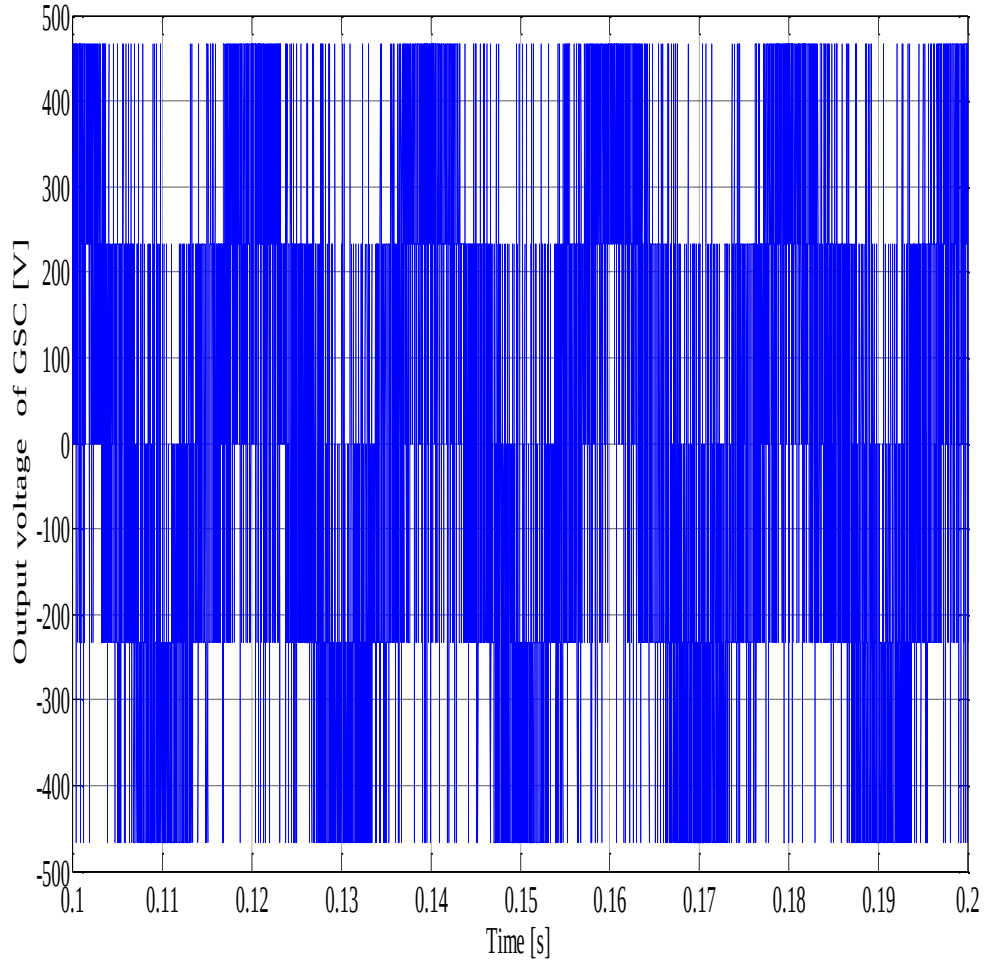


Figure 3-12 Unfiltered output voltage waveform of the Grid-Side Converter (GSC)

This final figure displays the raw, high-frequency switching voltage waveform generated by the two-level Grid-Side Converter before passing through the grid filter. The signal exhibits the discrete voltage levels dictated by the DC-link voltage and the applied modulation algorithm. This high-frequency switching behavior is fundamentally required to synthesize the required grid voltages and precisely shape the injected grid currents into the highly sinusoidal waveforms previously demonstrated. The successful generation of this switching pattern confirms the proper operation of the converter's internal switching logic.

GENERAL CONCLUSION

The global transition towards sustainable energy sources has positioned wind power as a vital component of the modern electrical grid. This thesis aimed to contribute to the advancement of wind energy technology by developing, modeling, and validating a robust predictive control framework for a grid-connected Wind Energy Conversion System (WECS) based on a direct-drive Permanent Magnet Synchronous Generator (PMSG).

To achieve this objective, a comprehensive mathematical foundation was first established. The aerodynamic characteristics of the turbine, the mechanical dynamics of the single-mass drivetrain, and the electrical behavior of the PMSG were accurately modeled. By formulating the continuous time-varying equations into a discrete state-space model in the synchronous $d - q$ reference frame, a precise predictive architecture was created. Furthermore, the inclusion of the grid-side filter dynamics ensured that the entire power conversion chain, from wind capture to grid injection, was fully defined.

Building upon this foundation, an advanced control strategy was designed to overcome the inherent limitations of classical PI-based Field-Oriented Control (FOC), such as delayed dynamic response and parameter sensitivity. The Optimal Torque Control (OTC) strategy was implemented to guarantee Maximum Power Point Tracking (MPPT). For the Machine-Side Converter, the Finite-Set Model Predictive Control (FS-MPC) algorithm was proposed, enabling fast, multivariable optimization and strict adherence to safety constraints without requiring a traditional PWM modulator. Concurrently, Voltage Oriented Control (VOC) was employed for the Grid-Side Converter to regulate the DC-link voltage and synchronize the extracted power with the electrical grid at a unity power factor.

The theoretical framework was rigorously validated through extensive MATLAB/Simulink simulations under highly dynamic operating conditions. The simulation results demonstrated the exceptional performance of the proposed FS-MPC strategy, showcasing instantaneous reference tracking, minimal current ripple, and the successful elimination of overshoots. The system consistently maintained the d -axis current at zero to minimize losses, effectively decoupled the generator from grid disturbances via stable DC-link voltage regulation, and injected high-quality active power into the grid. Ultimately, these findings confirm that the proposed predictive

control scheme significantly enhances the efficiency, reliability, and dynamic robustness of PMSG-based wind turbines.

Future Perspectives

While this thesis has successfully established and validated a robust theoretical and practical framework for the predictive control of a grid-connected PMSG wind turbine, several avenues for future research remain open. Future work could focus on:

1. Conducting extensive hardware-in-the-loop (HIL) simulations or experimental laboratory tests on a physical prototype to validate the proposed FS-MPC algorithm under real-world operational constraints.
2. Integrating sensorless control techniques, such as the Model Reference Adaptive System (MRAS), to estimate the rotor speed and position without mechanical encoders, thereby further increasing the system's reliability and reducing hardware costs.
3. Expanding the control strategy to address grid-fault scenarios, such as implementing Low Voltage Ride Through (LVRT) capabilities, to ensure the wind turbine remains connected and supports the grid during voltage dips.

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