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Control and Performance of wind turbine Generator Based on Synchronous Machine

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بسم الله الرحمن الرحيم

Dedication

To my dear and beloved father,
as a token of my deep affection.
To my dear and beloved mother, as a token of my deep affection.
To my sister "Ghada and Israa", to my brother "Mohamed Amine and Oussama" for their support.
To all the members of my family.
To all my friends
To my friend and also teammate Boujaber
To my classmates of the 2025–2026 cohort.
To all the people I love.
I dedicate this modest work.

Aimen

Dedication

To my dear and beloved father and mother
as a token of my deep affection.
To my sisters and brothers for their moral support.
To all my friends, especially.
To my friend and also teammate Aimen
To my classmates of the 2025–2026cohort.
To all the people I love.
I dedicate this Modest work.

Mohamed Abderraouf

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Table of Abbreviations

Abbreviation	Designations
PMSG	Permanent Magnet Synchronous Generator (PMSG),
WECS	Wind Energy Conversion System
PI	Proportional Integral Controller
SMC	Sliding Mode Control
MPPT	Maximum Power Point Tracking
RES	Renewable Energy System
PE	Power Electronics.
ρ	Air density
V	Wind speed
S	Rotor swept area
P	Power
Cp	Power coefficient
λ	Specific speed ratio
β	Blade pitch angle
Ω	
G	Gearbox gain
Tm	Mechanical turbine torque
Te	Generator electromagnetic torque
J	Moment of inertia
ωr	Rotor angular velocity
Vs, Is	Stator voltage and current
φs	Stator flux
Ls , Rs	Stator inductance and resistance
Vdc	DC bus voltage
Vac	Inverter output voltage
Id, Iq	Direct components and quadrature of stator current
Vd, Vq	Direct components and quadrature of stator voltage
MSAP	Permanent magnet synchronous machine
MPPT	Maximum power point tracking,
VAWT	Vertical axis wind turbine
HAWT	Horizontal axis wind turbine
PWM	Pulse width modulation

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ملخص : تركز هذه الأطروحة على نمذجة نظام تحويل طاقة الرياح القائم على مولد متزامن مغناطيسي دائم (PMSG)، والتحكم فيه، وتحسين أدائه. وقد طُوّرت نماذج رياضية لتوربين الرياح، والمولد المتزامن المغناطيسي الدائم، ومحولات الطاقة الإلكترونية المرتبطة به، لتمثيل ديناميكيات النظام بدقة. ولتحسين أداء نظام تحويل طاقة الرياح في ظل ظروف رياح متغيرة، حيث تمت راسة استراتيجيتان للتحكم: وحدة التحكم التناسبية التكاملية التقليدية (PI)، ووحدة التحكم بالنمط الانزلاقي (SMC). أُجريت دراسات محاكاة لتقييم ومقارنة أداء وحدات التحكم المقترحة من حيث تتبع المرجع، والاستجابة الديناميكية، والمتانة، واستخلاص الطاقة القصوى. تُظهر النتائج المُتحصل عليها فعالية كلا نهجي التحكم في ضمان استقرار تشغيل النظام. علاوة على ذلك، تُظهر وحدة التحكم بالنمط الانزلاقي متانة وأداءً ديناميكيًا مُحسّنًا مقارنةً بوحدة التحكم التناسبية التكاملية التقليدية، لا سيما في ظل ظروف التشغيل المتغيرة.

الكلمات المفتاحية: نظام تحويل طاقة الرياح (WECS)، مولد متزامن ذو مغناطيس دائم (PMSG)، وحدة تحكم تناسبية تكاملية (PI)، التحكم بالوضع الانزلاقي (SMC)، تتبع نقطة الطاقة القصوى (MPPT)، الطاقة المتجددة، إلكترونيات الطاقة.

Abstract: This dissertation focuses on the modeling, control, and performance improvement of a PMSG-based wind energy conversion system. Mathematical models of the wind turbine, the PMSG, and the associated power electronic converters are developed to represent the system dynamics accurately. To enhance the performance of the WECS under varying wind conditions, two control strategies are investigated: the conventional Proportional–Integral (PI) controller and the Sliding Mode Controller (SMC). Simulation studies are carried out to evaluate and compare the performance of the proposed controllers in terms of reference tracking, dynamic response, robustness, and maximum power extraction. The obtained results demonstrate the effectiveness of both control approaches in ensuring stable system operation. Furthermore, the Sliding Mode Controller exhibits improved robustness and dynamic performance compared with the conventional PI controller, particularly under variable operating conditions.

Keywords: Wind Energy Conversion System (WECS), Permanent Magnet Synchronous Generator (PMSG), Proportional–Integral Controller (PI), Sliding Mode Control (SMC), Maximum Power Point Tracking (MPPT), Renewable Energy, Power Electronics.

Résumé : Résumé : le présent travail porte sur la modélisation, la commande et l'amélioration des performances d'un système de conversion d'énergie éolienne basé sur une génératrice synchrone à aimants permanents (PMSG). Des modèles mathématiques de l'éolienne, de la PMSG et des convertisseurs électroniques de puissance associés sont développés afin de représenter avec précision la dynamique du système. Pour améliorer les performances du système de conversion d'énergie éolienne (SCEE) sous différentes conditions de vent, deux stratégies de commande sont étudiées : la commande proportionnelle-intégrale (PI) conventionnelle et la commande par modes glissants (SMC). Des simulations sont réalisées pour évaluer et comparer les performances des commandes proposées en termes de suivi de consigne, de réponse dynamique, de robustesse et d'extraction de puissance maximale. Les résultats obtenus démontrent l'efficacité des deux approches de commande pour assurer un fonctionnement stable du système. De plus, la commande par modes glissants présente une robustesse et des performances dynamiques supérieures à celles de la commande PI conventionnelle, notamment sous différentes conditions de fonctionnement.

Mots-clés : Système de conversion d'énergie éolienne (SCEE), génératrice synchrone à aimants permanents (PMSG), commande proportionnelle-intégrale (PI), commande par modes glissants (SMC), suivi du point de puissance maximale (MPPT), énergies renouvelables, électronique de puissance.

General Introduction

Renewable energy has become a major issue in the context of the energy transition and sustainable development. Faced with the challenges of climate change, the depletion of fossil fuel resources, and the need for cleaner energy production, renewable energies, such as solar, hydropower, biomass, and wind power, are emerging as essential alternatives. Among these sources, wind power is playing an increasingly important role due to its low environmental impact and significant production potential.

Today, wind energy plays a vital role in the global transition toward sustainable energy systems, contributing significantly to electricity generation and environmental protection. As technology continues to improve, wind energy systems are expected to become even more efficient, reliable, and cost-effective in meeting future energy demands.

A wind energy system is a technology that converts the kinetic energy of moving air (wind) into useful electrical or mechanical energy. Wind energy is one of the fastest-growing renewable energy sources because it is clean, sustainable, and widely available. By harnessing natural wind resources, wind energy systems help reduce dependence on fossil fuels and lower greenhouse gas emissions [1].

Wind energy has several major advantages: it is clean, renewable, and generates neither greenhouse gas emissions nor air pollution. Furthermore, it contributes to diversifying the energy mix and reducing dependence on fossil fuels. However, it also presents challenges, such as the intermittency of wind, the need for storage solutions or complementarity with other energy sources, as well as visual and noise impacts that can generate local resistance [2].

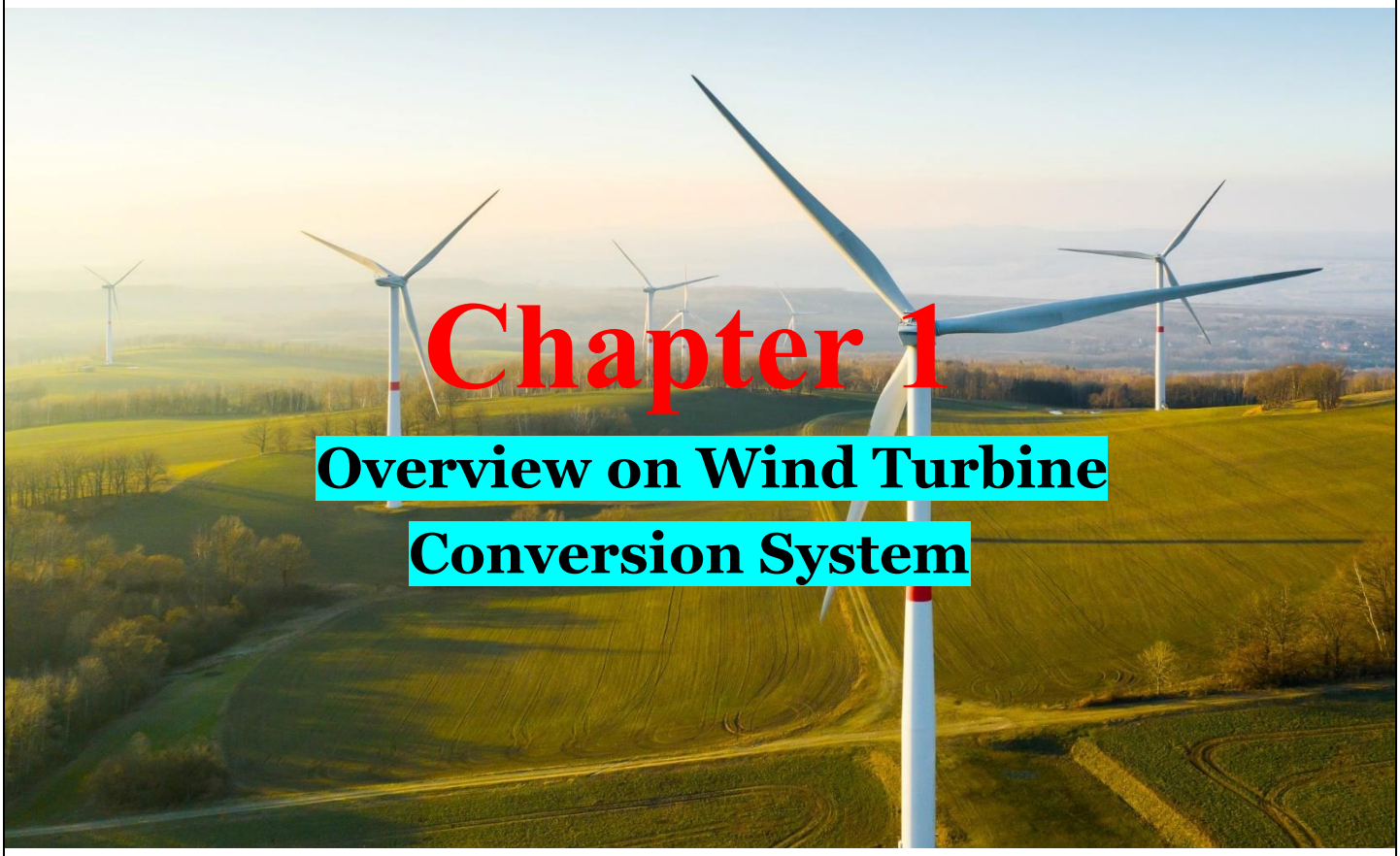
In a global context marked by ambitious carbon neutrality targets, wind energy represents a key solution to meet growing electricity needs while reducing the environmental footprint. Its development relies on technological advances, appropriate support policies and rigorous planning to maximize its efficiency and social acceptability [3].

The main objective of this dissertation is to improve and develop some effective control strategies to enhance the performance of a wind energy conversion system (WECS) based on a Permanent Magnet Synchronous Generator (PMSG). Particular emphasis is placed on enhancing the overall system performance in terms of efficiency, stability, robustness, under variable wind conditions. To achieve this objective, two control approaches, namely the Proportional-Integral (PI) controller and the Sliding Mode Controller (SMC), are designed, implemented, simulated and evaluated. A comprehensive comparative analysis is conducted to assess their effectiveness in maximizing power extraction, regulating generator operation, and improving the dynamic behaviour

of the WECS. The obtained results provide valuable insights into the suitability of these control approaches for high-performance renewable energy applications.

To achieve the aforementioned objectives, this dissertation is organized into four main chapters as follows:

- The first Chapter provides a general overview of wind energy conversion systems (WECSs), highlighting their operating principles, advantages, challenges, and their growing importance in the global energy transition toward sustainable and renewable energy sources.
- The second Chapter focuses on the mathematical modeling of the considered wind energy conversion system based on a Permanent Magnet Synchronous Generator (PMSG). In addition, the power electronic converters associated with the system are presented and modeled.
- The third Chapter is dedicated to the design and implementation of the control strategies applied to the considered wind energy conversion system. Particular attention is given to the Proportional–Integral (PI) controller and the Sliding Mode Controller (SMC), including their operating principles and control objectives.
- The last one presents the simulation results and performance evaluation of the proposed control strategies. A comparative analysis is conducted to validate the effectiveness of the controllers in terms of dynamic response, robustness, stability, and maximum power extraction under varying operating conditions.



Chapter 1

Overview on Wind Turbine Conversion System

I.1. Introduction

The increasing global demand for energy, coupled with concerns regarding environmental sustainability and the depletion of fossil fuel resources, has accelerated the development of renewable energy technologies. Among the various renewable energy sources, wind energy has emerged as one of the most promising and rapidly growing alternatives due to its abundance, cleanliness, and cost-effectiveness. Wind power generation plays a significant role in reducing greenhouse gas emissions and supporting the transition toward sustainable energy systems[4].

A Wind Power Conversion System (WPCS) is a system that converts the kinetic energy contained in moving air masses into electrical energy suitable for consumption or integration into the electrical grid [5].

The evolution of wind energy technology has led to significant improvements in power output, reliability, and operational efficiency. Modern wind turbines are available in various configurations, including fixed-speed and variable-speed systems, as well as different generator types such as squirrel-cage induction generators, doubly-fed induction generators (DFIGs), and permanent magnet synchronous generators (PMSGs). These technologies enable efficient energy extraction under varying wind conditions while maintaining power quality and grid stability [6][7].

The operating principle of a wind power conversion system is based on the aerodynamic interaction between the wind and the turbine blades. As wind flows over the blades, aerodynamic forces are generated, causing the rotor to rotate. The mechanical energy produced by the rotor is transmitted through the drivetrain to the generator, where it is converted into electrical energy. Power electronic converters and control systems regulate voltage, frequency, and power flow to ensure efficient operation and compliance with grid requirements [8][9]. Wind power conversion systems offer numerous advantages, including renewable energy generation, low operating costs, and minimal environmental impact during operation. However, challenges such as wind intermittency, power fluctuations, grid integration issues, and maintenance requirements must be addressed through advanced control techniques, energy storage solutions, and improved system design [10].

This chapter provides a general overview of wind energy and wind power conversion systems, presenting their fundamental principles, major components, classifications, and operational characteristics. The chapter also discusses the technological developments and challenges associated with modern wind energy conversion, establishing the foundation for the subsequent chapters that focus on system modeling, control strategies, performance analysis, and optimization techniques.

I.2. Overview on wind energy conversion system

Wind energy is one of the most important renewable energy sources and plays a significant role in the global transition toward sustainable power generation. Wind turbine energy conversion systems transform the kinetic energy of moving air into electrical energy that can be supplied to isolated loads or integrated into the electrical grid. It Wind energy is one of the fastest-growing renewable energy sources worldwide and plays a crucial role in reducing greenhouse gas emissions and dependence on fossil fuels. Wind Energy Conversion Systems (WECSs) convert the kinetic energy contained in moving air masses into electrical energy that can be utilized by consumers or injected into the electrical grid [11].

The basic principle of wind energy conversion relies on the aerodynamic interaction between the wind and the turbine blades. As wind passes over the blades, aerodynamic forces are generated, causing the rotor to rotate. The mechanical energy captured by the rotor is transmitted through a shaft, either directly or through a gearbox, to an electrical generator. The generator converts the mechanical energy into electrical energy, which is then conditioned by power electronic converters before being delivered to the grid or local loads [12].

Modern wind turbines generally operate at variable speeds to maximize energy capture under changing wind conditions. Variable-speed operation enables the turbine to maintain an optimal tip-speed ratio, thereby improving the energy conversion efficiency. To achieve this objective, advanced control techniques and power electronic converters are employed [13].

Various types of electrical generators are used in WECSs, including squirrel-cage induction generators (SCIGs), doubly-fed induction generators (DFIGs), and permanent magnet synchronous generators (PMSGs). Among these technologies, PMSGs have gained significant attention due to their high efficiency, high power density, reduced maintenance requirements, and elimination of external excitation systems. Consequently, PMSG-based WECSs are increasingly adopted in both onshore and offshore wind energy applications [14].

The overall performance of a wind energy conversion system depends on the aerodynamic characteristics of the turbine, generator efficiency, converter performance, and the effectiveness of the control strategy. Therefore, accurate modeling and advanced control techniques are essential to ensure maximum power extraction, stable operation, and compliance with grid requirements [15].

The operating principle of a wind turbine is based on the aerodynamic interaction between the wind and the turbine blades. When wind flows across the blades, a lifting force is generated, causing the rotor to rotate. The mechanical power extracted from the wind is transmitted through

a shaft, either directly or through a gearbox, to an electrical generator. The generator then converts the mechanical energy into electrical energy [16]

A typical wind energy conversion system consists of several main components, including the wind turbine rotor, gearbox (in geared systems), generator, power electronic converters, control system, and grid interface. The performance of the system depends on various factors such as wind speed, turbine design, generator type, and control strategy.

The power available in the wind is proportional to the cube of the wind speed, making wind velocity the most influential parameter affecting energy production. However, according to aerodynamic limitations, only a fraction of the available wind power can be extracted by a turbine. This limitation is described by the Betz theory, which states that the maximum achievable power coefficient is approximately 59.3%.[17].

Modern wind turbines operate using variable-speed control to maximize energy capture and improve efficiency. Among the different generator technologies, the Permanent Magnet Synchronous Generator (PMSG) has become widely used due to its high efficiency, high power density, reduced maintenance requirements, and suitability for variable-speed operation. To ensure optimal performance under varying wind conditions, advanced control techniques and power electronic converters are employed to regulate power flow and maintain system stability.

As wind energy continues to expand worldwide, improvements in turbine technology, control methods, and grid integration strategies remain essential for enhancing the reliability and efficiency of wind energy conversion systems.

I.3. History of wind energy

Wind energy is one of the oldest forms of renewable energy utilized by humanity. The use of wind power dates back several thousand years, when ancient civilizations harnessed it to propel sailing vessels and perform mechanical work. Historical evidence suggests that wind-powered boats were used along the Nile River in ancient Egypt as early as 5000 BC, enabling transportation and trade [5].

The first known windmills appeared in Persia (modern-day Iran) around the seventh century AD. These early vertical-axis windmills were primarily used for grinding grain and pumping water. The technology later spread throughout the Middle East and eventually reached Europe during the medieval period. By the twelfth century, horizontal-axis windmills had become common across Europe, particularly in countries such as England, France, and the Netherlands, where they were widely used for agricultural and industrial applications [18].

During the seventeenth and eighteenth centuries, windmills played a crucial role in economic development, especially in the Netherlands, where they were employed for land drainage, water

management, and industrial processing. However, the importance of wind power declined during the Industrial Revolution as steam engines and later internal combustion engines provided more controllable and reliable sources of mechanical power [19].

The development of wind-generated electricity began in the late nineteenth century. In 1887, Scottish engineer James Blyth built one of the first wind turbines for electricity production at his holiday home in Scotland. Shortly afterward, in 1888, American inventor Charles F. Brush constructed a large wind-powered electricity generator in Ohio, United States. These pioneering systems demonstrated the feasibility of converting wind energy directly into electrical energy [20].

Significant advancements occurred during the twentieth century. In the 1940s, the Smith–Putnam Wind Turbine in Vermont, United States, became the first megawatt-scale wind turbine, with a rated capacity of 1.25 MW. Although technical limitations prevented its long-term success, the project established important engineering foundations for modern wind turbine design [21].

The modern wind energy industry emerged following the global oil crises of the 1970s, which highlighted the vulnerability of fossil fuel dependence. Governments and research institutions invested heavily in alternative energy technologies, leading to substantial improvements in wind turbine aerodynamics, materials, control systems, and generator technologies. Denmark played a particularly important role in developing reliable commercial wind turbines, laying the foundation for the contemporary wind industry [22]

Since the 1990s, wind energy has experienced rapid global growth driven by technological innovation, environmental concerns, and supportive government policies. Modern wind turbines are significantly larger and more efficient than their predecessors, with individual offshore turbines now exceeding 15 MW in rated capacity. Advances in power electronics, variable-speed operation, and permanent magnet generators have enhanced energy capture and grid integration capabilities [23].

Today, wind energy is one of the fastest-growing renewable energy technologies worldwide and plays a vital role in reducing greenhouse gas emissions and supporting sustainable development. Both onshore and offshore wind farms contribute substantially to electricity generation in many countries, and continued technological progress is expected to further increase the role of wind power in future energy systems. 2110 GW generated capacity could be reached by 2030 which would be equivalent to 20% of the Global needs. This is to be supported by many key factors such as the dramatic decrease in the wind energy systems price which brightens the feasibility of the deployment of such systems which make it economically competitive. In addition, the recent advancement in those technologies and the developments in the smart grids could well be the new battery storage achievements. Therefore, an increased movement towards growing the market for electric vehicles as well as public transport increasing the future demand for electricity. Wind energy power systems are

more likely able to supply this electricity demand; Figure I.1 shows the predicted and expected cumulative generated capacity in 2030[24] [25].

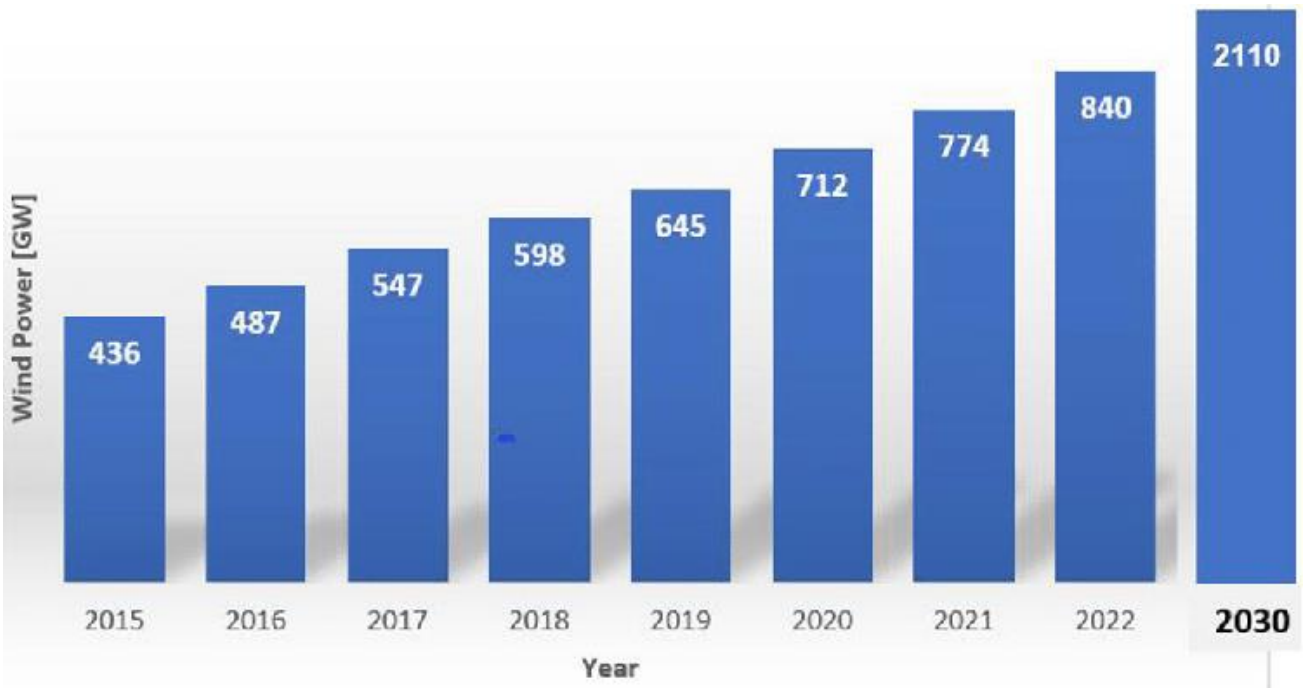


Fig. I.1. Expected cumulative generated capacity in 2030 In GW [25].

I.4. Classification of Wind Turbines

Wind turbines can be classified according to several criteria, including the orientation of the rotor axis, aerodynamic operating principle, operating speed, power regulation method, location of installation, and generator configuration. It can be also classified based on several technical and operational characteristics. Horizontal-axis, variable-speed, pitch-controlled turbines equipped with DFIG or PMSG generators currently dominate the wind energy industry because they provide high efficiency, improved energy capture, and superior grid integration capabilities. Understanding these classifications is essential for analyzing and designing modern wind power conversion systems and helps in understanding the design, performance, and application of different wind energy conversion systems.

I.4.1. Classification According to Rotor Axis Orientation

I.4.1. 1. Horizontal-Axis Wind Turbines (HAWTs)

Horizontal-Axis Wind Turbines (HAWTs) are the most widely used wind turbines for electricity generation. In these turbines, the axis of rotation is parallel to the direction of the wind. The rotor is mounted on a tower and typically consists of two or three aerodynamic blades. It offers several advantages, including high aerodynamic efficiency, high power output, and suitability for large-scale power generation. Modern commercial wind farms predominantly employ three-bladed

horizontal-axis turbines because of their superior performance and reliability but it requires a yaw mechanism to align with wind direction and their installation and maintenance can be more complex [25].

I.4.1. 2. Vertical-Axis Wind Turbines (VAWTs)

In Vertical-Axis Wind Turbines (VAWTs), the rotor axis is perpendicular to the wind direction. These turbines can capture wind from any direction without requiring a yaw control system. It offers several advantages including their omnidirectional operation, simpler mechanical design and the generator and gearbox can be installed near ground level but their efficiency is lower compared to (HAWTs) and higher cyclic stresses and vibration. Figure I.2 (a, b and c) shows the common wind turbine types. The two most common types of VAWTs are:

- **Darrieus Turbine**

The Darrieus turbine uses curved airfoil blades and operates primarily through lift forces. It provides relatively high efficiency but often requires an external starting mechanism.

- **Savonius Turbine**

The Savonius turbine operates using drag forces generated by cup-shaped blades. Although less efficient than lift-based turbines, it is simple, robust, and capable of self-starting at low wind speeds.

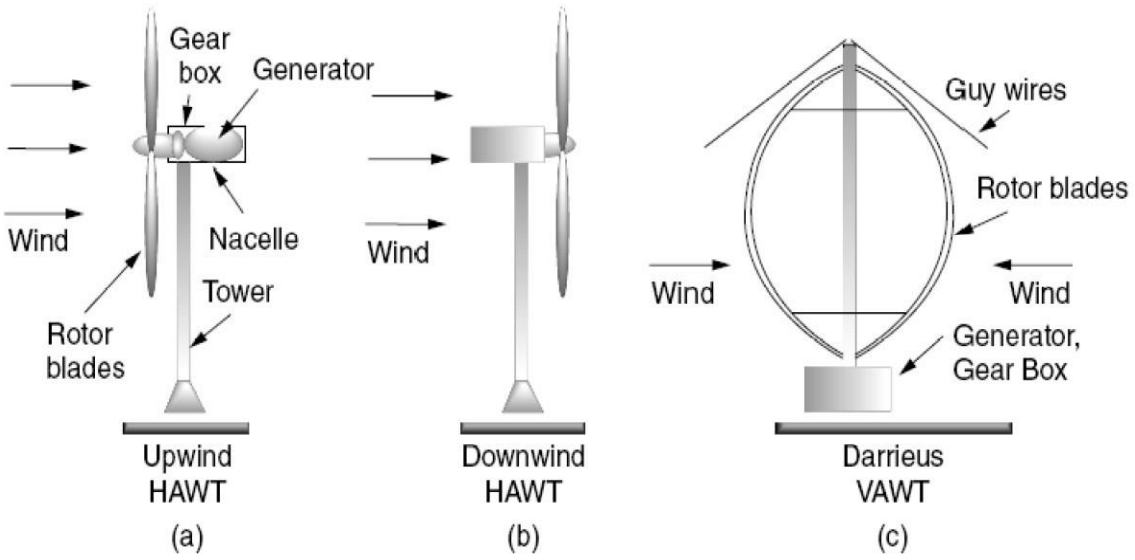


Fig. I.2. Common wind turbine types [16]

I.4.2. Classification According to Rotor Axis Orientation

I.4.2.1. Lift-Type Turbines

Lift-type turbines generate torque through aerodynamic lift forces acting on airfoil-shaped blades. Most modern commercial wind turbines belong to this category because lift forces are significantly greater than drag forces, resulting in higher efficiency.

I.4.2.2. Drag-Type Turbines

Drag-type turbines operate using the force exerted directly by the wind on the blades. The Savonius rotor is the most common example. These turbines are simple and self-starting but generally exhibit lower efficiencies.

I.4.3. Classification According to Rotor Axis Orientation

I.4.3.1. Fixed-Speed Wind Turbines

Fixed-speed turbines operate at nearly constant rotor speed regardless of wind speed variations. They are typically equipped with squirrel-cage induction generators directly connected to the grid. They have a simple construction and lower initial cost but it reduces the captured energy, higher mechanical stress and limited control flexibility.

I.4.3.1. Variable-Speed Wind Turbines

Variable-speed turbines adjust rotor speed according to wind conditions to maximize energy extraction. Power electronic converters regulate the generated electrical power. It offers an increased energy production, reduced mechanical stress and improves power quality and grid support. For that and due to these benefits, variable-speed turbines dominate modern wind energy installations.

I.4.4. Classification According to Power Regulation Method

I.4.4.1. Stall-Controlled Turbines

Stall-controlled turbines regulate power by designing blades to naturally stall at high wind speeds. When the wind speed exceeds a certain value, airflow separation occurs, limiting power output.

I.4.4.2. Pitch-Controlled Turbines

Pitch-controlled turbines use blade pitch mechanisms to adjust blade angles continuously. This enables precise control of power output and rotor speed.Pitch control is the most common regulation method in modern large-scale wind turbines due to its superior performance and operational flexibility.

I.4.5. Classification According to Installation Location

I.4.5.1. Onshore Wind Turbines

Onshore turbines are installed on land and represent the largest share of global wind energy capacity. They offer lower installation and maintenance costs compared to offshore systems.

I.4.5.2. Offshore Wind Turbines

Offshore turbines are installed in coastal waters and offshore regions where wind resources are generally stronger and more consistent with higher wind speeds, greater energy production and reduced visual and noise impact on populated areas but with higher installation and maintenance costs, more complex grid connection requirements.

I.4.6. Classification According to Generator Type

Wind turbines can also be classified according to the electrical generator employed:

- Squirrel-Cage Induction Generator (SCIG)
- Wound Rotor Induction Generator (WRIG)
- Doubly-Fed Induction Generator (DFIG)
- Permanent Magnet Synchronous Generator (PMSG):
- Electrically Excited Synchronous Generator (EESG)

Among these technologies, DFIG and PMSG systems are the most widely used in modern variable-speed wind power conversion systems due to their high efficiency and excellent controllability.

I.5. Components of a Wind Power Conversion System (WPCS)

Wind energy is rapidly becoming a major contributor to world green future. As we strive to decrease our carbon footprint and generate sustainable power to run our industries, wind energy systems appear to be a stable and dependable source. However, how does the system work? What components are included in a wind energy conversion system that make it capable of generating clean power? This subsection, will summarize the basic structure of wind energy system, while identifying and outlining each important component that makes type wind power generation system. These components range from mechanical gears to intelligent controllers that help in the conversion of energy from wind into a usable source of power [25].

A Wind Power Conversion System (WPCS) is designed to convert the kinetic energy available in wind into electrical energy that can be supplied to local loads or integrated into the electrical grid. Modern wind power conversion systems consist of several mechanical, electrical, and control components that work together to ensure efficient energy extraction, power conversion, and safe operation. The main components of a WPCS are illustrated conceptually in Figure I.3 and described below.

A wind energy conversion system (WECS) includes a combination of the mechanical and electrical components of WECS to capture wind energy and convert it to usable electricity.

These installations can include larger wind farms or smaller systems. The sector is being reshaped by future wind farm trends such as hybridization, digital monitoring, and higher-capacity turbine deployment. The conversion process essentially consists of the collection of wind using blades, converting the wind kinetic energy into mechanical energy, and finally, converting mechanical energy into electricity using the generator.

The conversion process is reliant on the overall interaction of a number of wind energy conversion system components, including aerodynamic components of wind turbines, control systems, shafts, gearboxes, and electronics units.

A Wind Power Conversion System is composed of interconnected aerodynamic, mechanical, electrical, and control subsystems that collectively convert wind energy into usable electrical power. The rotor captures wind energy, the drivetrain transfers mechanical power, the generator and power electronics perform energy conversion, and the control system optimizes operation while ensuring safety and reliability. Understanding the function of each component is essential for the design, modeling, analysis, and control of modern wind energy conversion systems.

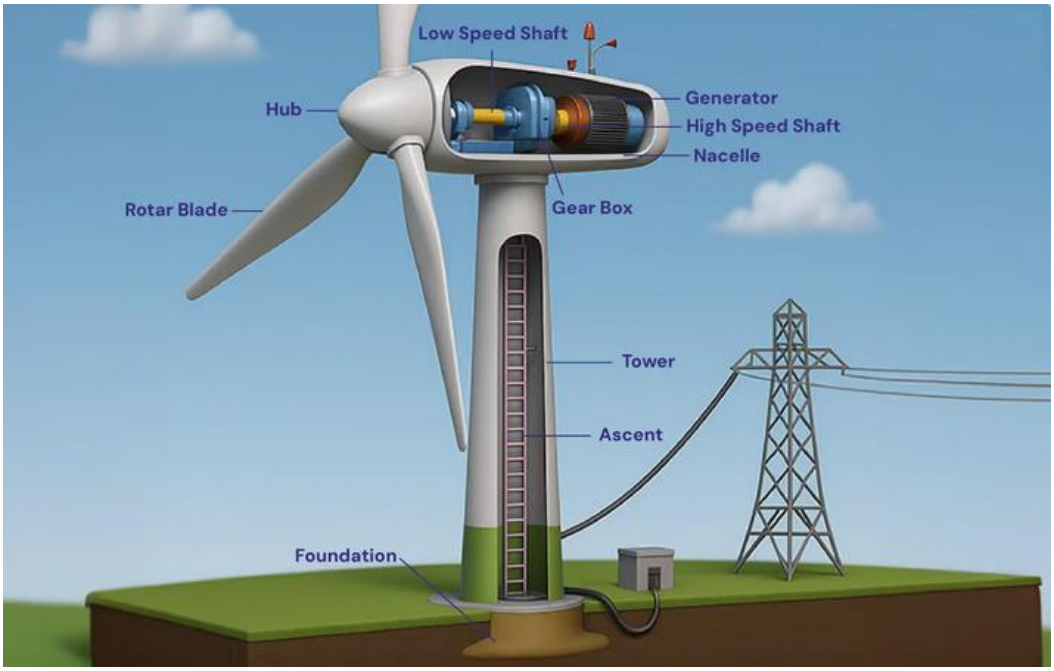


Fig. I.3. Core Components of Wind Energy Conversion Systems [25]

I.5.1. The Aerodynamic Core (Rotor and Blades)

The rotor is one of the most important aerodynamic components of a wind turbine. It consists of blades that are connected to a central hub. Wind traveling over the blades creates a lift force, similar to wings on an airplane, causing rotational displacement of the rotor.The rotor is the primary energy-capturing component of a wind turbine. It consists of a hub and aerodynamic blades designed to extract energy from the wind through lift and drag forces. When wind passes over the blades, aerodynamic

forces cause the rotor to rotate, converting wind kinetic energy into mechanical energy. The amount of power captured by the rotor depends on several factors, including wind speed, blade design, rotor diameter, and air density. Since the power available in the wind is proportional to the cube of wind speed, even small increases in wind velocity can significantly increase power production.

- **Blades:** The blades are designed to capture as much wind as possible but are made of fiberglass, occasionally carbon-reinforced plastic, and usually are optimized to capture wind. Many wind turbines use two or three blades.
- **Hub:** This plays a role in adjusting pitch to regulate rotation speed. The hub connects the turbine blades to the main shaft and transfers the aerodynamic torque generated by the rotor to the drivetrain. In modern wind turbines, the hub may also contain blade pitch mechanisms that allow adjustment of blade angles to optimize power production and protect the turbine during high wind conditions. Together, these aerodynamic components of wind turbine help in the conversion of wind's kinetic energy into mechanical rotation that starts the power generation process.

I.5.2. Mechanical Conversion (Low-Speed Shaft and Gearbox)

This combination of mechanical and electrical components of WECS ensures efficient transmission of energy from wind to the generator.

- **Low-Speed Shaft:** Transfers the rotational energy from the rotor to the gear box. The low-speed shaft transmits the mechanical power produced by the rotor to the gearbox. It rotates at relatively low speeds, depending on the turbine size and operating conditions
- **Gearbox:** The gearbox is used in many wind turbine designs to increase the rotational speed from the low-speed shaft to a higher speed suitable for driving the electrical generator. The gearbox is one of the most critical and heavily loaded components of the turbine. However, some modern wind turbines employ direct-drive configurations that eliminate the gearbox and connect the rotor directly to a low-speed generator, thereby improving reliability and reducing maintenance requirements.Steps up the low-speed rotation (30–60 RPM) to a speed that is appropriate for power generation (1000–1800 RPM).
- **High-Speed Shaft:** The high-speed shaft transfers mechanical power from the gearbox to the generator. It rotates at significantly higher speeds than the low-speed shaft and is often equipped with a mechanical brake used for emergency shutdowns and maintenance operations.

I.5.3. Electrical Generator

At the heart of every wind power generation system is the generator. This converts mechanical rotation into electrical energy through electromagnetic induction. These generators are made to produce high-quality, grid-compliant electricity, making them important wind turbine generator components. Several generator technologies are used in wind power systems, including:

- **Squirrel-Cage Induction Generator (SCIG)**

SCIGs are simple, robust, and relatively inexpensive. They are commonly used in fixed-speed wind turbines but offer limited control flexibility.

- **Doubly-Fed Induction Generator (DFIG)**

DFIGs are widely employed in modern variable-speed wind turbines. They allow variable-speed operation while requiring power electronic converters rated at only a fraction of the turbine's total power capacity.

- **Permanent Magnet Synchronous Generator (PMSG)**

PMSGs provide high efficiency, high power density, and excellent performance over a wide speed range. They are frequently used in direct-drive wind turbines and offshore wind applications

I.5.4 Power Electronic Converter

Modern wind turbines use power electronic converters to regulate voltage, frequency, and power flow between the generator and the electrical grid. These converters improve power quality, enable variable-speed operation, and facilitate compliance with grid codes. Power converters play a crucial role in maximizing energy extraction and maintaining stable grid operation A typical converter consists of:

- AC/DC rectifier
- DC-link capacitor
- DC/AC inverter
- Control and protection circuits

I.5.5. Control and Safety Systems

The control system continuously monitors turbine operating conditions and adjusts key parameters to optimize performance and ensure safe operation. Advanced control systems significantly improve energy capture and reduce mechanical stresses on turbine components.Major control functions include:

- Maximum Power Point Tracking (MPPT)
- Pitch angle control
- Yaw System
- Speed regulation

- Generator control
- Protection and fault detection

I.5.5.1. Pitch Control System

The pitch control system adjusts the angle of the turbine blades relative to the wind. This mechanism regulates aerodynamic power capture and protects the turbine from excessive loads during high wind speeds. Pitch control provides:

- Increased energy capture at moderate wind speeds.
- Power limitation above rated wind speed.
- Enhanced safety during extreme weather conditions.

I.5.5.2. Yaw System

The yaw system aligns the wind turbine rotor with the wind direction to maximize energy extraction. It typically consists of sensors, motors, gears, and control units that rotate the nacelle around the tower axis. Accurate yaw control improves turbine efficiency and reduces aerodynamic losses.

I.5.6. Nacelle (The Protective Housing)

The nacelle is the enclosure mounted on top of the tower that houses major mechanical and electrical components, including: Gearbox, Generator, Brake system, Power electronics, Cooling equipment and control systems. The nacelle protects these components from environmental conditions while providing access for maintenance activities. The nacelle helps to protect the wind turbine generator components (the gearbox and generator) from the different environmental factors like dust, rain, and extreme temperatures, and reduces the amount of repair and maintenance by providing a compact unit to keep the system safe and operating at its highest level. Long-term asset performance depends on turbine maintenance strategy covering component inspections, servicing cycles, and downtime control. Operational continuity also depends on wind turbine weather resilience built for storms, heatwaves, lightning exposure, and structural protection.

I.5.7. Tower and Foundation: Structural Support

The basic structure of wind energy system relies on sturdy towers and solid foundations. The tower supports the nacelle and rotor at an elevation where wind speeds are generally higher and less turbulent. Towers are commonly manufactured from steel tubular sections, although concrete and hybrid structures are increasingly used for large turbines. Tower height significantly influences energy production because wind speed generally increases with altitude. It raises the turbine to heights where wind speeds are optimal. It also supports the weight of the nacelle and rotor.The Foundation: Customized based on soil and wind conditions. It ensures structural integrity over time.

I.5.8. Brake System

The brake system ensures safe turbine operation during emergency conditions, maintenance procedures, or extreme wind events. These systems provide multiple layers of operational safety Wind turbines typically employ: Aerodynamic braking (pitch control), Mechanical disc braking and Electrical braking

I.9. Transformer and Grid Connection System

The electrical output of the generator is processed and stepped up to an appropriate voltage level by a transformer before being delivered to the utility grid. These components ensure safe and reliable integration of wind-generated electricity into the power network The grid connection system includes: - Transformer; - Circuit breakers; - Protection relays; -Switchgear and Power quality equipment

I.6.Operating Principle of Wind Energy Conversion Systems

Wind Power Conversion System (WPCS) converts the kinetic energy contained in moving air masses into electrical energy suitable for local consumption or grid integration. The conversion process involves several stages, including aerodynamic energy extraction, mechanical energy transmission, electrical energy generation, and power conditioning illustrated in Figure I.3. The overall objective of a WPCS is to maximize energy extraction from the wind while ensuring efficient, reliable, and safe operation under varying wind conditions.

The operating principle of a wind power conversion system is based on the interaction between the wind and the turbine rotor blades. As wind flows over the blades, aerodynamic forces are generated, causing the rotor to rotate. The resulting mechanical power is transmitted through the drivetrain to an electrical generator, which converts the mechanical energy into electrical power. It involves a sequence of energy transformations from wind kinetic energy to electrical energy. The turbine rotor extracts energy from the wind, the drivetrain transmits mechanical power, the generator converts it into electrical energy, and power electronic converters regulate the output before grid integration. Advanced control systems optimize energy capture while ensuring safe and reliable operation. Understanding these operating principles is fundamental for the analysis, modeling, and control of modern wind energy conversion systems.



Fig. I.4. Operating Principle of Wind Energy Conversion Systems

- **Wind Blows:** The wind blows and moves the blades of the turbine.
- **Blades Turn The Rotor:** The spinning blades rotate the rotor and the low-speed shaft.
- **Speed Increases:** The gearbox increases the speed of rotation.
- **Generator Starts Working:** The fast-moving shaft powers the generator.
- **Electricity Is Made:** The generator produces electricity. This power goes to the electric grid or is stored in batteries.

Each stage requires different parts of wind energy conversion system to work together efficiently to produce electricity.

1.7. Conclusion

This chapter has presented a comprehensive overview of wind energy and Wind Power Conversion Systems (WPCS), establishing the fundamental concepts required for understanding modern wind power generation technologies. The historical development of wind energy was reviewed, highlighting its evolution from traditional mechanical applications to advanced electricity-generation systems that play a significant role in today's renewable energy sector.

The chapter also discussed the classification of wind turbines based on rotor orientation, aerodynamic operating principles, speed regulation methods, installation location, and generator technologies. Particular attention was given to horizontal-axis and vertical-axis wind turbines, as well as fixed-speed and variable-speed configurations, which represent the most common technologies employed in contemporary wind energy systems.

Furthermore, the main components of a Wind Power Conversion System were described, including the rotor, gearbox, generator, power electronic converters, control systems, tower, and grid connection equipment. The functions and interactions of these components were explained to illustrate how wind energy is captured, converted, and delivered to the electrical network.

Finally, the operating principle of a WPCS was examined by analyzing the successive energy conversion stages from wind kinetic energy to electrical energy. Fundamental concepts such as wind power extraction, aerodynamic efficiency, the Betz limit, tip-speed ratio, electrical generation, power conditioning, and grid integration were introduced. These principles provide the theoretical basis for understanding the performance and control of wind energy conversion systems.

Overall, wind energy represents one of the most promising renewable energy resources due to its sustainability, environmental benefits, and technological maturity. The knowledge presented in this chapter forms the foundation for the subsequent chapters, which will focus on the modeling, analysis, control strategies, and optimization of wind power conversion systems to improve their efficiency, reliability, and integration into modern power networks.

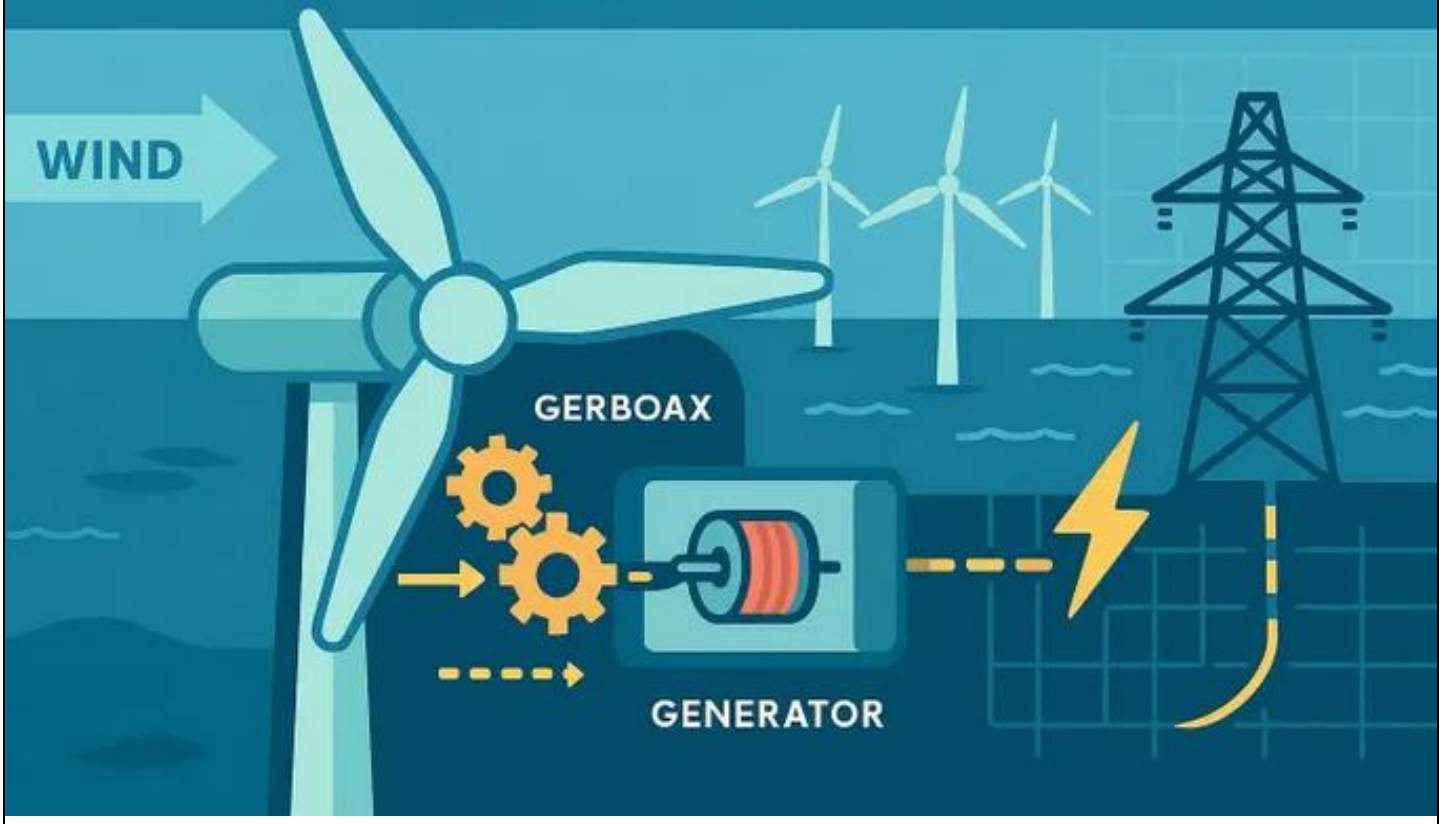
References-Chapter 1

[1]	IEA – International Energy Agency, Renewables 2023 Report, 2023
[2]	Christopher Jung, Leon Sander and Dirk Schindler,'' Future global offshore wind energy under climate change and advanced wind turbine technology'', Energy conversion and management, Volume 321, 2024.
[3]	Medhat Elkelawy, Zeiad Ayman Atta, And Hussein Seleem;"Technological Advances, Efficiency Optimization, and Challenges in Wind", Pharos Engineering Science Journal. Volume 01, Issue 01, 2025 .
[4]	Haiyan Qin, Hongyuan Yang, Haoran Li, Guangping Du; "Highlights of key advances in China's wind turbines technology ", Frontiers in Energy, Vol. 19, N° 1, 2025.
[5]	Avri Eitan, "Climate Change Adaptation through Renewable Energy: The Cases of Australia, Canada, and the United Kingdom ", Environments, 2025.
[6]	International Energy Agency, 'Renewables 2023 – Analysis and forecasts to 2028''. IEA,2023
[7]	Lukasz Pawlik, Grzegorz Wilk-Jakubowskin and Radoslaw Harabin," State-of-the-Art in the Use of Renewable Energy Sources on the Example of Wind, Wave Energy, Tidal Energy, and Energy Harvesting: A Review from 2015 to 2024"; Energies, 2025
[8]	World Wind Energy Association (WWEA). World Wind Energy Report 2023..
[9]	Luca Cimmino and Maria Vicidomini;" Renewable Energy Systems 2023"; Applied *Sciences.* 2024,
[10]	Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E.; "Wind Energy Handbook (3rd ed.). John Wiley & Sons",2021.
[11]	Ambati Bhimaraju and Aeidapu Mahesh, '' Recent developments in PV/wind hybrid renewable energy systems: a review"; Energy Systems; 2024.
[12]	Amina Bensalah, Georges Barakat and Yacine Amara;"Electrical Generators for Large Wind Turbine: Trends and Challenges"; *Energies* 2022,
[13]	Asmaa Sobhy Sabik,Ahmed Hassan Adel and Adel S. Nada,"Comparative Performance Evaluation of Wind Energy Systems Using Doubly Fed Induction Generator and Permanent Magnet Synchronous Generator", Wind, 2025.
[14]	Muller, S., Deicke, M., & De Doncker, R. W; '' Doubly fed induction generator systems for wind turbines. IEEE Industry Applications Magazine, 8(3), 26-33;2002.
[15]	Wind Energy Handbook, Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, ''Wind Energy Handbook'', 3rd edition; Wiley. 2021.
[16]	Firoz Alam, Yingai Jin and Xingjun Hu;"Current Status and Future Prospects of Commercial Wind Power Generation", Energies,2025.
[17]	M. Abdelateef Mostafa, Enas A. El-Hay, Mahmoud M. Elkholy, " An overview and case study of recent low voltage ride through methods for wind energy conversion system", Renewable and Sustainable Energy Reviews, September 2023.
[18]	Billel Bouchemal and Mohamed Chemachema, "Model-free control for variable-speed wind energy conversion systems based on power tracking"; Electrical Engineering, 2024.
[19]	Isah A. Jimoh, Taimur Zaman, Mazheruddin Syed, Hong Yue, and Graeme Burt, and Mohamed Shawky El Moursi, " Tube-Based Linear Parameter-Varying Model Predictive Control for Wind Energy Conversion Systems", IEEE Transactions on Sustainable Energy; 2024.

[20]	Eduardo Rausell , Santiago Arnaltes , José Luis Rodríguez , Marcos Lafoz and Gustavo Navarro," Control of wind energy conversion systems with permanent magnet synchronous generator for isolated green hydrogen production», International, 2025
[21]	Farid Merahi, Hamza Mernache, Djamal Aouzelag,Abd Essalam Badoud, Mohit Bajaj and Ievgen Zaitsev;" Power control of an autonomous wind energy conversion system based on a permanent magnet synchronous generator with integrated pumping storage " ; Scientific Reports, 2024
[22]	Endalew Ayenew, Getachew Biru, Asrat Mulatu, M. Berhanu ; " Modelling and control of wind energy conversion system: performance enhancement"; International Journal of Dynamics and Control, 2023.
[23]	Abdul Salam Darwish, Riadh Al-Dabbagh; " Wind energy state of the art: present and future technology advancements", Renewable Energy and environment Sustainability, 2020.
[24]	Amina Mseddi, Khouloud Wali, Ahmed Abid, Omar Naifar, Mohamed Rhaima, Lassaad Mchiri; " Advanced modeling and control of wind conversion systems based on hybrid generators using fractional order controllers", Asian Journal of control, 2024.
[25]	https://kpenergy.in/blog/wind-energy-conversion-system-components

Chapter II

Modeling of the wind energy conversion system



II.1. Introduction

The increasing penetration of wind energy into modern power systems has created a growing need for accurate analysis, design, control, and optimization of Wind Energy Conversion Systems (WECS). To achieve these objectives, mathematical modeling plays a fundamental role in representing the dynamic behavior of wind turbines, generators, power electronic converters, and control systems. Accurate models enable researchers and engineers to predict system performance under various operating conditions, evaluate control strategies, improve energy extraction efficiency, and ensure reliable grid integration [26].

A Wind Energy Conversion System is a complex electromechanical system involving multiple energy conversion stages. The process begins with the aerodynamic conversion of wind kinetic energy into mechanical energy by the turbine rotor. This mechanical energy is then transmitted through the drivetrain and converted into electrical energy by the generator. Finally, power electronic converters and control systems regulate the generated power before it is delivered to the electrical grid. Since each subsystem exhibits different dynamic characteristics, comprehensive mathematical models are required to describe their interactions and overall system behavior.

The modeling of a WECS generally involves several interconnected subsystems, including the wind model, aerodynamic turbine model, mechanical drivetrain model, electrical generator model, power electronic converter model, and control system model. The wind model characterizes wind speed variations and turbulence effects, while the aerodynamic model describes the conversion of wind energy into mechanical power through the turbine blades. The drivetrain model represents the transmission of torque between the rotor and the generator, accounting for shaft dynamics and mechanical losses. The generator and converter models describe the electrical energy conversion process and its interaction with the grid [27].

Modern wind energy systems are predominantly variable-speed turbines equipped with advanced generators such as Doubly-Fed Induction Generators (DFIGs) and Permanent Magnet Synchronous Generators (PMSGs). These systems require sophisticated mathematical models to analyze their transient and steady-state performance. Furthermore, advanced control techniques such as Maximum Power Point Tracking (MPPT), pitch angle control, and vector control rely heavily on accurate system models for effective implementation and performance evaluation.

Mathematical modeling also serves as an essential tool for simulation studies. Software environments such as MATLAB/Simulink, is widely used to simulate wind energy conversion

systems and assess their behavior under different wind conditions, grid disturbances, and operating scenarios. Such simulations reduce development costs, improve system reliability, and facilitate the design of efficient control algorithms before practical implementation.

This chapter focuses on the mathematical modeling of the Wind Energy Conversion System. The fundamental models describing wind characteristics, turbine aerodynamics, mechanical dynamics, electrical generators, power converters, and control systems are presented and analyzed. These models provide the theoretical foundation necessary for the simulation, control, and performance analysis of modern wind energy conversion systems.

II.2. Modeling of the wind turbine components

The wind turbine is the primary energy conversion device in a Wind Energy Conversion System (WECS). It converts the kinetic energy available in the wind into mechanical energy that drives the electrical generator. To accurately analyze the dynamic behavior and performance of a WECS, mathematical models of the wind turbine components are required. These models describe the mechanical and aerodynamic interactions among the rotor, shafts, gearbox, and associated rotating masses.

The wind turbine can be represented by several interconnected subsystems, including the rotor, hub, drive train, gearbox, and mechanical shaft system. Depending on the desired level of accuracy, either simplified or detailed dynamic models may be employed. For that, a model of the wind turbine components will be presented to achieve optimal performance. Figure II-1 aims to describe the energy conversion steps of the wind turbine components [28].

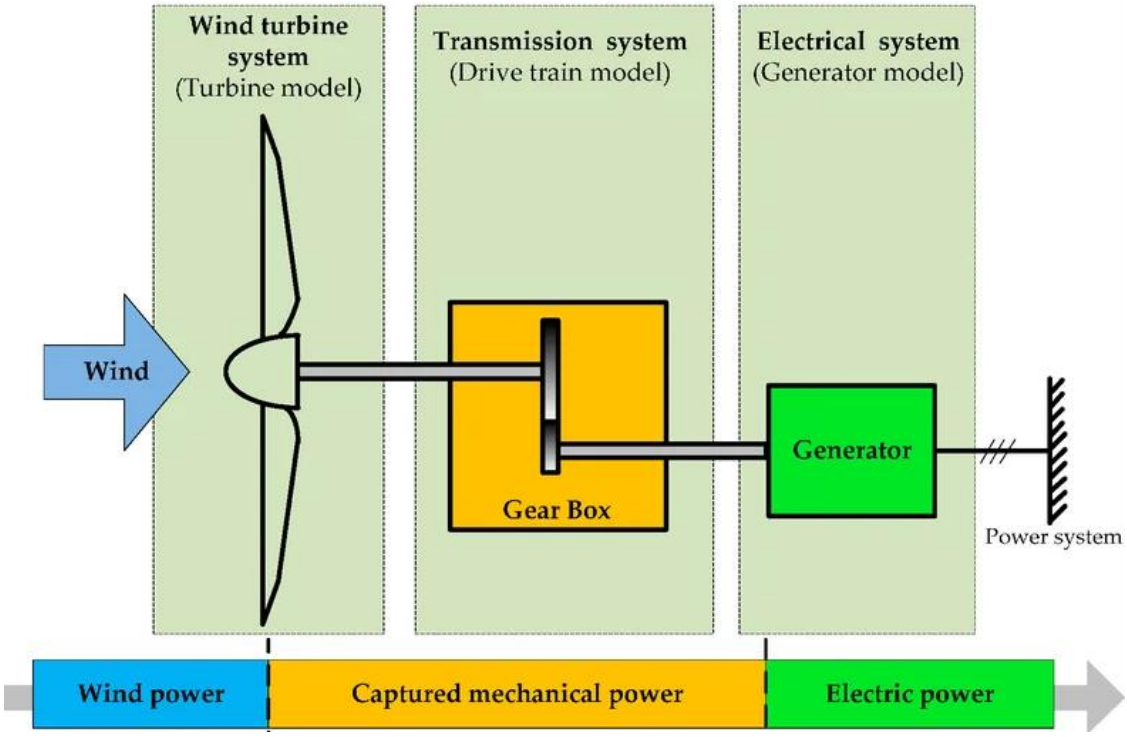


Fig. II.1. Overall schematic of a wind energy conversion system

II.3. Modeling of the mechanical part

II.3.1. Wind speed modeling

Wind, by definition, is the movement of an air mass resulting from local differences in temperature and pressure. The speed and geographical extent of winds can vary greatly in space and time. Wind plays a role in many processes on Earth, such as the oxygenation of oceans and rivers, soil erosion, and the movement of minerals. Humans today use it as a source of energy: wind turbines, which rely on the force of the wind's movement on the blades.

The main interest in analyzing wind turbine dynamics lies in its electrical behavior. One of the important characteristics is the power variations that influence its behavior, caused by air movement. The energy stored in the wind is of poor quality due to numerous factors, such as atmospheric fluctuations, which affect wind speed. The wind speed profile is represented by equation (II-1). The wind model is given by a Fourier series representation of the wind; whose signal consists of a sum of several harmonics. The expression is defined as follows [29]:

$$V(t) = Vmoy + \sum_{k-1}^{i} V_k . sin(w_n\, t) \qquad \text{(II-1)}$$

Where: $Vmoy$ is the average wind speed;V_k is the kth harmonic amplitude et w_n is the kth harmonic angular frequency.

This model allows us to represent wind fluctuations caused by atmospheric turbulence.

II.3.2. Turbine modeling

II.3.2.1 Simplifying assumption of the turbine model

- Uniformity of wind speed across the blades
- Rigidity of the blades and drive shaft
- Neglect of mechanical losses in the gearbox
- Use of a power coefficient *Cp* to model aerodynamic efficiency

Figure II-2 aims to mathematically translate the behavior of the constraints related to mass forces, along the transmission shaft of the mechanical energy of the wind turbine, on the rotor of the electric generator of a wind power system [30].

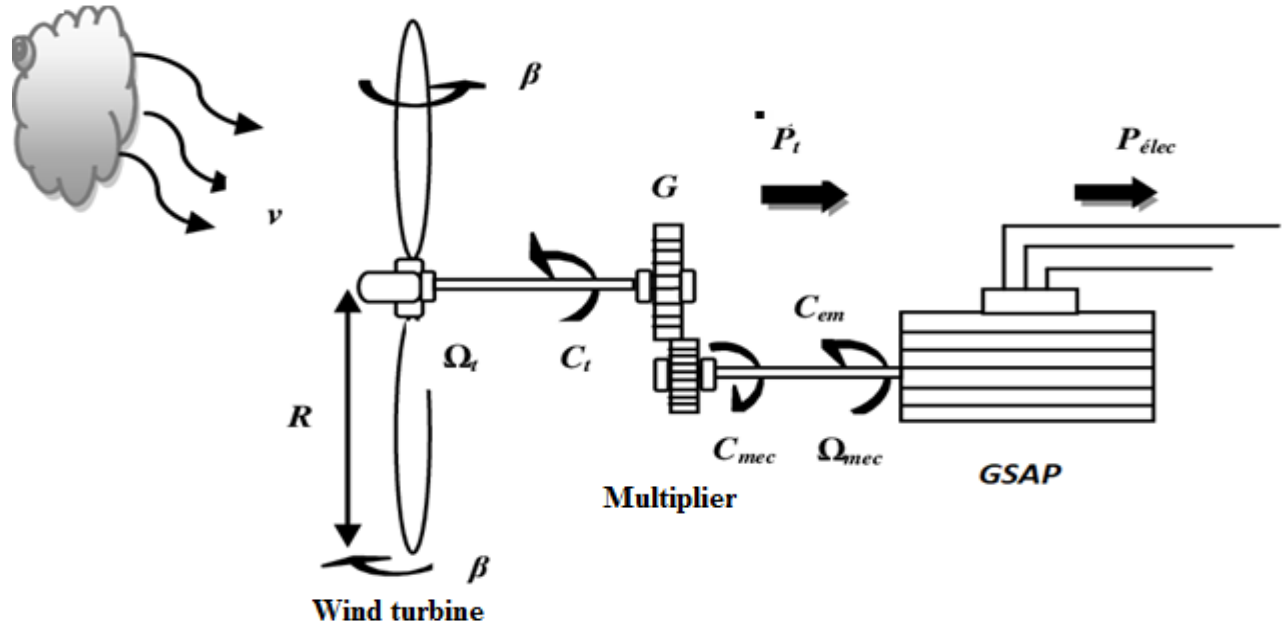


Fig. II.2. Mass forces on the mechanical energy transmission shaft of the turbine.

II.3.2.2. Wind power

Wind is air in motion, and like any moving body, it possesses kinetic energy, which depends on the mass and speed of the air mass. If we consider the air density (mass of air per unit volume) to be constant, the energy supplied by the wind is a function of its speed given by the following equation [31]:

$$E_C = \frac{1}{2} m.\vartheta^2 \qquad \text{(II-2)}$$

With: m is the mass of the wind in Kg and ϑ is the instantaneous speed of the wind in m/s.

At normal atmospheric pressure and a temperature of 15 degrees Celsius, air has a density ρ of approximately 1.225 kg/m^3. However, the volumic density decreases slightly as the humidity of the air increases. Its expression is given by the following relationship:

$$m = \rho.V \qquad \text{(II-3)}$$

The volume of air that passes through a surface S in a time t is given by:

$$V = S.\vartheta.t \qquad \text{(II-4)}$$

The expression for mass therefore becomes:

$$m = \rho.S.\vartheta.t \qquad \text{(II-5)}$$

Wind power is defined as energy per unit of time

$$P_V = \frac{E_c}{t} \qquad \text{(II-6)}$$

Substituting expressions (II-2) and (II-5) into expression (II-6) we obtain the following expression:

$$P_V = \frac{1}{2}\rho.S.\vartheta^3 \qquad \text{(II-7)}$$

Based on this final expression, we can conclude that three factors influence wind power:

- Air density.

- The area swept by the rotor, which depends on the turbine's radius.

- Wind speed, which is the most important factor since it is the third power.

II.3.2.3 Power coefficient

In reality, a wind turbine cannot capture all the energy of the wind, even if it is considered ideal, due to aerodynamic and mechanical losses. The ratio between the power of the wind turbine and the power of the wind is called the power coefficient, and the expression is written in the following form:

$$C_p = \frac{P_{aéro}}{P_v} \qquad \text{(II-8)}$$

In the context of the study presented in this chapter, we focused on an approximation of the power coefficient C_p, the expression of which is used in many research works to better characterize a wind turbine, and which is defined as follows:

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \qquad \text{(II-9)}$$

Given that:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0{,}008\beta} - \frac{0{,}035}{\beta^3+1} \qquad \text{(II-10)}$$

C_1à C_6 are known constants related to the type of wind turbine rotor. The first parameter, denoted λ, called the tip speed ratio (TSR), designates the efficiency, or the ratio between the blade speed (related to the turbine's rotation) and the wind speed, and is defined as follows:

$$\lambda = \frac{\vartheta_t}{\vartheta} = \frac{\Omega_t.R}{\vartheta} \qquad \text{(II-11)}$$

Where: Ωt is the angular speed of the blades expressed in radians per second (rad/s), and R represents the radius of the blades expressed in meters (m).

The second parameter, denoted β, represents the blade pitch angle, more precisely between the blade chord and the plane perpendicular to the rotor's axis of rotation. This angle is measured to regulate the power extracted by the wind turbine, as illustrated in Figure II-3.

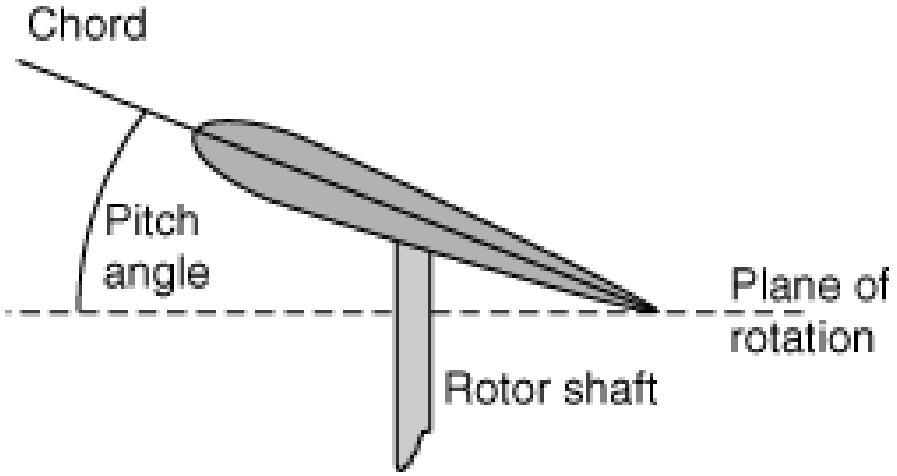


Fig. II.3. The blade pitch angle

The power coefficient of a wind turbine is used to measure the efficiency with which the wind turbine converts wind energy into electricity; its second expression is directly related to the following two parameters: the ratio λ, which allows us to study how it varies as a function of wind speed and blade rotation speed (related to turbine rotation), and the blade pitch angle β. This helps to understand the conditions under which the turbine is most efficient.

II.3.2.4. Turbine Power

The turbine is the rotating part of the wind turbine; it converts the kinetic energy of the wind into mechanical energy. However, the turbine power can be directly derived from equation (II-8) of the power coefficient [33].

$$P_t = C_p(\lambda,\beta).P_v = \frac{1}{2} C_p(\lambda,\beta).\rho.S.\vartheta^3 \qquad \text{(II-12)}$$

While the mechanical torque developed by the turbine obtained from the mechanical power of the turbine is expressed by (II-13):

$$C_t = \frac{P_t}{\Omega_t} \qquad \text{(II-13)}$$

Returning to the turbine's energy relationship, it's worth noting that air density and wind speed are two factors that cannot be controlled, as they are linked to the turbine's location and height. The area of the circle traced by the turbine is related to the blade length, which can be controlled. Therefore, increasing the blade length leads to an increase in energy converted and thus an increase in the resulting electrical energy output of the turbine. The key factor for

optimizing wind energy is therefore controlling the power coefficient *Cp*, which varies according to its two parameters λ and β, as illustrated in Figure II-4.

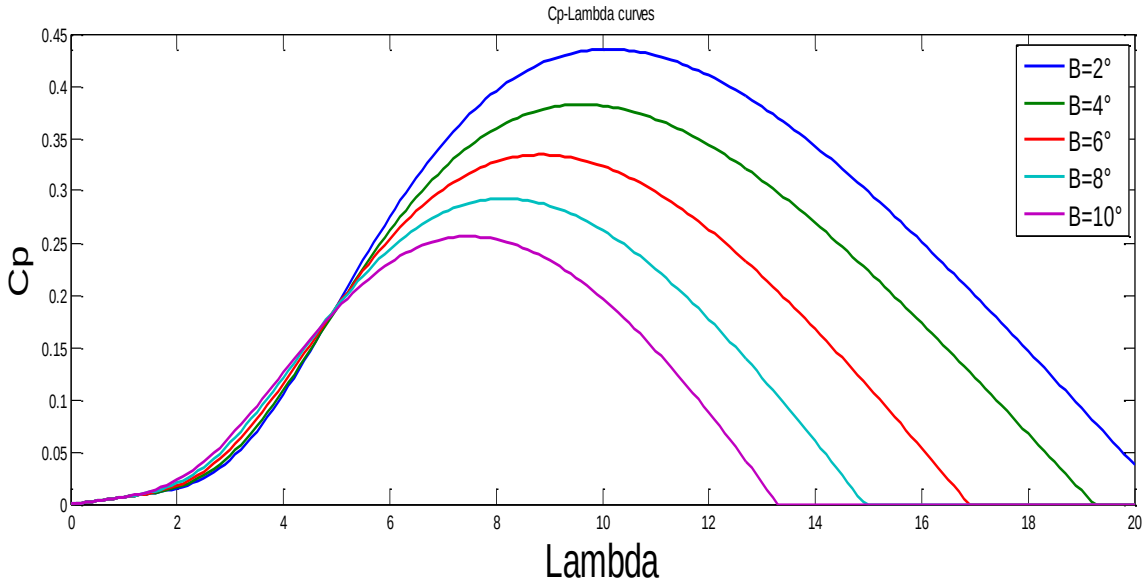


Fig. II.4. Power coefficient of the wind turbine

II.3.2.5 Betz Limit

In 1919, the German scientist Betz established laws relating to wind turbines and concluded that a wind turbine cannot recover 100% of the captured aerodynamic power due to inefficiencies and losses attributed to various configurations, rotor blade profiles, finished wings, friction, and turbine designs. The following figure shows how air flows through it.

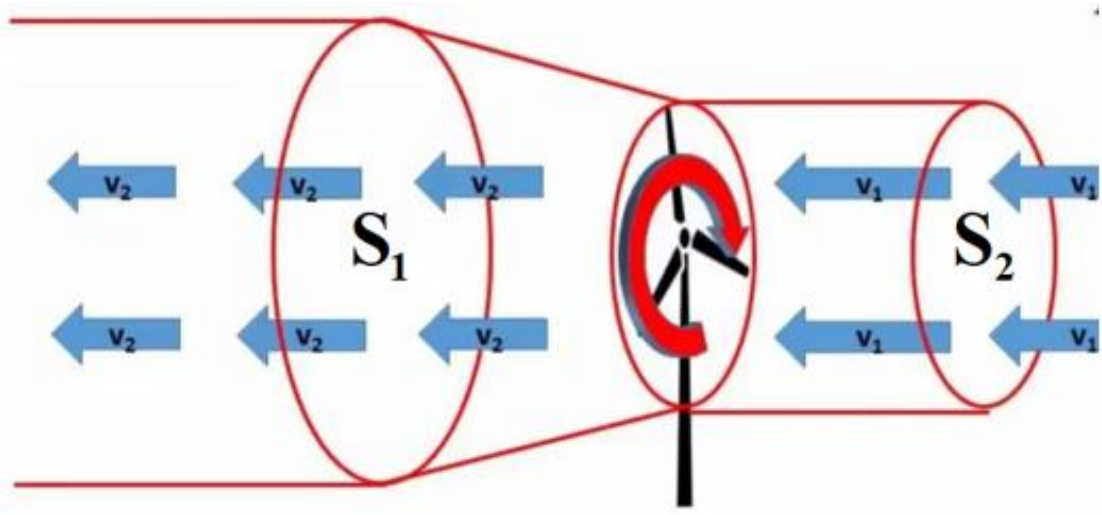


Fig. II.5. Wind flow through a simple wind turbine rotor model

The generated power by the wind turbine is expressed as [34]:

$$P_{th} = P_1 - P_2 = \frac{1}{2}\rho.S.\vartheta.\vartheta_1^2 - \frac{1}{2}\rho.S.\vartheta.\vartheta_2^2 = \frac{1}{2}\rho.S.\vartheta(\vartheta_1 - \vartheta_2)^2 \qquad \text{(II-14)}$$

Therefore, ϑ_1 is the incoming wind speed (before the rotor) and ϑ_2 is the outgoing wind speed (after the rotor). Such that: $\vartheta_2 < \vartheta_1$

The average wind speed is:

$$\vartheta = \frac{\vartheta_1+\vartheta_2}{2} \quad \text{(II-15)}$$

Substituting this velocity into the power equation, we obtain the following:

$$P_{th} = \frac{1}{4}\rho.S(\vartheta_1+\vartheta_2)(\vartheta_1-\vartheta_2)^2 \quad \text{(II-16)}$$

Putting : $\vartheta_2 = x\vartheta_1$ with :$0 < x < 1$

The theoretical power becomes:

$$P_{th} = \frac{1}{4}\rho.S.{\vartheta_1}^3(1+x)(1-x^2) = \frac{1}{4}\rho.S.{\vartheta_1}^3(-x^3-x^2+x+1) \quad \text{(II-17)}$$

To find the value of ϑ_2, that maximizes this power, let's take the derivative of the power equation and set it equal to zero:

$$\frac{dP}{dx} = \frac{1}{4}\rho.S.{\vartheta_1}^3(-3x^2-2x+1) = 0 \quad \text{(II-18)}$$

This is a quadratic equation to solve:

$$-3x^2-2x+1=0 \quad \text{(II-19)}$$

We obtain two different solutions:

$x_1 = -1$ (Refused solution)

$x_2 = \frac{1}{3}$ (Accepted solution)

So : $\vartheta_2 = \frac{1}{3}\vartheta_1$

Therefore, we substitute this result back into the power equation:

$$P_{max} = \frac{1}{4}\rho.S.{\vartheta_1}^3\left(-(\tfrac{1}{3})^3-(\tfrac{1}{3})^2+\tfrac{1}{3}+1\right) = \frac{32}{27}.\frac{1}{4}\rho.S.{\vartheta_1}^3 \quad \text{(II-20)}$$

The maximum power output of the wind turbine is therefore

$$P_{max} = \frac{16}{27}.\frac{1}{2}\rho.S.{\vartheta_1}^3 = 0{,}59P_v \quad \text{(II-21)}$$

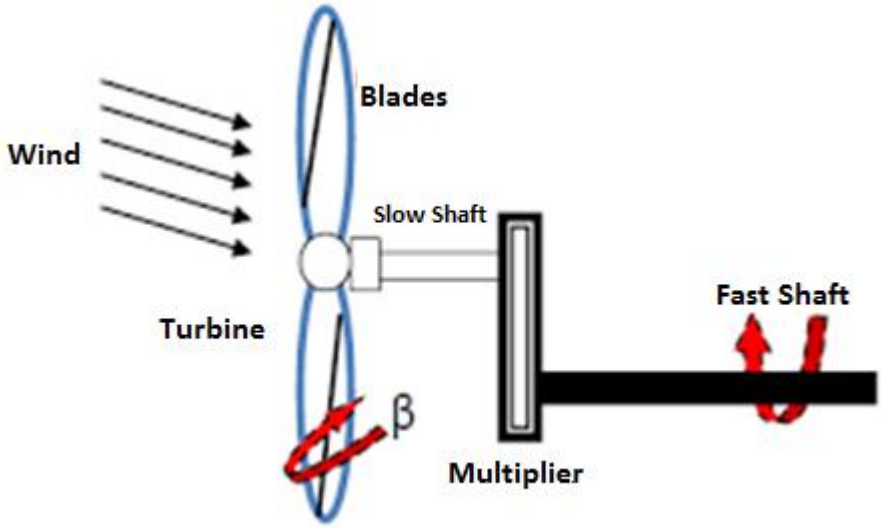
The maximum achievable power is 59% of the wind's kinetic power.

$$C_{p_max} = \frac{P_{max}}{P_v} = \frac{16}{27} = 0{,}59 = 59\% \quad \text{(II-22)}$$

The C_p of a real wind turbine is between 0 and 0.59. A real wind turbine will therefore be able to recover less than 59% of the energy or kinetic power of the wind, this theoretical value called the Betz limit.

II.3.3. Modeling the multiplier

In the wind turbine nacelle, the propeller rotates on a single axis. Its rotational speed varies between 5 and 20 (rpm), as does the generator's speed, which varies between 750 and 3600 rpm. Since the input speed is insufficient to generate electricity, a speed multiplier with a gain of G is used to increase the turbine speed, matching it to the generator's rotational speed. The following figure shows the general diagram of the speed multiplier.



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Fig. II.6. Speed multiplier diagram

The mechanical model of the speed multiplier, taking into account the input and output torques, the rotational speeds of the shafts, as well as the Dux losses due to friction, is illustrated in Figure II.7.

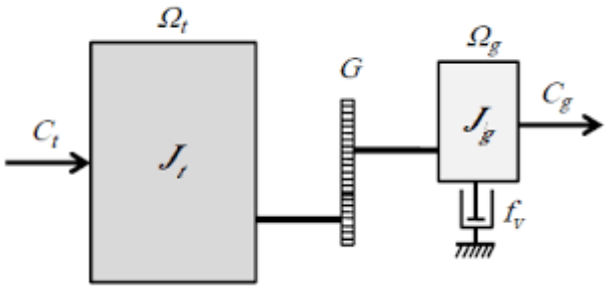


Fig. II.7. Multiplier mechanical model

Since a speed multiplier with gain *G* is used, the mechanical speed transmitted to the generator shaft is therefore the gain multiplied by the turbine shaft speed. The expression for the mechanical speed on the generator side is as follows:

$$\Omega_g = G.\Omega_t \qquad \text{(II-23)}$$

What we gain in speed, we lose in torque; we obtain the following expression for the torque of the generator.

$$C_g = \frac{1}{G} C_t \quad \text{(II-24)}$$

II.3.3.1. Multiplier selection

The rotor torque generates power, but it also applies significant moments and forces to the wind turbine's transmission. The chosen speed multiplier must be able to withstand these loads and resist the operating environment. Mechanical losses are considered negligible since the multiplier is assumed to be ideal (its efficiency is equal to 1), allowing us to write:

$$G = \frac{\Omega_g}{\Omega_t} = \frac{C_t}{C_g} \quad \text{(II-25)}$$

II.3.4. Mechanical shaft modeling

The mechanical shaft of the system is modeled using the equations of dynamics for rotating systems based on the moment of inertia and applied torques. The masses of the various turbine components are represented as a total inertia *J*, comprising the masses of the turbine blades and rotor. The proposed mechanical model considers the total inertia to consist of the turbine's inertia transferred to the generator rotor and the generator's own inertia [31].

$$J = J_g + J_t \quad \text{(II-26)}$$

The fundamental equation of the dynamics of mechanical systems comes from Newton's second law:

$$C_m = J \frac{d\Omega_g}{dt} \quad \text{(II-27)}$$

$$C_m = C_t = C_g - C_{em} - C_f = J \frac{d\Omega_g}{dt} \quad \text{(II-28)}$$

$$C_t = C_g - C_{em} - f\Omega_g = J \frac{d\Omega_g}{dt} \quad \text{(II-29)}$$

$$C_t = C_g - C_{em} = J \frac{d\Omega_g}{dt} + f\Omega_g \quad \text{(II-30)}$$

By rearranging the expressions of the equations for the mechanical torque of the turbine (II-13), the gain multiplier G (II-24), the mechanical shaft (II-30), the second formula power coefficient (II-9) and the specific speed ratio (II-11), the model of the functional diagram of the wind turbine is determined, illustrated by Figure II-8.

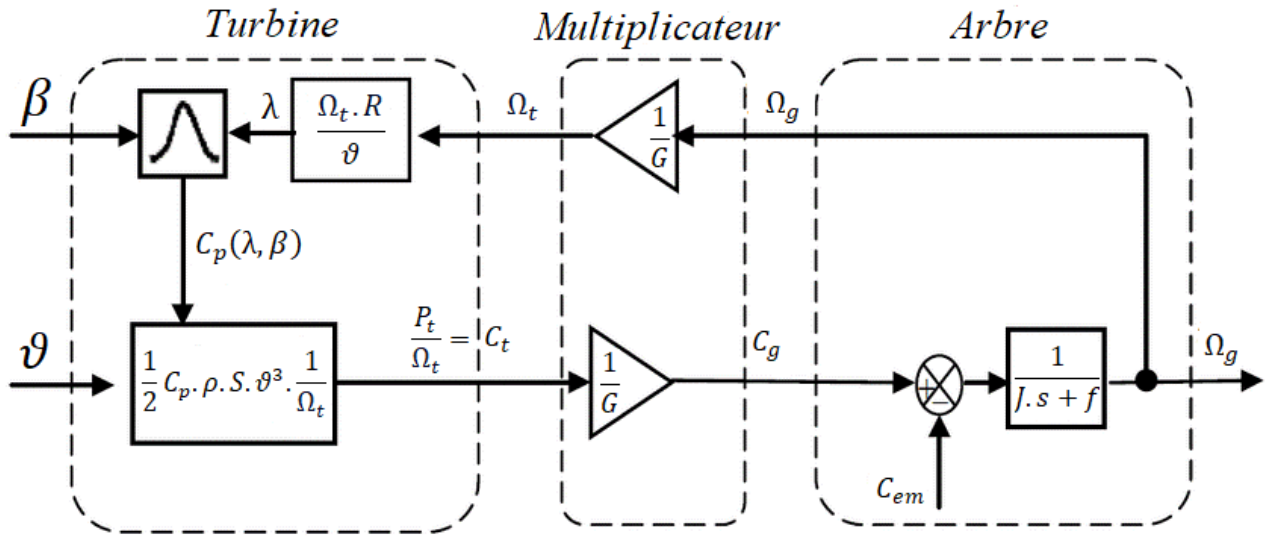


Fig. II.8. Wind turbine block diagram

II.4. Maximum Power Point Tracking (MPPT) method

II.4.1. Turbine maximum power equation

To compete with other renewable energy sources, it is necessary to improve the performance of the mechanical power produced as a function of wind speed. Under optimal operating conditions, the maximum mechanical power extractable by an ideal turbine can be obtained using the following equation [32].

$$P_t^{max}=\frac{1}{2}C_p^{max}(\lambda_{opt},\beta_{opt}).\rho.S.\vartheta_{est}^3 \qquad \text{(II-31)}$$

Knowing that:

$$\lambda_{opt}=\frac{\Omega_t.R}{\vartheta_{est}} \qquad \text{(II-32)}$$

While the estimate of the wind speed ϑ_{est} can be determined from the equation of the optimal specific speed λ_{opt}, it is therefore written by the relation:

$$\vartheta_{est}=\frac{\Omega_t.R}{\lambda_{opt}} \qquad \text{(II-33)}$$

We substitute (II-25) into the equation for the maximum power of the turbine (II-23):

$$P_t^{max}=\frac{1}{2}C_p^{max}.\rho.S.(\frac{\Omega_t.R}{\lambda_{opt}})^3 \qquad \text{(II-34)}$$

After simplification, the equation for the maximum power of the turbine becomes:

$$P_t^{max}=\frac{1}{2}\rho.S.R^3.\Omega_t^3.\frac{C_p^{max}}{\lambda_{opt}^3} \qquad \text{(II-35)}$$

II.4.2. Turbine optimal torque equation

We previously defined in equation (II-13) that the turbine torque is equal to the turbine power divided by its speed Ω_t. While the expression for the optimal turbine torque is written as follows:

$$C_{t_opt} = \frac{P_t^{max}}{\Omega_t} \quad \text{(II-36)}$$

The estimation of the electromagnetic torque is written as follow:

$$C_{em_est} = \frac{1}{G} C_{t_opt} \quad \text{(II-37)}$$

II.5. Modeling of the permanent magnet synchronous generator (GSAP)

II.5.1. Introduction

The study of the behavior of an electric machine is a difficult task that requires, above all, a thorough understanding of its dynamic model in order to accurately predict, through simulation, its behaviour in the various operating modes considered [32].

For a long time, DC machine powered most industrial equipment (robots and machine tools). However, the presence of the brush-commutator system has always been a major drawback of the motor, limiting power and maximum speed, and presenting maintenance difficulties and operational interruptions. It is for this reason that the use of AC electric machine has become advantageous in order to eliminate this drawback [2][3].

Among the AC machine used in variable-speed drives, the permanent magnet synchronous motor remains a good candidate. Its selection is becoming attractive and competitive with that of asynchronous motors thanks to the evolution of permanent magnets, whether alloy-based or rare-earth-based. This allowed them to be used as inductors in synchronous motors, offering many advantages over other types of motors, including no rotor losses, low inertia, and high torque density [2][4].

This section presents the operating principle and modeling of a permanent magnet synchronous machine coupled with a static converter.

II.5.2. Operating principle of the permanent magnet synchronous machine

The principle of permanent magnet machine is quite simple. Only the coils are energized. The magnetic field created by the windings orients the rotor, which is made up of magnets. Figure (II.9) shows a motor with a bipolar rotor and a stator with one pair of poles. Phases *a* and *b* are carried by opposing windings. The presence of currents in the phases orients the rotor. An elementary "step" θp is defined as the angular displacement of the rotor when the

power supply is switched from one phase to the next. For this structure, we obtain θp = 90°. This corresponds to the transition from Figure (II.9.a) to Figure (II.9.c). Half-steps are obtained by energizing two phases simultaneously (Figure (II.9.b)). Many motors on the market use this type of structure.

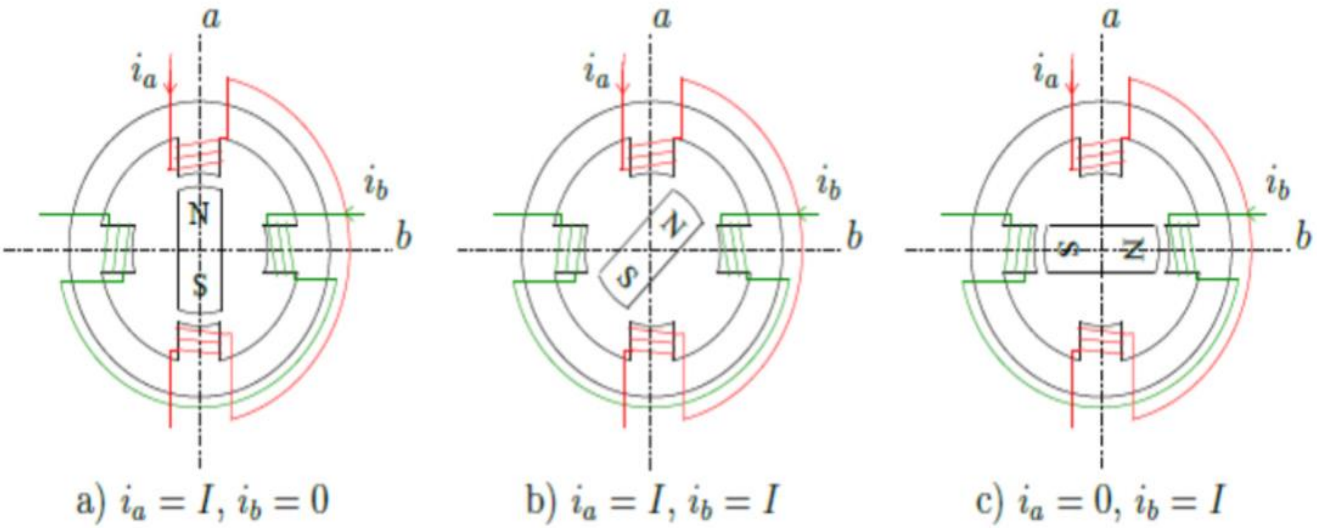


Fig. II.9. Operating principle of the permanent magnet synchronous machine

II.5.3. Types of synchronous machines

There are many configurations of permanent magnet synchronous machines. The main reason for this diversity is that users have specific needs. Permanent magnet synchronous machine structures are classified according to the arrangement of the magnets on the rotor. Their different configurations include radial flux, axial flux, and transverse flux machines.

- Radial Flux Machines
- Axial Flux Permanent Magnet Synchronous Machines
- Transverse Flux Permanent Magnet Synchronous Machines

II.5.4. Operation of the permanent magnet synchronous machine (PMSM)

III.5.4.1. Generator operation

It is important to note that the simulation model in permanent magnet synchronous generator mode is essential for verifying control algorithms and optimizing the system. Therefore, in most studies, a mathematical model is created for the GSAP to analyze the system's operation.

The generator mode modeling is based on electrical equations containing voltage equations and mechanical equations containing the torque produced in response to a mechanical load, which describe its behaviour.

II.5.5. Modeling of the permanent magnet synchronous machine

The development of a mathematical model of a magnetically controlled automatic pulse (MCAP) is necessary for studying its control in the various transient and steady-state operating regimes [5].

The usual simplifying assumptions adopted in the modeling of the machine, given in most references [5-6]:

- The absence of saturation in the magnetic circuit,
- The sinusoidal distribution of the magnetic flux density (MFD) created by the stator windings,
-Hysteresis is neglected with respect to eddy currents and the skin effect,
- The notch effect is negligible,
-The resistance of the windings does not vary with temperature.

II.5.5.1. Machine Equations in the coordinate system (abc)

Figure (II.10) shows the representation of the windings for a three-phase permanent magnet synchronous machine.

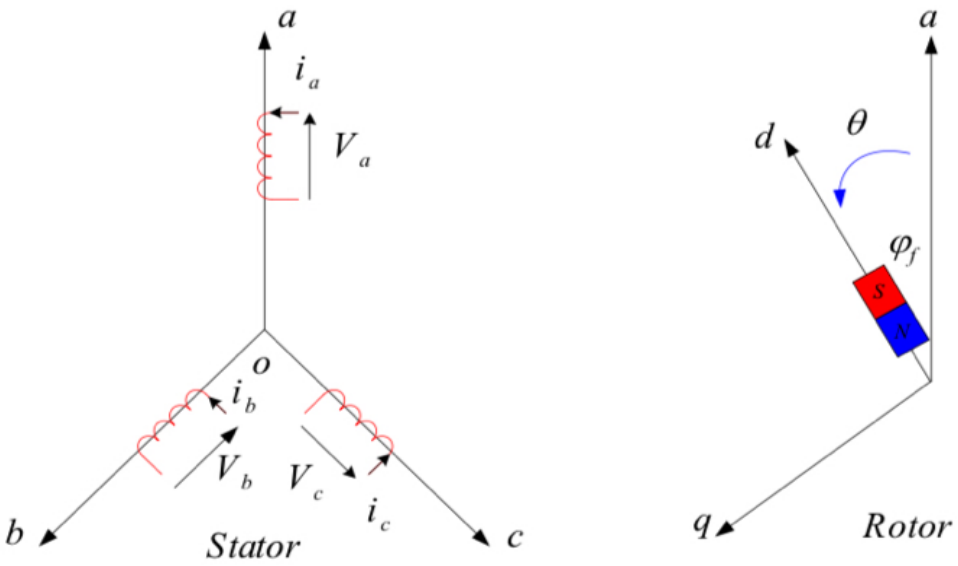


Fig. II.10. Diagram of the MSAP in the abc coordinate system

The machine's behavior is entirely defined by three types of equations:

- Electrical equations,
- Magnetic equations,
- Mechanical equations.

II.5.5.1.1. Electrical equations

The electrical equations for the stator of a three-phase permanent magnet synchronous machine without dampers are written as follows:

$$[Vs] = [Rs][is] + \frac{d}{dt}[\varphi s] \qquad \text{(II.38)}$$

Where:

$[Vs] = [VaVbVc]^T$: Stator voltage vector

$[is] = [iaibic]^T$: Stator current vector

$[\varphi s] = [\varphi a \varphi b \varphi c]^T$: Stator flux vector

$[Rs] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}$: Stator resistance matrix

II.5.5.1.1. Magnetic equations

$$[\varphi s] = [Ls][is] + [\varphi f abc] \qquad \text{(II.39)}$$

Where:

$[\varphi s] = [\varphi a \varphi b \varphi c]^T$: Stator flux vector,

$[is] = [iaibic]^T$: Stator current vector,

$[\varphi f abc] = [\varphi f a \varphi f b \varphi f c]^T$: Flux vector created by the magnet through the stator winding

The matrix [Ls] is a square matrix containing constant terms grouped in [Ls 0], while variable terms depending on (θ) are grouped in [Ls 2 (θ)]. In the general case, it takes the form:

$$[Ls\ ] = [Ls0] + [Ls2(\theta)] \qquad \text{(II.40)}$$

With :

$$[Ls0(\theta)] = \begin{vmatrix} Ls0 & Ms0 & Ms0 \\ Ms0 & Ls0 & Ms0 \\ Ms0 & Ms0 & Ls0 \end{vmatrix} \quad \text{Et} [Ls2(\theta)] = \begin{vmatrix} Cos(2\theta) & Cos2\left(\theta - \frac{2\pi}{3}\right) & Cos2\left(\theta - \frac{4\pi}{3}\right) \\ Cos2\left(\theta - \frac{2\pi}{3}\right) & Cos2\left(\theta - \frac{4\pi}{3}\right) & Cos(2\theta) \\ Cos2\left(\theta - \frac{4\pi}{3}\right) & Cos(2\theta) & Cos2\left(\theta - \frac{2\pi}{3}\right) \end{vmatrix}$$

Where :

Ms0 : Mutual inductance between two stator phases,

Ls0 : Self-inductance of a stator phase,

θ : Characterizes the angular position of the rotor relative to the stator.

II.5.5.1.2 Mechanical Equation

The last important equation that completes the model of the permanent magnet synchronous machine and the fundamental equation of mechanics describing the dynamics of the machine's rotor:

$$J\frac{d\omega r}{dt} = Cem - \qquad \text{(II.41)}$$

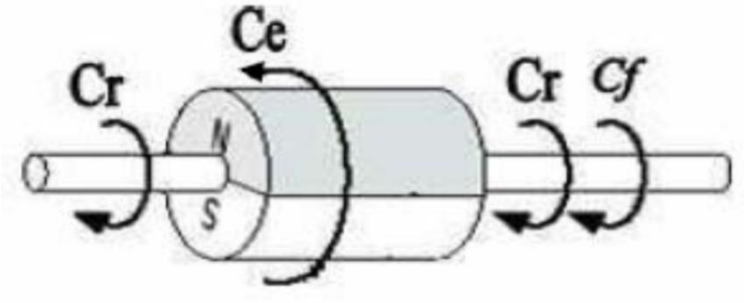


Fig. II.11. Different torques that act on the rotor.

Analytical study of the behaviour of equations (II.38) and (II.39) is relatively laborious, given the large number of variable coefficients. Mathematical transformations are then used to describe the behaviour of the motor using differential equations with constant coefficients. One such transformation is the Park transformation [5].

II.5.5.2. Park Transformation [6][7]

The two-phase model of the MSAP is achieved by transforming the real three-phase frame into a fictitious two-phase frame. This transformation is essentially a change of basis for the physical quantities (voltages, fluxes, and currents), leading to relationships independent of the angle θ and a reduction in the order of the machine equations. The most well-known transformation among electrical engineers is the Park transformation. The (d,q) frame can be fixed to the stator, the rotor, or the rotating field, depending on the application. Figure (II.12) presents the MSAP in the Park model. The (oa) frame is fixed. The (d,q) frame rotates with the synchronous speed ω

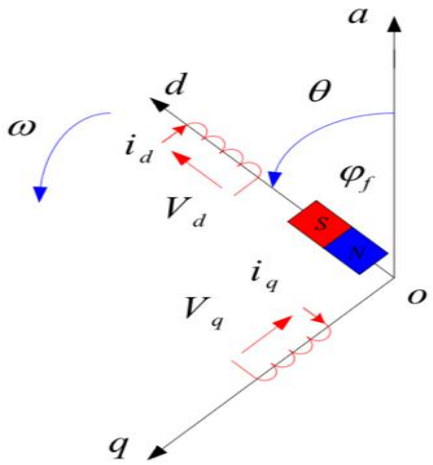


Fig. II.12. Equivalent scheme of the MSAP in the (d,q) frame.

II.5.5.2.1. Direct conversion: three-phases to two-phases

The equation that translates the transition from the three-phase system to the two-phase system (d,q) is given by:

$$[Xdqo] = [p(\theta)][Xabc] \quad \text{(II.42)}$$

With:

$[p(\theta)]$: Park's direct passage matrix,

X : Represents the machine variables under consideration (voltages, currents or fluxes),

X0 : The homopolar component, added to make the transformation reversible, is zero when the system is in equilibrium.

$$[P(\theta)]=\begin{vmatrix} Cos\theta & Cos\left(\theta-\frac{2\pi}{3}\right) & Cos\left(\theta-\frac{4\pi}{3}\right) \\ -sin\theta & -sin\left(\theta-\frac{2\pi}{3}\right) & -\sin(\theta-\frac{4\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix} \quad \text{(II.43)}$$

II.5.5.2.2. Reverse conversion: from two-phase to three-phase

The inverse Park transform is necessary to return to three-phase quantities; it is defined:

$$[Xabc] = [p(\theta]^{-1}[Xdqo]$$

And the inverse change-of-transition matrix of Park $[p(\theta)]^{-1}$ is given by:

$$[p(\theta)]^{-1} = \begin{vmatrix} Cos\theta & -\sin(\theta) & 1 \\ Cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) & 1 \\ Cos\left(\theta-\frac{4\pi}{3}\right) & -\sin\left(\theta-\frac{4\pi}{3}\right) & 1 \end{vmatrix} \quad \text{(II.45)}$$

II.5.5.3. Application of the Park transformation to the MSAP

By applying the Park transformation to the system of equations, all vectors can be expressed in a frame of reference attached to the rotor. After expanding the equations, we obtain a simplified system of equations for the synchronous machine, where the voltage equations are given by:

$$Vd = Rsid + \frac{d\varphi d}{dt} - \omega\varphi q \quad \text{(II.46)}$$

$$Vq = Rsiq + \frac{d\varphi q}{dt} + \omega\varphi d \quad \text{(II.47)}$$

And the flows being given by:

$$\varphi d = Ldid + \varphi f$$

$$\Phi q = Lqiq$$

Substituting the expressions for the fluxes φd and φq into system (II.48) we obtain:

$$Vd = Rsid = Ld\frac{did}{dt} - \omega Lqiq \qquad \text{(II.48)}$$

$$Vq = Rsiq + Lq\frac{diq}{dt} + \omega(Ldid + \varphi f)$$

The electromagnetic torque is expressed as the partial derivative of the electromagnetic energy with respect to the geometric angle of rotation of the rotor as follows:

$$Cem = \frac{dwe}{d\theta geo} = p\frac{dwe}{d\theta} \qquad \text{(II.49)}$$

According to Park, the transmitted expression is as follows:

$$P(t) = \frac{3}{2}(Vdid\ + Vqiq) \qquad \text{(II.50)}$$

By replacing Vd, Vq with their expressions, we will have:

$$P(t) = \frac{3}{2}[Rs(id^2 + iq^2) + \left(\frac{d\varphi d}{dt}id + \frac{d\varphi q}{dt}iq\right) + \frac{d\theta}{dt}(\varphi diq - \varphi qid) \qquad \text{(II.51)}$$

- $\frac{3}{2}Rs(id^2 + iq^2)$: represents the power dissipated as Joule losses in the stator windings,
- $\left(\frac{d\varphi d}{dt}id + \frac{d\varphi q}{dt}iq\right)$: represents the variation of magnetic energy stored in the stator windings,
- $(\varphi diq - \varphi qid)$: represents electromagnetic power

Knowing that :

$$Pe = Cem\ \omega r \qquad \text{(II.52)}$$

It Comes:

$$Cem = \frac{3}{2}\ P(\varphi d\ iq - \ \varphi q\ id) \qquad \text{(II.53)}$$

The expression for electromagnetic torque as a function of currents is as follows:

$$Cem = \frac{3}{2}p[(Ld - Lq)id\ iq + iq\ \varphi f] \qquad \text{(II.54)}$$

La représentation fonctionnelle du modèle de Park du MSAP est illustrée sur la Figure (II.13) :

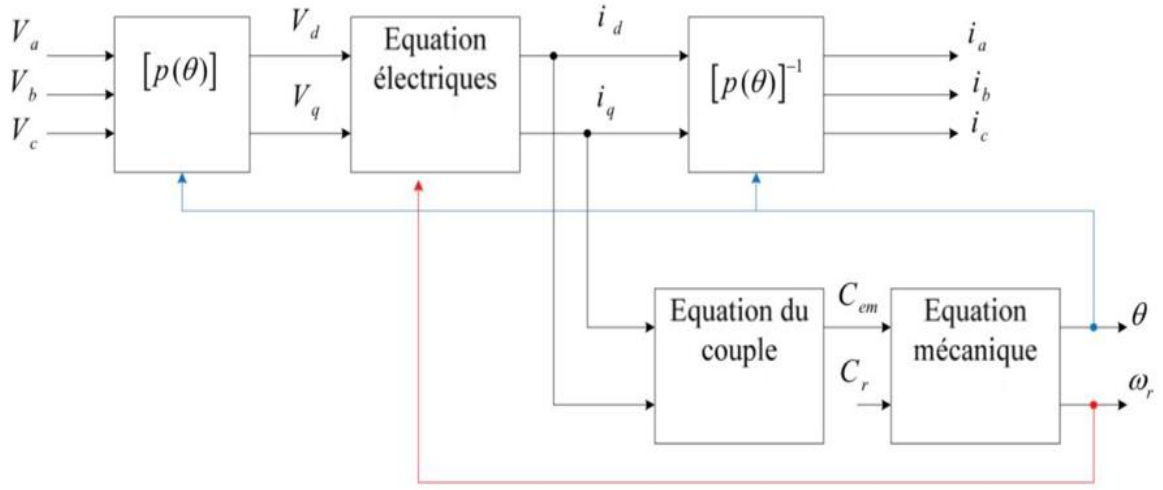


Fig. II.13. Functional diagram of Park's model

II.6. The power electronics converter

An inverter is a static converter capable of transforming the electrical energy from a direct current (DC) voltage source into alternating current (AC) electrical energy. Inverters have a wide range of applications in industry, such as variable speed drives for three-phase motors, backup power supplies, etc. Thanks to technological advancements in semiconductors and the emergence of new control techniques, inverters have become more efficient. Furthermore, the output voltage waveform of an inverter should be as close as possible to a sinusoid with the lowest possible harmonic distortion. This depends largely on the control technique used [1] [23][24]. There are several types of inverters:

- According to the source :
  - Voltage inverters,
  - Current inverters.
- According to the number of phases (single-phase, three-phase, etc.),
- According to the number of levels (2, 3, etc.).

II.6.1. PWM rectifier model

The voltages generated by the GSAP are transmitted to the first electronic power converter on the stator side (the rectifier), which converts the alternating voltage into direct voltage to obtain an average direct voltage used to power the inverter. A three-phase rectifier regulates the power captured by the turbine by managing the GSAP. To improve current quality, a sinusoidal-triangle PWM rectifier (ST-PWM) is used. This rectifier reduces higher-order harmonics. The chosen rectifier consists of three independent arms, each equipped with two switches: an IGBT and an antiparallel diode make up one switch, as shown in Figure II.14.

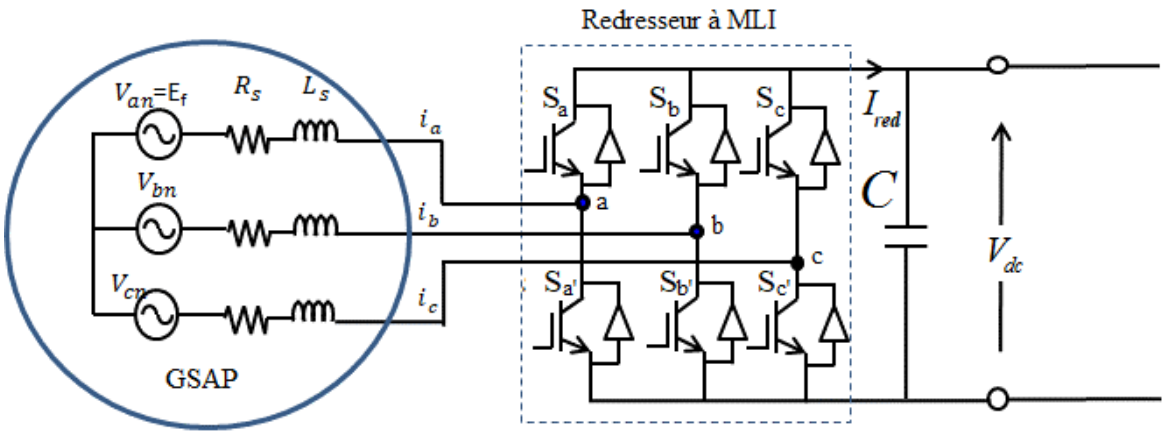


Fig. II.14. Operating diagram of the three-phase PWM-ST rectifier

The rectifier is controlled by PWM control signals Si: (i = a, b, c). Transistors Ti and Ti' are assumed to be ideal switches, and their states are defined as follows:

$$S_i = \begin{cases} +1\ ;\ T_i\ is\ closed\ and\ T_{i'}\ is\ open \\ 0\ ;\ T_i\ is\ open\ and\ T_{i'}\ is\ closed \end{cases}$$

The voltages at point 0 and the currents as a function of the control signals are written as follows:

$$v_{io} = S_i . v_{dc}\ \ ;\ \ i'_{S_i} = S_i . i_{S_i} \qquad \text{(II-66)}$$

The rectified current is obtained according to Kirchhoff's current law by the following equation:

$$i_{red} = i'_{S_a} + i'_{S_b} + i'_{S_c} = S_a . i_{S_a} + S_b . i_{S_b} + S_c . i_{S_c} \qquad \text{(II-67)}$$

The rectifier voltages are obtained according to Schale's relation by the following equation:

$$\begin{cases} v_{an} = v_{ao} + v_{on} \\ v_{bn} = v_{bo} + v_{on} \\ v_{cn} = v_{co} + v_{on} \end{cases} \qquad \text{(II-68)}$$

We aim to determine the rectifier model based on the control signals, so the entire expression must be written in terms of the S_i values: Let's start with the voltages v_{ao},$v_{bo}$and v_{co}. The voltages at point 0 as a function of the control signals are given by the following relationship:

$$\begin{cases} v_{ao} = S_a . v_{dc} \\ v_{bo} = S_b . v_{dc} \\ v_{co} = S_c . v_{dc} \end{cases} \qquad \text{(II-69)}$$

Now for the voltage v_{on} . We assume the system is symmetrical, therefore:

$$v_{an} + v_{bn} + v_{cn} = 0 \qquad \text{(II-70)}$$

$$(S_a . v_{dc} + v_{on}) + (S_b . v_{dc} + v_{on}) + (S_a . v_{dc} + v_{on}) = 0 \qquad \text{(II-71)}$$

Finally:

$$v_{on} = -\frac{v_{dc}}{3}(S_a + S_b + S_c) \qquad \text{(II-73)}$$

Substituting equations (II-69) and (II-70) into the rectifier voltage equation (II-68), we obtain:

$$\begin{cases} v_{an} = \frac{v_{dc}}{3}(2S_a - S_b - S_c) \\ v_{bn} = \frac{v_{dc}}{3}(2S_b - S_a - S_c) \\ v_{cn} = \frac{v_{dc}}{3}(2S_c - S_a - S_c) \end{cases} \qquad \text{(II-74)}$$

Therefore, the rectifier model becomes:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{v_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad \text{(II-75)}$$

III.6.2. The importance of coupling the rectifier with the GSAP

The speed of the GSAP varies due to variations in wind speed. The relationship between the speed of the GSAP and the frequency of the generated AC voltage is given by: N = 60f/p. Therefore, the frequency of the generated voltage is proportional to the rotation speed; as this speed varies, so does the frequency. This makes direct connection to the 50 Hz grid impossible, so it is necessary to use an AC/DC rectifier to eliminate this variable frequency, followed by an inverter to adapt to the grid.

III.6.3. DC bus modeling

The DC bus located between the rectifier and the inverter is essential for transferring electrical energy as direct current (DC), while stabilizing this voltage with the help of a capacitor. It is modeled as a capacitor C connected between two terminals of the DC bus, as illustrated in Figure II.15.

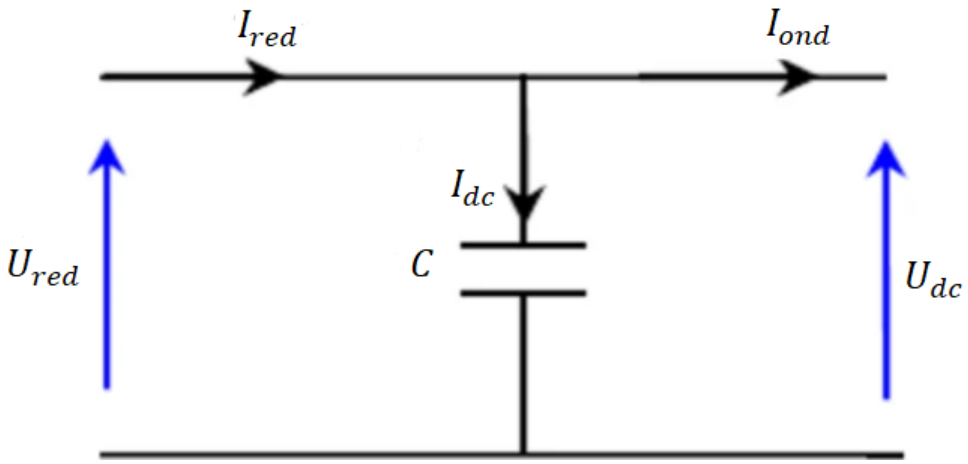


Fig. II.15. Electrical diagram of the continuous bus

The capacitor is considered a filter to smooth out voltage fluctuations due to current variations. The relationship between the DC bus voltage and the current through the capacitor is as follows:

$$U_{dc} = \frac{1}{C}\int I_{dc}dt \qquad \text{(II-76)}$$

With : $I_{dc} = I_{red} - I_{ond}$ (II-77)

II.7. Conclusion

In this chapter, a comprehensive mathematical model of the Wind Energy Conversion System (WECS) has been developed, covering the entire energy conversion chain from the aerodynamic subsystem to the electrical energy conversion stage. The modeling process began with the representation of the wind characteristics, wind turbine aerodynamics, and mechanical drive train components. These models provide an accurate description of the system dynamics and enable the analysis of the mechanical phenomena that influence energy extraction and overall system performance.

Subsequently, the mathematical model of the Permanent Magnet Synchronous gerator (PMSG) was established, together with the associated power electronic converter. This electrical subsystem plays a crucial role in converting the mechanical energy captured by the turbine into electrical energy while ensuring efficient power transfer and adaptability to varying operating conditions.

To ensure effective control of the power conversion stage, a sinusoidal Pulse Width Modulation (SPWM) strategy was developed for the inverter. This control technique enables precise regulation of the output voltage and current while improving the quality of the electrical power supplied to the load or grid. The proposed control approach contributes to reducing harmonic distortion and enhancing the overall performance of the conversion system.

The work presented in this chapter establishes a solid theoretical and simulation framework for further investigations. It provides the necessary basis for the next chapter, which will focus on advanced control strategies, performance enhancement, and the analysis of the WECS under various operating and grid conditions.

References-Chapter 2

[26]	Adaika Zineb and Tebbal Riadh AbdelHalim ;''La Commande non linéaire adaptative d'une machine synchrone à aimants permanents'', Master Dessertation,High School on applied Sciences, 2021
[27]	Jingyao Peng and Ming Yao,'' Overview of Predictive Control Technology for Permanent Magnet Synchronous Motor Systems ''; Applied Sciences, 2023.
[28]	S. Karthikeyan, C. Ramakrishnan ; ''A hybrid fuzzy logic-based MPPT algorithm for PMSG-based variable speed wind energy conversion system on a smart grid'', Energy Storage and Saving,Volume 3, Issue 4, Pages 295-304,December 2024,
[29]	Boussekra Fayza; ''Commande sans Capteur de Vitesse de la Machine Synchrone ''. Thèse de Doctorat; Université de Batna 2; 2022.
[30]	Mamenia Nour-Eddine Aymen et Bourahla Abdenour ; '' Etude de l'association d'un générateur synchrone à aimant permanent à un redresseur à diodes ou MLI alimentant un bus de tension continue'' ; Higher School In Applied Sciences, Tlemcen,2025.
[31]	Segueni Ali ; '' Commande vectorielle de la machine synchrone a aimants permanents'', mémoire de Master, Université Mouloud Maamri, Tizi-Ouzou , 2024.
[32]	Abdelaziz Belhait, Sihem Ghoudelbourk, G. Boukhalfa, Abdessmad Milles, '' Comparative Study of Three Types of MPPT Controllers for a Wind Energy Conversion System,''; International Conference on Electrical Engineering and Automatic Control (ICEEAC),2024.



Chapter III

Strategies and Control Techniques of wind energy conversion system

III.1. Introduction

The rapid growth of wind energy as a major renewable energy source has increased the need for advanced control strategies capable of improving the performance, efficiency, and reliability of Wind Energy Conversion Systems (WECS). Due to the inherently variable and unpredictable nature of wind, wind turbines operate under continuously changing environmental conditions. Consequently, effective control techniques are essential to maximize energy capture, ensure system stability, reduce mechanical stress, and maintain the quality of the electrical power delivered to the grid [1][2].

Modern wind energy conversion systems are complex electromechanical structures composed of aerodynamic, mechanical, electrical, and power electronic subsystems. The interaction among these subsystems requires sophisticated control algorithms capable of regulating turbine operation over a wide range of wind speeds. These control techniques aim not only to maximize power extraction under low and medium wind conditions but also to protect the system from excessive mechanical and electrical stresses during high wind speeds [3].

One of the primary objectives of wind turbine control is to achieve maximum energy extraction from the available wind resource. This objective is commonly realized through Maximum Power Point Tracking (MPPT) strategies, which continuously adjust the operating conditions of the turbine to maintain the optimal tip-speed ratio and maximize aerodynamic efficiency. In addition, pitch angle control plays a crucial role in regulating turbine power and limiting rotor speed when the wind speed exceeds the rated value [4].

On the electrical side, advanced generator control techniques are employed to regulate torque, speed, voltage, and power flow. For Permanent Magnet Synchronous Generator (PMSG)-based wind energy systems, vector control and field-oriented control methods are widely used due to their fast dynamic response and accurate control capabilities. Furthermore, power electronic converters are controlled using modulation techniques such as Sinusoidal Pulse Width Modulation (SPWM) or Space Vector Pulse Width Modulation (SVPWM) to ensure efficient power conversion and high-quality electrical output [5].

The integration of wind energy systems into modern electrical grids also requires compliance with strict grid code requirements. Therefore, control strategies must provide voltage regulation, frequency support, reactive power compensation, and fault ride-through capabilities while maintaining overall system stability and power quality [6].

The objective of this chapter is to present the main control strategies and techniques employed in the proposed wind energy conversion system. The principles of Maximum Power

Point Tracking, pitch control, generator control, converter control, and inverter modulation techniques are discussed in detail. The mathematical foundations, operating principles, and implementation aspects of these control methods are analyzed to demonstrate their contribution to improving the performance and efficiency of the wind energy conversion system [7].

This chapter provides the theoretical framework necessary for understanding the control architecture adopted in the WECS and serves as a basis for the performance evaluation and optimization studies presented in the subsequent chapters.

III.2. Control Objectives of WECS

The performance of a Wind Energy Conversion System (WECS) is highly dependent on the effectiveness of its control system. Due to the variable and intermittent nature of wind, the operating conditions of a wind turbine continuously change, affecting both the mechanical and electrical behavior of the system. Consequently, advanced control strategies are required to ensure efficient energy conversion, system stability, and reliable operation under different wind conditions.

The primary objective of a WECS control system is to maximize energy production while maintaining safe operation and complying with grid requirements. To achieve these goals, several control functions are implemented at different levels of the system, including aerodynamic control, generator control, converter control, and grid-side control figure III.1. show a general control structure the wind gererator.

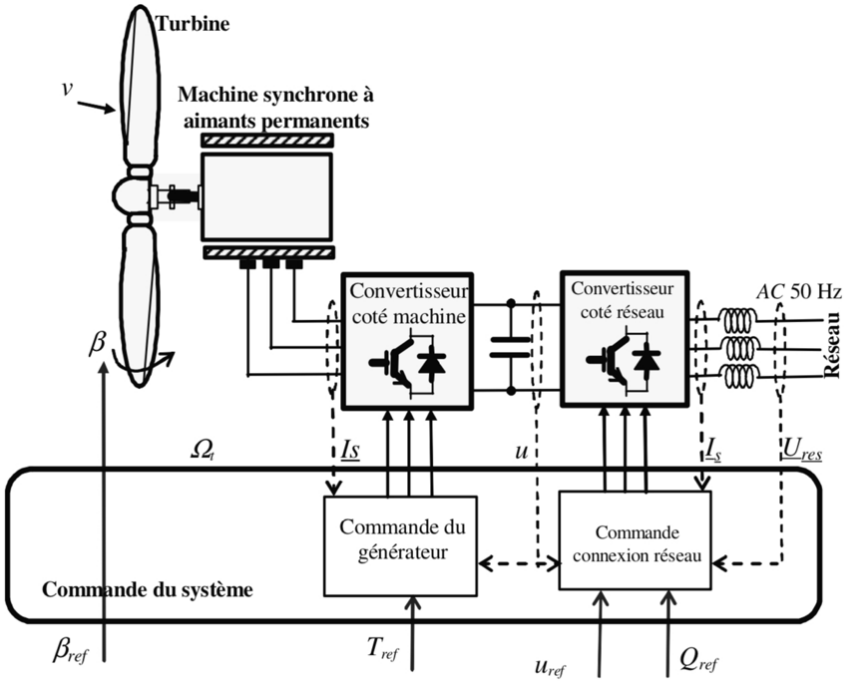


Fig.III.1. Control structure of the wind generator

III.2.1. Maximum Energy Extraction

One of the most important objectives of a WECS is to maximize the amount of energy captured from the wind. To maximize the extracted power, the turbine must operate at the optimal tip-speed ratio corresponding to the maximum value of the power coefficient *(Cp)*. This objective is generally achieved using Maximum Power Point Tracking (MPPT) algorithms. The control system continuously adjusts the generator speed to maintain the turbine at its optimum operating point despite wind speed variations.

III.2.2. Rotor Speed Regulation

Wind speed fluctuations directly affect turbine rotational speed. Excessive rotor speed may lead to mechanical stress and damage to turbine components. Proper speed regulation ensures optimal energy extraction and protects the turbine against excessive mechanical loads. The speed control objective is therefore to:

-Maintain stable rotor operation.

-Track the reference speed generated by the MPPT algorithm.

-Prevent overspeed conditions.

-Improve system dynamic performance.

III.2.3. Power Regulation

Wind turbines are designed to operate at a rated power level above which electrical and mechanical components may be overloaded. Therefore, another important control objective is to regulate the generated power and limit it to the rated value when wind speed exceeds the rated wind speed. This prevents excessive power production and extends the lifetime of system components. The power regulation is generally achieved through:

-Pitch angle control.

-Generator torque control.

-Converter control.

III.2.4. Mechanical Load Reduction

Wind turbulence, gusts, and rapid speed variations generate dynamic mechanical stresses on turbine blades, shafts, and other rotating components. Reducing mechanical stress improves reliability and decreases maintenance requirements. The control system aims to minimize:

-Torsional oscillations.

-Shaft fatigue.

-Blade vibrations.

-Mechanical shock loads.

III.2.5. Generator Torque Control

The generator electromagnetic torque must be properly controlled to ensure efficient energy conversion and stable operation. For PMSG-based systems, torque control is often achieved using field-oriented control techniques operating in the dq reference frame. Accurate torque regulation allows rapid adaptation to wind speed changes while maintaining system stability. The objectives of torque control include:

-Tracking the optimal torque reference.

-Regulating generator speed.

-Maximizing power extraction.

-Improving transient response.

III.2.6. DC-Link Voltage Regulation

In variable-speed wind energy systems, the generator output is connected to the grid through power electronic converters. A DC-link capacitor is generally used between the rectifier and inverter stages.The DC-link voltage must remain constant to ensure proper converter operation. Stable DC-link operation is essential for reliable energy transfer from the generator to the load or grid.The control objectives are:

-Maintain a stable DC voltage.

-Balance input and output power.

-Minimize voltage fluctuations.

-Improve converter performance.

III.2.7. Power Quality Improvement

Modern grid codes impose strict requirements regarding the quality of electrical power delivered by renewable energy systems. Modulation techniques such as Sinusoidal Pulse Width Modulation (SPWM) are widely used to improve power quality and reduce harmonics. The control system must ensure:

-Sinusoidal output voltage.

-Low harmonic distortion.

-Balanced phase currents.

-Stable frequency.

-Voltage regulation.

III.2.8. Active and Reactive Power Control

Grid integration is a critical control objective of WECS. It ensures that wind-generated electricity is delivered efficiently, safely, and in compliance with grid standards while

maintaining power quality, voltage stability, and frequency regulation. As wind power penetration increases, advanced control strategies, power electronics, and energy storage systems become increasingly important for reliable grid operation.

In grid-connected wind energy systems, active and reactive power must be controlled independently. These capabilities facilitate the integration of wind energy into modern power systems. The control objectives include:

- **Active Power Control**
  -Maximize power generation.
  -Follow grid operator commands.
  -Contribute to frequency regulation.
- **Reactive Power Control**
  -Support grid voltage.
  -Improve power factor.
  -Enhance network stability.

III.2.9 Grid Integration

Grid integration refers to the process of connecting a wind energy conversion system to the electrical power grid while ensuring stable, reliable, and high-quality power delivery. The Objectives of Grid Integration.

1. **Maintain Grid Stability**
   -Keep voltage and frequency within acceptable limits.
   -Support the grid during disturbances.
2. **Deliver Quality Power**
   -Minimize harmonics and voltage fluctuations.
   -Ensure smooth and consistent power output.
3. **Control Active and Reactive Power**
   -Active power controls the real energy delivered to the grid.
   -Reactive power supports voltage regulation and improves power factor.
4. **Meet Grid Code Requirements**
   -Comply with utility regulations regarding voltage, frequency, fault ride-through, and power quality.

III.2.10. Safe Operation and Protection in WECS

Safe operation and protection are essential control objectives of a WECS to ensure the safety of personnel, protect equipment from damage, and maintain reliable power generation under normal and abnormal operating conditions. The objectives are:

-Prevent damage to turbine components.
-Ensure safe operation during extreme weather conditions.
-Protect electrical and mechanical systems from faults.

-Minimize downtime and maintenance costs.

-Enhance the overall reliability and lifespan of the wind turbine.

- **Protection Functions**

1. Overspeed Protection

-Prevents the rotor from rotating beyond its safe speed limit.

-Excessive rotor speed can damage blades, gearbox, and generator.

-Achieved through:

- Blade pitch control
- Mechanical brakes
- Electrical braking systems

2. Overload Protection

-Protects the generator, converter, and transformer from excessive current or power.

-Limits power output when operating conditions exceed rated values.

3. High Wind Speed Protection

-When wind speed exceeds the cut-out speed (typically around 20–25 m/s), the turbine is shut down.

-Blades are pitched to a feathered position to reduce aerodynamic forces.

4. Temperature Protection

-Monitors temperatures of:

- Generator
- Gearbox
- Bearings
- Power electronic converters

-Initiates alarms or shutdown if temperatures exceed safe limits.

5. Vibration Monitoring

-Detects abnormal vibrations caused by:

-Blade imbalance

-Mechanical wear

-Structural faults

-Excessive vibration triggers protective actions or shutdown.

6. Electrical Fault Protection

Protects against:

-Overcurrent

-Short circuits

-Ground faults

-Overvoltage and undervoltage

-Frequency deviations

7. Lightning Protection

-Wind turbines are highly exposed to lightning strikes due to their height.

-Lightning receptors and grounding systems safely dissipate lightning currents.

8. Emergency Shutdown System

-Activated during severe faults or emergency situations.

-Stops turbine operation rapidly and safely.

Uses mechanical brakes and blade pitch mechanisms.

III.3. Wind turbine control strategies

III.3.1. Pitch control

Equipment efficiency can be improved by controlling rotor speed. Rotor distortion and oscillations lead to higher system costs. The goal of pitch control is to achieve an optimal angle of wind incidence on the pitch. When wind speed exceeds the permissible level, the blades orient themselves in a direction appropriate to the wind speed to reduce its effect [12]. Pitch control prevents the imposition of wind power exceeding the equipment's tolerance. By controlling the pitch at high wind speeds, the aerodynamic load and the power generated by the rotor are adjusted. This also helps minimize mechanical fatigue of the wind turbine components [13].

Pitch control allows the pitch angle of a wind turbine's blades to be adjusted to regulate its aerodynamic efficiency. The pitch angle is a key parameter of the wind turbine, as it determines the angle of attack of the wind [14][15]. Thus, rotating the blades around their own axis modifies the relative airflow and, consequently, the aerodynamic loads exerted on the rotor. Furthermore, the power coefficient varies with the pitch angle, which also results in a variation in the power captured [16].

By using Pitch Control, the power coefficient Cp is no longer adjusted as a function of λ as before, but rather as a function of wind speed at a constant rotational speed [17]. This allows the power to be maintained constant in Zone III (Figure III.2) at its maximum value. It should be noted that to adjust the pitch angle in the Pitch Control system, an electronic controller is required, equipped with either centrifugal weights or servomotors [18], The effective power transmitted by the wind speed is shown in figure III.2,thus enabling figure:

- Start-up at a reduced wind speed Vd.

- Regulation of the turbine's angular speed Ωt for wind speeds exceeding the nominal speed.

- Optimization of the energy conversion regime as the wind speed varies between Vd and Vn.

- Protection of the wind turbine against high wind speeds (>Vmax) by feathering the blades, without requiring a powerful braking system for emergency stops.

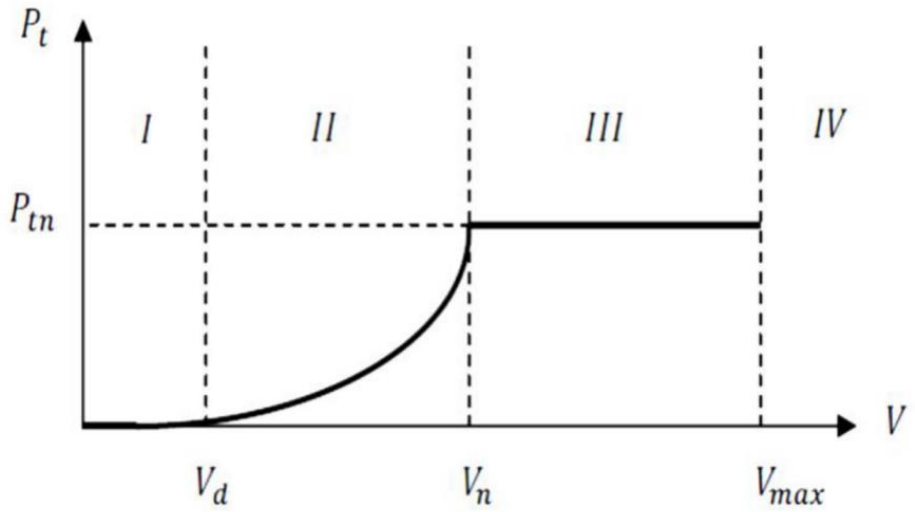


Fig.III.2. The effective power transmitted by the wind speed

- **Zone I:** The wind turbine starts operating at the connection wind speed, at a rotational speed Ωt-min.
- **Zone II:** When the generator speed is between Ωmin and Ωnom, a control algorithm is applied to extract the maximum power from the wind. The maximum power coefficient in this case corresponds to an optimal and constant pitch angle.
- **Zone III:** This zone corresponds to the case where the nominal rotational speed is reached, while the generated power reaches significant values but is lower than the nominal power.
- **Zone IV:** Upon reaching the nominal power, a pitch control system is applied to limit the generated power.

III.3.2. MPPT (Maximum PowerPoint Tracking) Strategy

Maximum Power Point Tracking (MPPT) aims to maintain the wind turbine at its maximum power point despite wind variability by adjusting the speed or torque set point of the converter system in real time. Traditional methods rely on hill-climbing techniques (Perturb & Observe, Hill Climb Search) or maintaining the optimal Tip Speed Ratio (TSR), while advanced approaches leverage fuzzy logic, neural networks, predictive control (MPC),

or reinforcement learning to improve speed, robustness, and oscillation reduction. Hybrid schemes combining several techniques make it possible to reconcile simplicity, performance, and resilience to disturbances.

III.3.2.1. Principles and objectives of the MPPT

The goal of MPPT is to continuously monitor the operating point that maximizes the power extracted from the wind turbine, defined by the power coefficient curve Cp(λ). The discrepancy between wind speed and engine speed necessitates a dynamic adjustment of the generator's torque or speed set point. MPPT contributes to increasing the overall system efficiency, reducing mechanical stresses, and stabilizing power injection into the grid under variable conditions.

III.3.3. Indirect power control technique

III.3.3.1. MPPT algorithm based on the blade tip speed ratio (TSR)

The TSR algorithm maintains the ratio between rotor speed and blade tip speed at an optimal value to achieve maximum power output, regardless of wind fluctuations [19, 20]. Although the controller is simple to implement, its operating cost is high. Such an approach requires accurate wind speed estimation, which increases the system's complexity and cost.

The application of an efficient wind speed evaluator, enabling maximum power extraction in commercial wind turbines, is implemented and investigated by optimizing the basic industrial controller through TSR monitoring and optimal pitch angle adjustment [21].

The TSR and optimal torque (OT) methods are tested on a 1.5 MW wind turbine model to determine their efficiency under different wind speed conditions. Comparative tests reveal that, under all wind conditions, the TSR control system extracts relatively more wind energy, but at the cost of significant loads on the components, compared to the other method. Moreover, the two control methods exhibit similar trends in power reduction, which is relevant depending on wind speed and turbulence intensity [22].

The proposed strategy is based on the Model Reference Adaptive Control (MRAC) method using the TSR. This adaptive control method yields better results than traditional methods [23]. An Integral Sliding Mode Voltage Regulation (ISMVR) method is used to improve the efficiency of the MPPT technique. This method is proposed for the TSR-based MPPT technique. It allows for fast and robust tracking. Furthermore, to generate the control signal, it is not necessary to know the generator parameters [24]. Figure III.3 shows the block diagram of a Wind Energy Conversion System using TSR control.

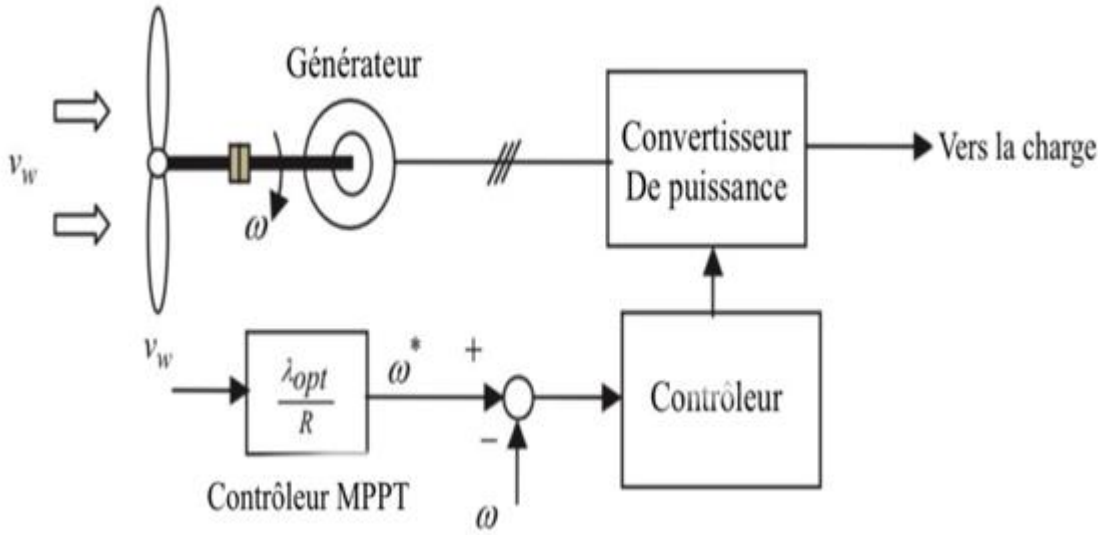


Fig.III.3. Tip speed ratio control of wind power conversion system

III.3.3.2. Power signal feedback technique (PSF)

In the power signal feedback (PSF) control technique, it is necessary to know the maximum power curve of the wind turbine and to track this curve using suitable control mechanisms [25]. Maximum power curves must be obtained through simulations or offline tests performed on each wind turbine individually [25]-[26]. In this method, the reference power is generated either from a recorded maximum power curve or using the mechanical power equation of the wind turbine, taking the wind speed or rotor speed as input [27]. Figure III.4 shows the block diagram of a wind power conversion system with a PSF controller for maximum power extraction.

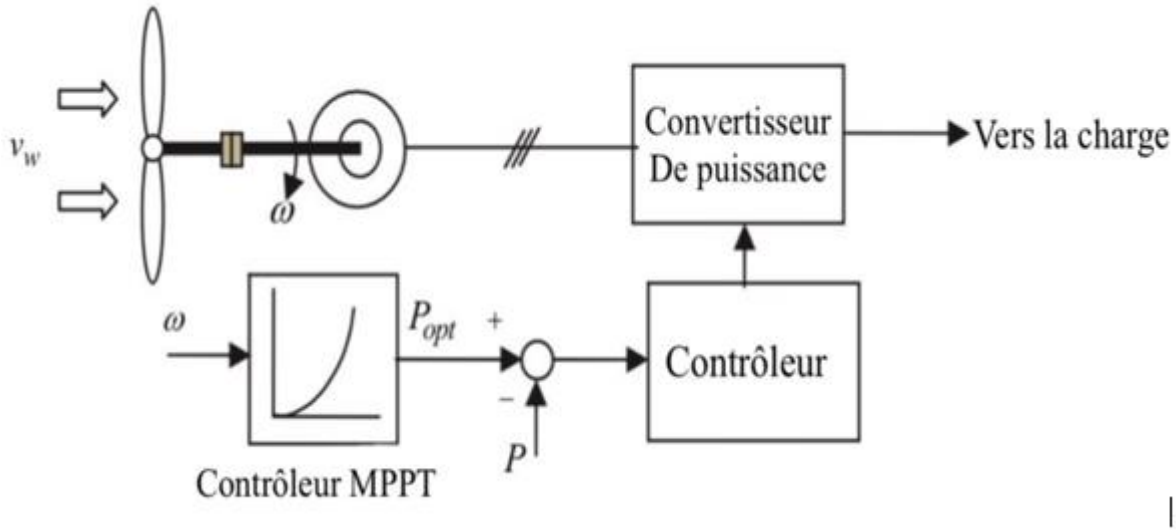


Fig.III.4. Power signal feedback technique de control.

III.3.4. Direct power control technique

III.3.4.1. Hill climb search technique (HCS)

The Hill Climb Search (HCS) control algorithm continuously searches for the maximum power point of the wind turbine. It overcomes some of the problems commonly associated with the other two methods [28]. The tracking algorithm, based on the position of the operating point and the relationship between power and speed variations, calculates the optimal signal needed to drive the system to the maximum power point. Fig. III.5 illustrates the principle of HCS control, and Fig. III.6 shows a wind energy conversion system (WECS) equipped with an HCS controller for tracking maximum power points [29].

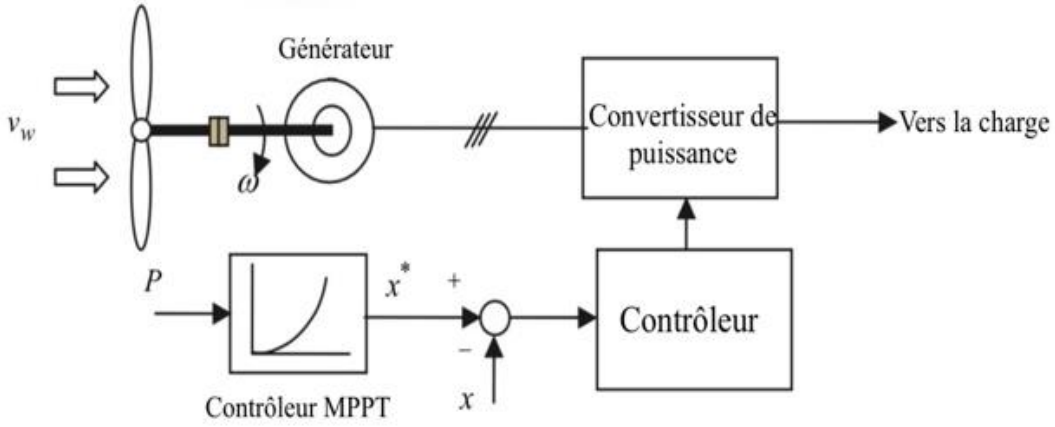


Fig. III.5. Principe de la commande HCS.

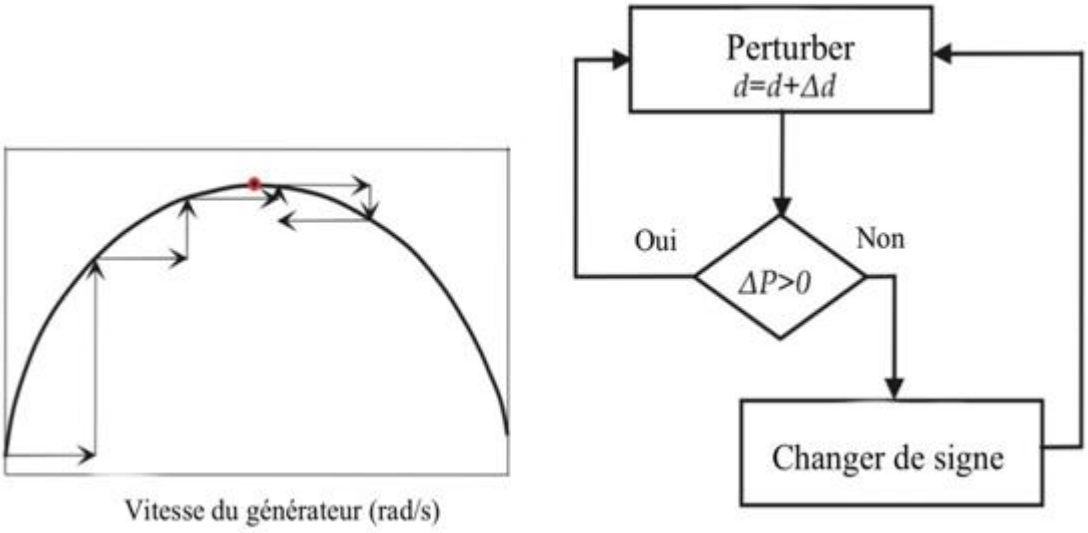


Fig.III.6. Wind energy conversion system with HCS control

III.3.4.1. Perturb and Observe Algorithm(PO)

The PO algorithm is highly regarded for its simple implementation and low cost. This algorithm measures the output current of the previous cycle, generates the correct phase for the next cycle, and adjusts various parameters such as the duty cycle and input voltage [28]. This technique fails to keep pace with wind speed fluctuations. Several modified versions of PO have been implemented to overcome the drawbacks of traditional PO [29, 30].

An advanced version of the PO technique is presented for finding optimal power in wind power systems. This MPPT method provides an initial power demand based on error-driven control. It uses smart stored data to control the inverter and extract maximum power without needing to know the turbine characteristics [31].

III.4. Control Strategy of the MSAP

III.4.1. Vector control of the MSAP supplied with voltage

Controlling AC machines is difficult due to the complex coupling between flux and torque. This difficulty has encouraged the development of several control techniques to make these machines behave like DC machines, characterized by a natural decoupling of flux and torque. Among these control techniques, vector control is the best known [32].

III.4.2. Principle of vector control:

The fundamental idea of this strategy is to model the behaviour of the synchronous machine as that of a DC machine, i.e., a linear and decoupled model, which improves its dynamic behaviour [33][34]. Equation (III.1), gives the torque, shows that it depends on two variables id, iq.

$$Cem = \frac{3}{2}P\big((Ld - Lq)id\ iq + \ iq\ \varphi f\big) \qquad \text{(III.1)}$$

Among the control strategies, one often used is to maintain the id component at zero. This strategy allows for a simplified control law with a linear relationship between torque and current. The resulting characteristic is similar to that of a separately excited DC machine [35]. The expression for torque becomes:

$$Cem = \frac{3}{2}P\varphi f\ iq \qquad \text{(III.2)}$$

Since the flux φf is constant, the torque is directly proportional to iq. Therefore:

$$Cem = Kt\ iq \quad \text{(III.3)}$$

With :

$$Kt = \frac{3}{2} p\ \varphi f \quad \text{(III.4)}$$

We observe that the torque equation is analogous to that of the separately excited DC machine torque and that independent control of torque and flux is established

III.4.2.1. Decoupling

The synchronous machine model in the Park frame leads to a system of differential equations where the currents id and iq are not independent of each other. They are related by nonlinear terms Lq ωiq and Ld ωid.

$$Vd = \left(Rs\ id + Ld\frac{did}{dt}\right) - \omega Lq\ iq \quad \text{(III.5)}$$

$$Vq = \left(Rs\ iq + Lq\frac{diq}{dt}\right) + \omega(Ld\ id + \varphi f) \quad \text{(III.6)}$$

This coupling is eliminated by a compensation method. This method consists of adding terms to make the d and q axes completely independent.

III.4.2.1.1. Decoupling by compensation

The purpose of compensation, therefore, is to decouple the d and q axes. This decoupling allows for a simpler writing of the machine and control system equations, thus facilitating the calculation of the controller coefficients. The principle of this decoupling involves defining two new control variables, ed and eq, represented in Figure (III.7) as follows:

$$Vd = Vd1 - ed \quad \text{(III.6)}$$

$$Vq = Vq1 + eq$$

With :

$$Vd1 = Ld\frac{did}{dt} + Rs\ id \quad \text{(III.7)}$$

$$Vq1 = Lq\frac{diq}{dt} + Rs\ iq$$

and :

$$ed = Lq\ \omega iq \qquad \text{(III.8)}$$

$$eq = \omega(Ld\ id + \varphi f)$$

Therefore, the currents id and iq are decoupled. The current id depends only on Vd1 and iq depends only on Vq1. From equation (III.7), the currents id and iq can be written as follows:

$$id = \frac{Vd1}{Rs+pLd} \qquad \text{(III.9)}$$

$$iq = \frac{Vq1}{Rs+pLq}$$

p : Opérateur de Laplace. Laplace operator.

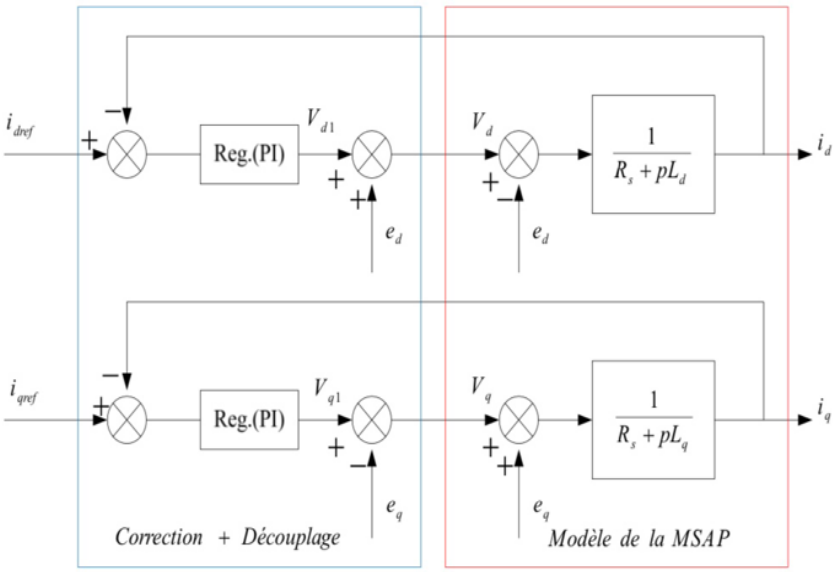


Fig. III.7. Decoupling by compensation

The actions on the d and q axes are therefore decoupled and represented by Figure III.8.

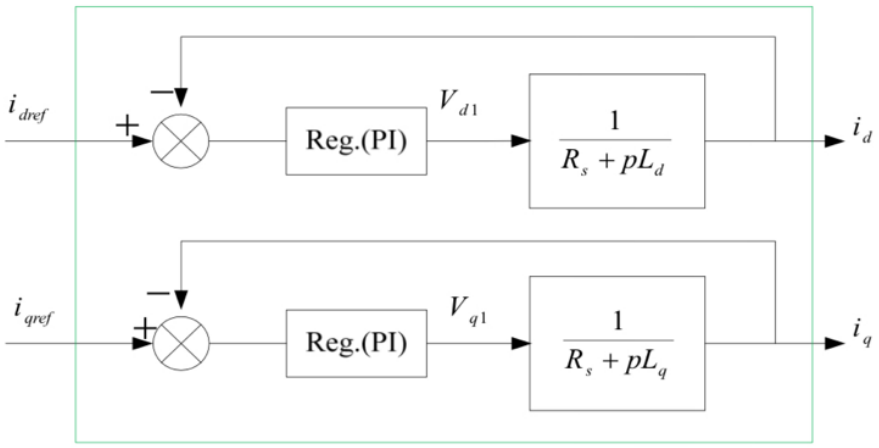


Fig.III.8. Decoupled control.

III.4.3. Description of the overall system

Since the machine is decoupled along two axes (d, q), regulation along the d axis is achieved by a single loop, while regulation along the q axis is achieved by two cascaded loops: an internal loop to regulate the current and an external loop to regulate the speed.

The speed is regulated through the external loop. The output of its regulator generates the reference current iqref, which is compared to the value of the current iq obtained from the measurement of the actual currents and their error, applied to the input of the current regulator iq. In parallel with this loop, there is a current regulation loop id, which is maintained at zero.

The outputs of the current regulators idet iq are applied to a decoupling block which generates the reference voltages Vdref and Vqref. By transitioning from the (d, q) to the (α, β) frame, this provides the two reference voltages Vαref and Vβref for the Vector PWM (Simultaneous Vectoring) control of the voltage inverter [33].

Figure III.9 shows the overall diagram of the vector speed control of a permanent magnet synchronous machine in the (d, q) frame.

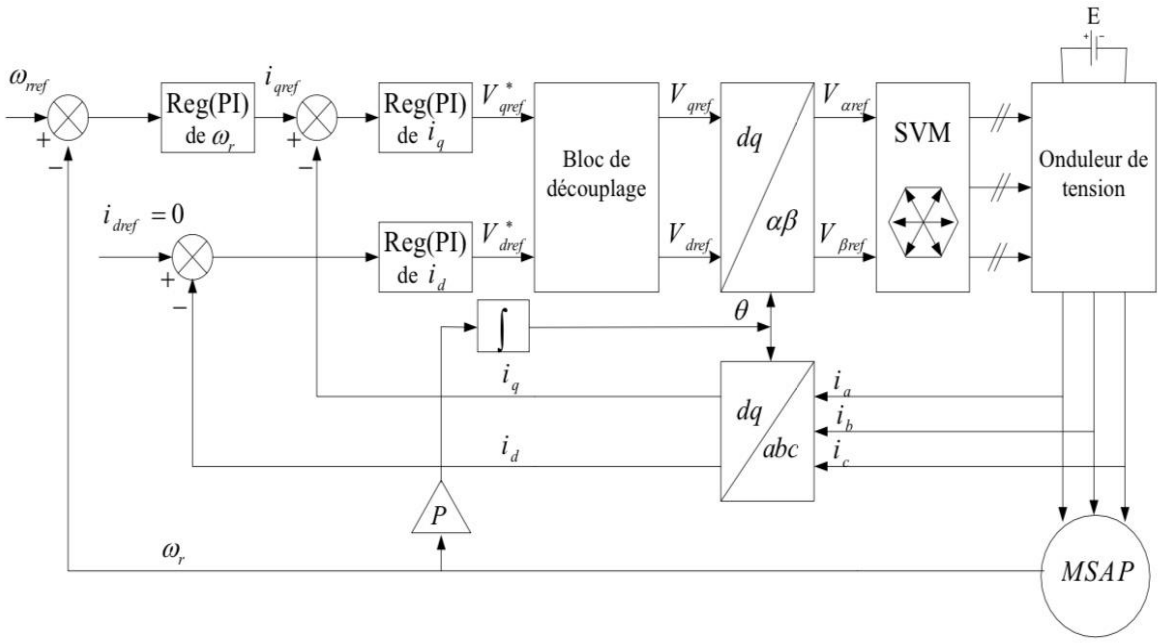


Fig. III.9. Overall diagram of the MSAP vector control.

III.5. Proportional and Integral (PI) control of WECS

Figure III.10, shows the control strategy of maximum torque angle control for MPPT. The control algorithm is conducted by generator side power converter through an inner current control loop and an outer speed control loop. By using the PI (Proportional and Integral) controller, the q-axis reference current is derived.

III.5.1. Current and Speed Controller

This section introduces the conventional Proportional-Integral (PI) control algorithm. Controller design method and control parameters tuning method are presented. There are three PI controllers are used in this control strategy. This PI control method is based on linear control ideas; any nonlinear items would be neglected in the control loop Figure III.10. The compensation items are added to improve the system dynamic behaviour [34]

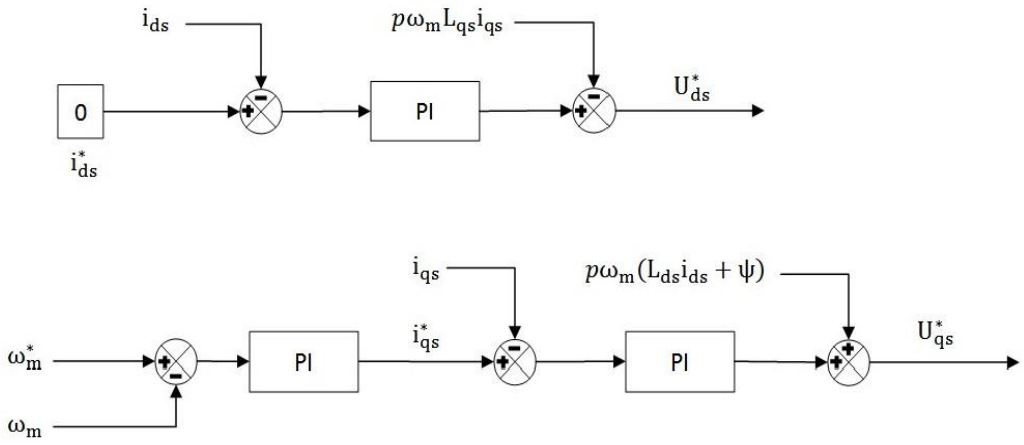


Fig.III.10. PI control scheme for current control

III.6. Sliding mode control (SMC) of WECS

Sliding Mode Control (SMC) is a robust nonlinear control technique extensively and widely applied in Wind Energy Conversion Systems (WECS) to address the challenges posed by wind variability, model uncertainties and due to its because of its robustness against parameter variations and model uncertainties, and external disturbances such as fluctuating wind speeds. SMC provides fast dynamic response, strong disturbance rejection, and robustness against parameter variations, making it suitable for controlling wind turbine rotor speed, generator torque, pitch angle, and grid-side converters. The main idea of SMC is to force the system states to reach and remain on a predefined sliding surface, ensuring desired system performance despite uncertainties. It is used in Wind turbines because it operates under highly

variable conditions due to: Wind speed fluctuations; Aerodynamic uncertainties; Mechanical parameter variations; Grid disturbances. SMC provides [35]:

- Fast dynamic response
- Strong robustness
- Good tracking performance
- Reduced sensitivity to disturbances

III.6.1. Control Objectives of SMC in WECS

1. Maximum Power Point Tracking (MPPT)
   - Extract maximum energy from the wind at below-rated wind speeds.
2. Rotor Speed Control
   - Maintain optimal rotor speed.
3. Generator Torque Control
   - Regulate electromagnetic torque for efficient operation.
4. Power Regulation
   - Maintain rated power at high wind speeds.
5. Grid-Side Control
   - Control active and reactive power injected into the grid.

III.6.2. Principle of Sliding Mode Control [36] [37]:

- Step 1: Tracking Error

  Let : $e = x - x_{ref}$

  where:

  (x) = actual state

  (x_{ref}) = desired reference state

- Step 2: Sliding Surface

  A common sliding surface is: $s=e+\lambda\dot{e}$

Where :

- S= Sliding surface
- e = tracking error
- $\lambda > 0$ = design parameter

The control objective is: $S = 0$

- Step 3: Design Control Law

The SMC control law is generally: $u=u_{eq}+u_{sw}$

Where :

- u_{eq} = equivalent control
- u_{sw} = switching control

A common switching term is: $u_{sw} = -K\ sign(s)$

Where:

- (K) = positive gain
- Sign(s) = switching function

SMC regulates turbine speed to maintain the optimal tip-speed ratio. Maintaining the optimal λ maximizes power extraction.The tip-speed ratio is:

$$\lambda=\omega rR\backslash Vw$$

Where :

- ωr= rotor speed
- R= blade radius
- Vw = wind speed

Sliding Mode Control is a powerful nonlinear control method for WECS. It provides robust and reliable control of rotor speed, generator torque, pitch angle, and grid-side converters under uncertain and rapidly changing wind conditions. Due to its excellent disturbance rejection and tracking capabilities, SMC is widely used in modern variable-speed wind energy systems, often with chattering-reduction techniques to improve practical performance[38][39]:. SMC adjusts generator torque to track the reference torque and maintain maximum power extraction. At high wind speeds, SMC controls the blade pitch angle to:

- Limit aerodynamic power
- Prevent over speed
- Reduce structural loads

III.6.3. Advantages of SMC in WECS

- Robust against parameter uncertainties.
- Effective under varying wind conditions.
- Fast transient response.
- Good disturbance rejection.
- Simple implementation compared to some advanced nonlinear controllers.

III.6.3. Disadvantages of SMC in WECS

- Chattering phenomenon: high-frequency oscillations caused by switching action.
  - May cause mechanical wear in actuators.
  - Requires careful tuning of control gains.
- Chattering Reduction Methods
  - Boundary layer approach
  - Saturation function
  - Higher-order sliding mode control
  - Adaptive sliding mode control

Sliding Mode Control is a powerful nonlinear control method for WECS. It provides robust and reliable control of rotor speed, generator torque, pitch angle, and grid-side converters

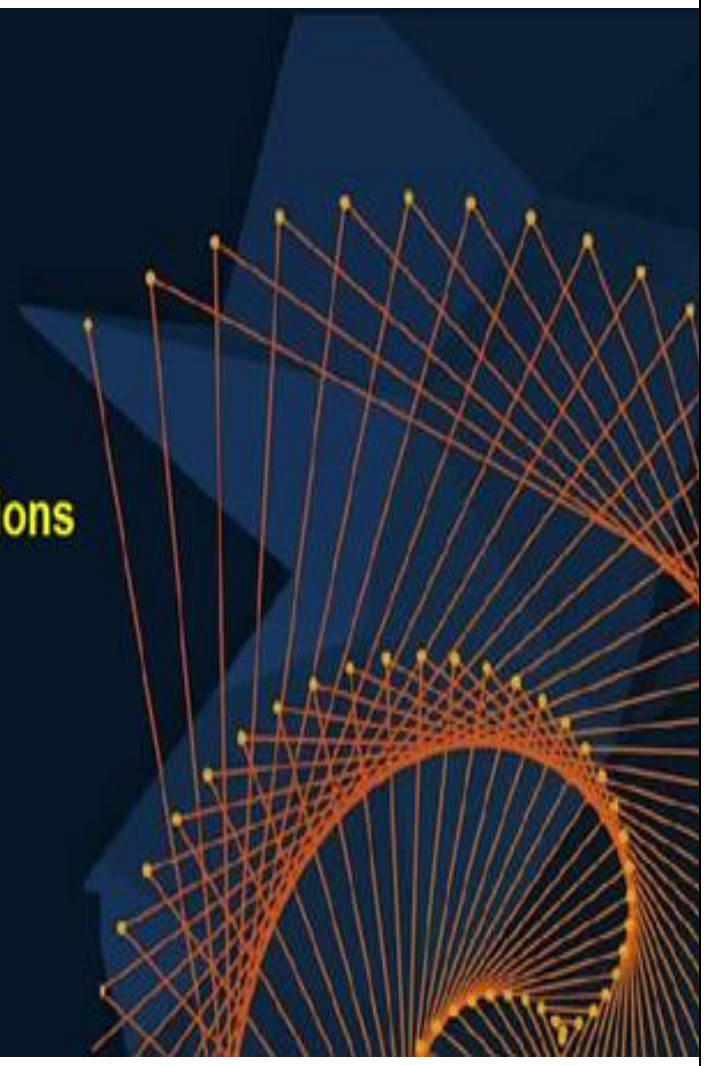
under uncertain and rapidly changing wind conditions. Due to its excellent disturbance rejection and tracking capabilities, SMC is widely used in modern variable-speed wind energy systems, often with chattering-reduction techniques to improve practical performance.

References-Chapter 3

[33]	Zina Larabi ,Kaci Ghedamsi,Djamal Aouzelag, Fares Nafa ,''Enhancing Wind Turbine Efficiency: A Comparative Study of Two Innovative MPPT Control Algorithms '', Journal of renewable energies;2024.
[34]	Omar Talal Mahmood ,Wan Zuha Wan Hasan, Luthffi Idzhar Ismail, Hafiz Rashidi Harun Ramli, Norhafiz Azis and Nor Mohd Haziq Norsahperi,''Sliding Mode Controller Optimization-Based Three-Phase Rectifier: Review Study,'',IEEE accesse ; 2025
[35]	Tran Thanh Tuyen,Jian Yang,Liqing Liao and Nguyen Gia Minh Thao ;''Recent Advances in Sliding Mode Control Techniques for Permanent Magnet Synchronous Motor Drives ''; Electronics 2025.
[36]	Arefe Shalbafian and Soheil Ganjefar,''A novel robust nonlinear optimal second-order sliding mode control scheme for power optimization of wind energy conversion systems'', Wind Engineering, 2024.
[37]	Amina Mseddi, Khouloud Wali, Ahmed Abid, Omar Naifar, Mohamed Rhaima, Lassaad Mchiri,''Advanced modeling and control of wind conversion systems based on hybrid generators using fractional order controllers'', Asian journal of control, 2024
[38]	Mourad Guediri, Slimane Touil ,Messaoud Hettiri ,Abdelhafid Guediri,Nabil Ikhlef, Bouchekhou Hocine and Abdelkarim Guediri ,''Control of a Doubly Fed Induction Generator for Variable Speed Wind Energy Conversion Systems using Fuzzy Controllers optimized with a Genetic Algorithm '', Engineering, technology and applied sciences research, 2025.
[39]	Amina Yachir, Abdallah Belabbes, Houari Merabet Boulouiha, Riyadh Bouddou, Allal El Moubarek Bouzid , Nasreddine Bouchikhi , Sarra Adiche ;''improved sliding mode control of a wind turbine system based on a developed permanent magnet synchronous generator''; Journal of renewable energies,2024.
[40]	Hichem Itouchene, Zoubir Boudries , Fayssal Amrane ,''improved power control based variable speed wind-turbine dfig under hard work conditions: application of sliding mode theory'', Periodica Polytechnica Electrical Engineering and Computer Science;2024

Chapter IV

Simulations Results and Interpretations



IV.1. Introduction

The development of accurate mathematical models is essential for understanding and evaluating the performance of Wind Energy Conversion Systems (WECS). However, the effectiveness and reliability of these models can only be confirmed through simulation studies that reproduce the dynamic behaviour of the system under various operating conditions. Simulation plays a crucial role in analyzing the interactions between the aerodynamic, mechanical, electrical, and control subsystems of a wind energy conversion chain, allowing the prediction of system performance before practical implementation.

In the previous chapters, a comprehensive model of the WECS was developed, including the wind model, wind turbine aerodynamics, mechanical drive train, Permanent Magnet Synchronous Machine (PMSM), power electronic converter, and the associated control strategy based on Sinusoidal Pulse Width Modulation (SPWM). These mathematical models provide the foundation for evaluating the behaviour of the system and assessing its ability to efficiently convert wind energy into electrical energy.

The objective of this chapter is to validate the developed models through simulation using MATLAB/Simulink and to analyze the performance of the proposed wind energy conversion system. Different operating scenarios are considered in order to evaluate the dynamic response of the turbine, generator, converter, and control system. Particular attention is given to the evolution of key variables such as wind speed, turbine mechanical power, rotor speed, electromagnetic torque, stator currents, output voltage, and generated power.

The simulation results are presented and interpreted to assess the effectiveness of the adopted modeling and control approaches. The analysis focuses on system stability, energy conversion efficiency, dynamic response, and power quality. Furthermore, the obtained results are compared with the theoretical expectations derived from the mathematical models to verify their accuracy and consistency.

Through this investigation, the chapter aims to demonstrate the capability of the proposed WECS to operate efficiently under varying wind conditions while maintaining satisfactory electrical performance. The results obtained provide valuable insights into the behaviour of the system and establish a basis for future improvements in control strategies, optimization techniques,and the possibility of practical implementation of wind energy conversion systems.

The present chapter is organized as follows. First, the simulation environment and system parameters are presented. Next, the simulation results of the different subsystems are

discussed in detail. Finally, a comprehensive interpretation of the results is provided, followed by the chapter conclusion.

IV.2. Simulation Environment and System Parameters

To evaluate the performance of the proposed Wind Energy Conversion System (WECS), a simulation model was developed using MATLAB/Simulink. This software environment provides powerful tools for modeling, simulation, and analysis of dynamic systems and is widely used in renewable energy research. The developed model integrates the aerodynamic, mechanical, electrical, and control subsystems of the WECS, enabling comprehensive analysis of the energy conversion process under different operating conditions.

The simulation study aims to verify the validity of the mathematical models presented in the previous chapter and to assess the dynamic behavior of the system. Particular attention is given to the performance of the wind turbine, Permanent Magnet Synchronous Machine (PMSM), power electronic converter, and the adopted Sinusoidal Pulse Width Modulation (SPWM) control strategy.

IV.2. 1. Simulation Environment

The complete Wind Energy Conversion System was implemented in MATLAB/Simulink and the simulation was performed under variable wind speed conditions to evaluate the dynamic response and robustness of the system using several specialized toolboxes, including:- Simulink; Sim Power Systems and Control System Toolbox.

The simulation model consists of the following interconnected subsystems:

1. Wind speed model
2. Aerodynamic wind turbine model
3. Mechanical drive train model
4. Permanent Magnet Synchronous Generator (PMSG/PMSM) model
5. Three-phase rectifier
6. DC-link circuit
7. Voltage source inverter
8. SPWM control system

IV.3. Wind Profile and Aerodynamic Results

The aerodynamic subsystem constitutes the first stage of the Wind Energy Conversion System (WECS), where the kinetic energy of the wind is transformed into mechanical energy by the turbine rotor. The performance of the turbine is strongly influenced by wind speed variations, making the analysis of the wind profile and aerodynamic response essential for evaluating the overall behaviour of the system.

In this section, the wind speed profile applied to the simulation model is presented, followed by an analysis of the turbine's aerodynamic performance in terms of mechanical power, rotor speed, tip-speed ratio, and power coefficient. The obtained results are compared with the theoretical expectations derived from the aerodynamic model.

IV.3.1. Wind Speed Profile

To evaluate the dynamic performance of the WECS, a variable wind speed profile was applied during the simulation period. The wind speed was intentionally modified to reproduce realistic operating conditions and to observe the response of the turbine to changing wind conditions.

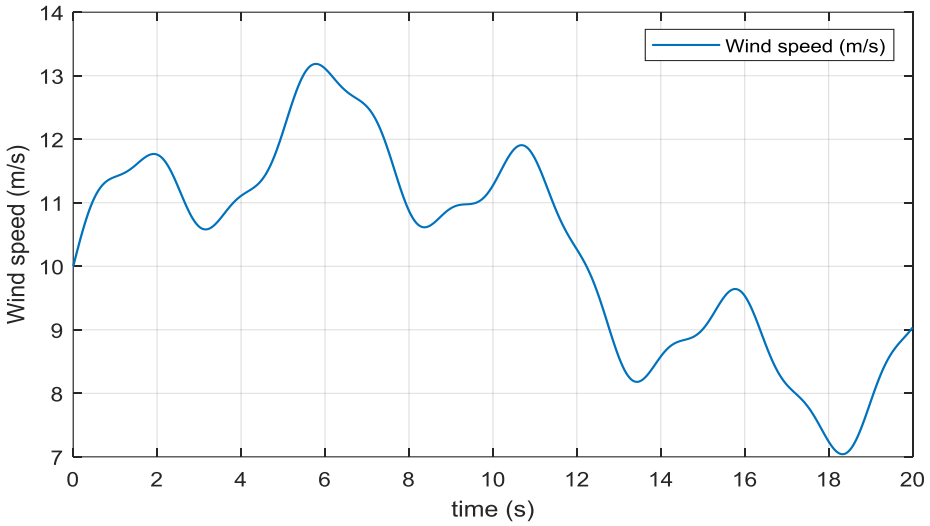


Fig. IV.1. Wind speed

The wind speed initially remains at 10 m/s, then gradually increases to 13 m/s before returning to its nominal value. These variations allow the assessment of the turbine's ability to adapt to fluctuating wind conditions and maintain efficient energy conversion. The observed wind profile reflects the stochastic nature of real wind resources and provides a suitable basis for testing the robustness of the proposed system.

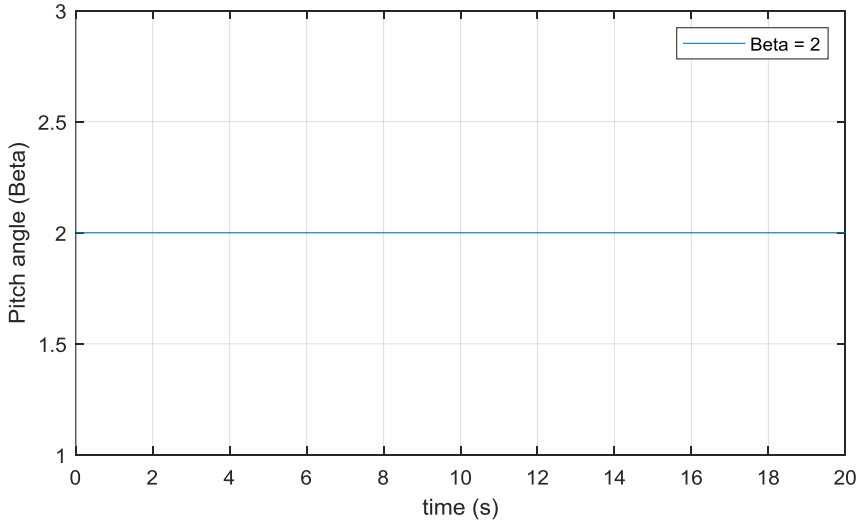


Fig. IV.2. Pitch angle

Figure IV.1. Shows the variation of wind speed according to the proposed equation model. It can be seen that this speed varies around its average value, estimated at 10 m/s. In order to obtain optimal values for the quantities related to the turbine's mechanical power, the pitch angle is set at 2°, as shown in Figure IV.2. This value allows for an optimal power coefficient *(Cp)* of approximately 0.48, as well as a tip-speed ratio (λ) that is almost constant and close to its optimal value of 8.1.

IV.3.2. Aerodynamic power response

The mechanical power extracted from the wind turbine is governed by the aerodynamic equation. This relationship indicates that the extracted power varies proportionally with the cube of the wind speed.

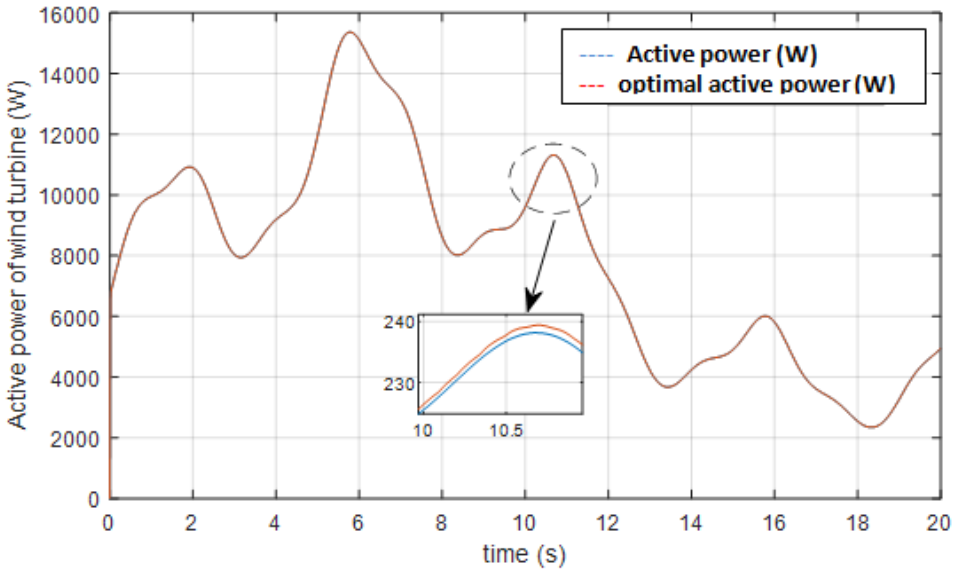


Fig. IV.3. Active power comparison

It can be observed that the mechanical power increases significantly when the wind speed rises. This behavior is expected since the available wind power increases rapidly with wind velocity. During periods of reduced wind speed, the extracted power decreases accordingly.

The simulation results demonstrate that the aerodynamic model accurately reproduces the theoretical relationship between wind speed and turbine power.

IV.3.2. Rotor speed response

The turbine rotor speed is directly influenced by changes in aerodynamic torque and wind velocity. The turbine output parameters, including mechanical power (Figure IV.3), mechanical speed, generator speed (Figure IV.4), Electrical and mechanical speed (Figure IV.5), and machine output torque (Figure IV.6), are presented respectively in the following figures.

The analysis of the results shows that these parameters reach optimal values under steady-state conditions. Indeed, the mechanical power exceeds *1.5 KW*, while the rotational speed stabilizes around its average value of 200 *rad/s*. Furthermore, the machine output torque reaches an optimal value of approximately 40 *N·m*. These performance characteristics demonstrate the system's stability and the effectiveness of the implemented control strategy.

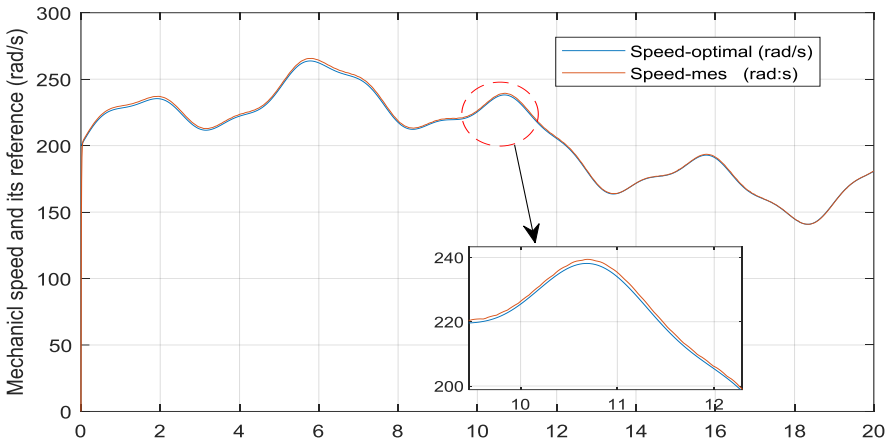


Fig. IV.4. Generator speed and its reference

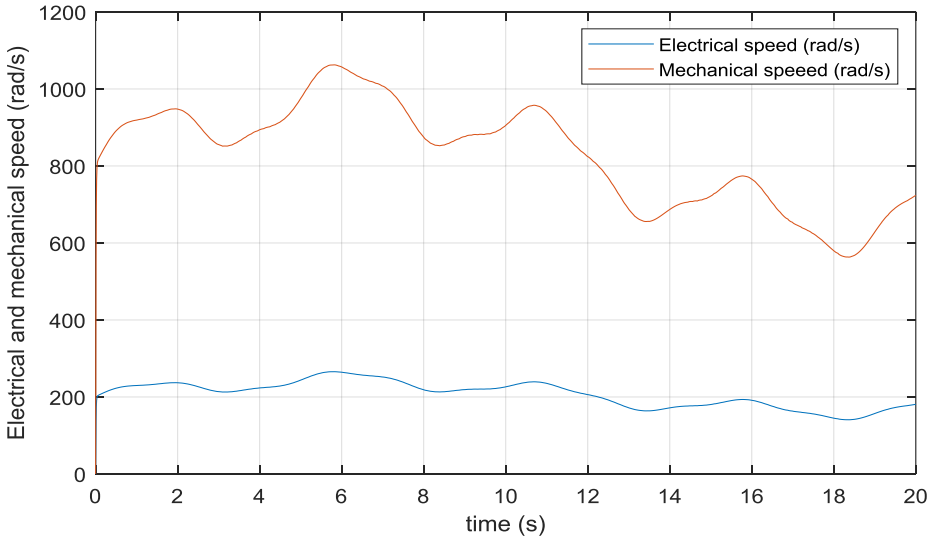


Fig. IV.5. Electrical and mechanical speed

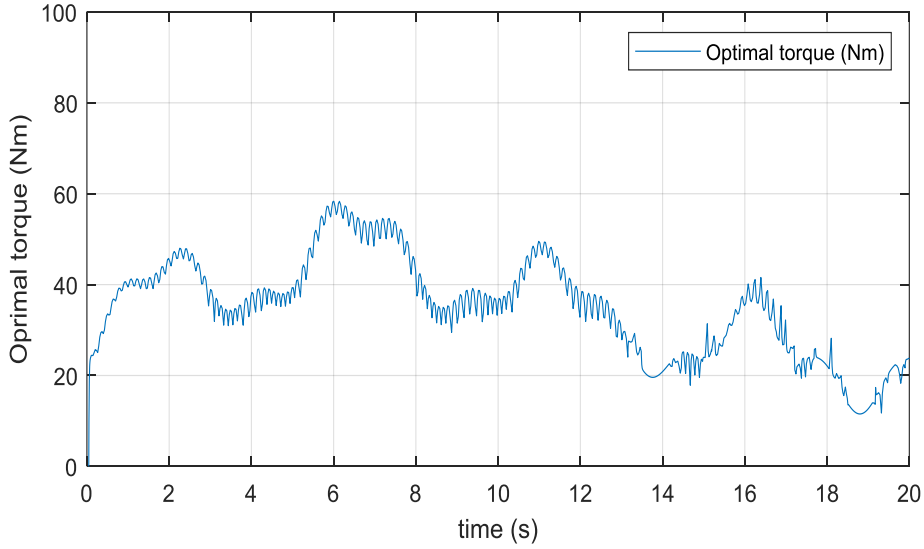


Fig. IV.6. Optimal torque

The appropriate selection of turbine input parameters such as wind speed and pitch angle combined with the integration of an MPPT algorithm based on a PI controller, ensures optimal tracking of the maximum power point. As illustrated in Figure IV.4, a nearly perfect alignment is observed between the turbine's rotational speed and its optimal reference value. Furthermore, the machine's speed remains close to its mean value of 200 rad/s, there by demonstrating the robust performance of the control system and the operational stability of the turbine.

The obtained simulation results confirm the validity of the aerodynamic model developed in the previous chapter. The wind turbine responds effectively to changes in wind speed and demonstrates stable operation throughout the simulation period. These results indicate that the aerodynamic subsystem operates efficiently and provides a stable mechanical input for the electrical conversion stage. Several important observations can be made:

-The extracted mechanical power increases significantly with wind speed, in accordance with aerodynamic theory.

-Rotor speed follows wind variations without instability.

-The tip-speed ratio remains close to its optimal value.

-The power coefficient is maintained near its maximum value, ensuring efficient energy extraction.

-The generated aerodynamic torque exhibits smooth dynamic behaviour.

The obtained results show also that, the rotor speed increases when the wind speed rises and decreases when the wind speed falls. The response is smooth and stable, indicating that the mechanical subsystem effectively absorbs wind fluctuations without excessive oscillations. The observed behavior confirms the effectiveness of the drive train model and its ability to represent the dynamic characteristics of the wind turbine.

IV.4. Simulation of the PMSG with the wind turbine without MPPT

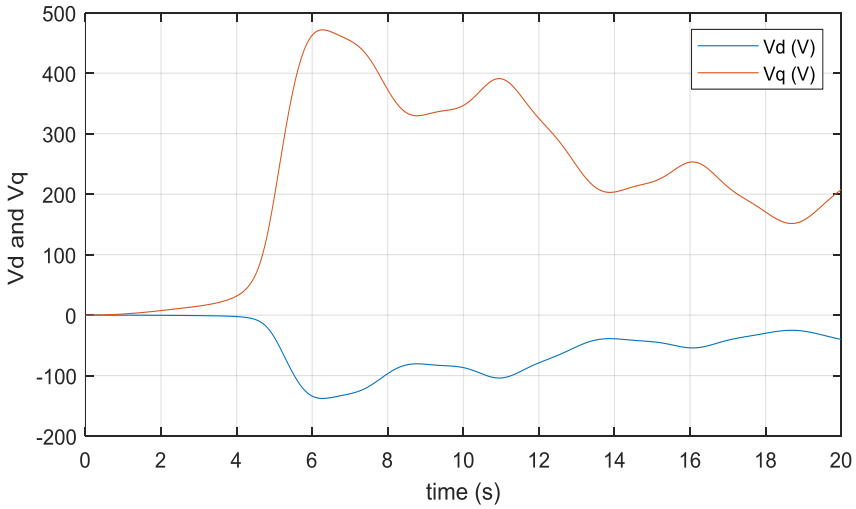


Fig. IV.7. V_d and V_q of the PMSG without MPPT

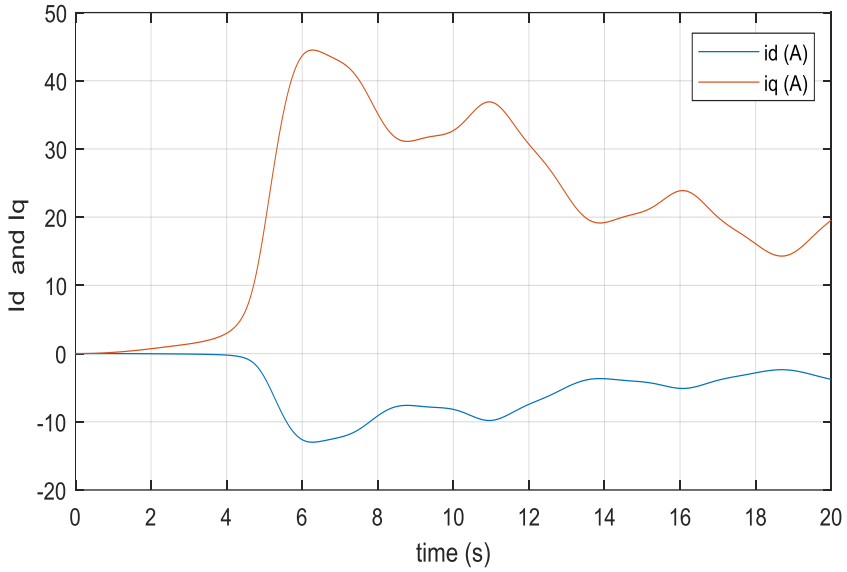


Fig. IV.8. Id and Iq de la GSAP without MPPT

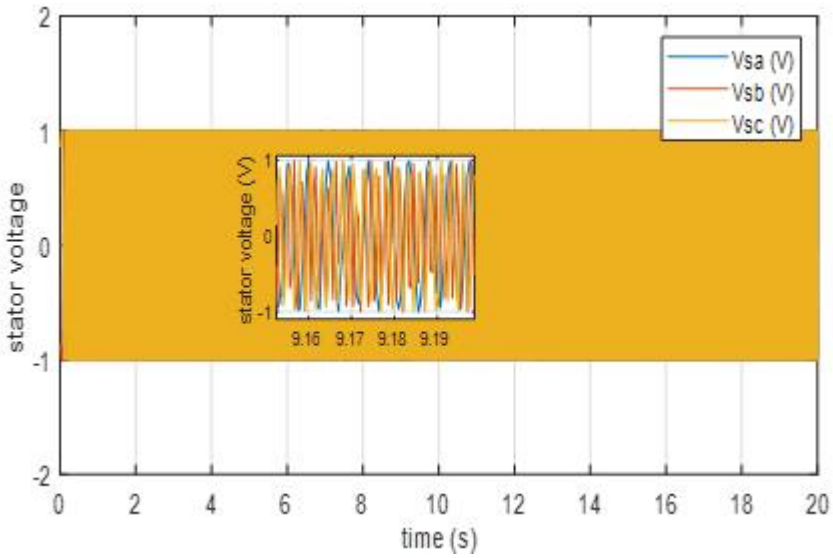


Fig. IV.9. Stator voltage of PMSG Without MPPT

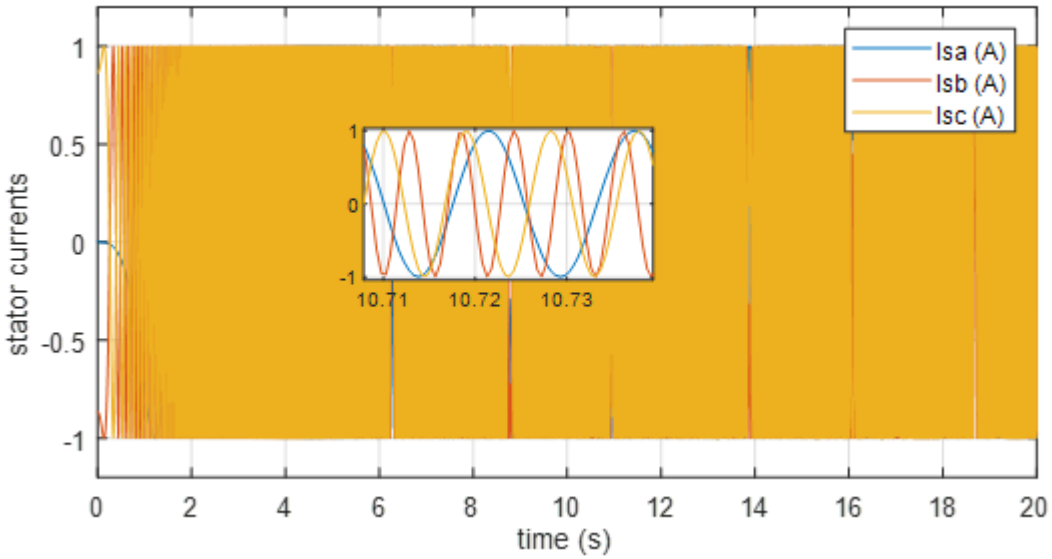


Fig. IV.10. Stator currents of PMSG Without MPPT

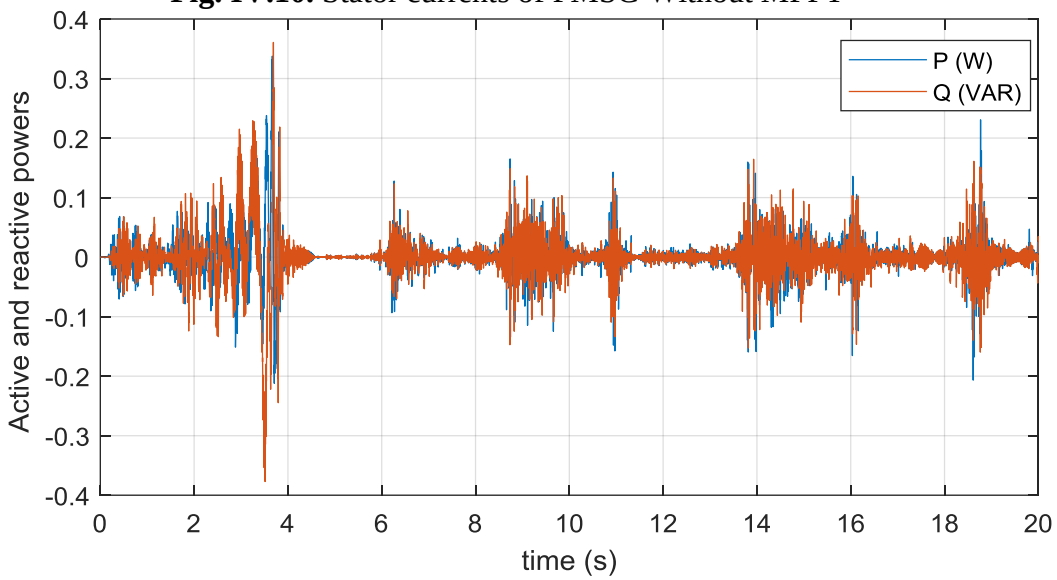


Fig. IV.11. Active and reactive powers of PMSG based on PI controller without MPPT

The obtained simulation results of the permanent magnet synchronous generator (PMSG), operating coupled to a wind turbine and without MPPT, are presented in the figures above. The analysis of figures IV.7 and Figure IV.8, represent respectively the voltages and currents in the (d, q) coordinate system and it shows that the components along the (q) axis are practically zero, while those along the (d) axis exhibit significant values. This behavior is due to the application of flux-oriented vector control of the PMSG.

In the three-phase (a, b, c) coordinate system, Figures IV.9 and figure IV.10 present respectively, the generator voltages and currents which exhibit balanced sinusoidal waveforms and a nearly constant amplitude. Regarding the active and reactive power of the PMSG, Figure IV.11 shows that their values remain very low, even near zero. This is explained by the machine's operation under no-load conditions. Furthermore, slight fluctuations in reactive

power may be observed. These are mainly due to the switching of the power switches of the converters associated with the machine, as well as to variations in wind speed when the generator is integrated into a wind power system.

IV.5. Simulation of the PMSG connected to the wind turbine with MPPT and using PI controller.

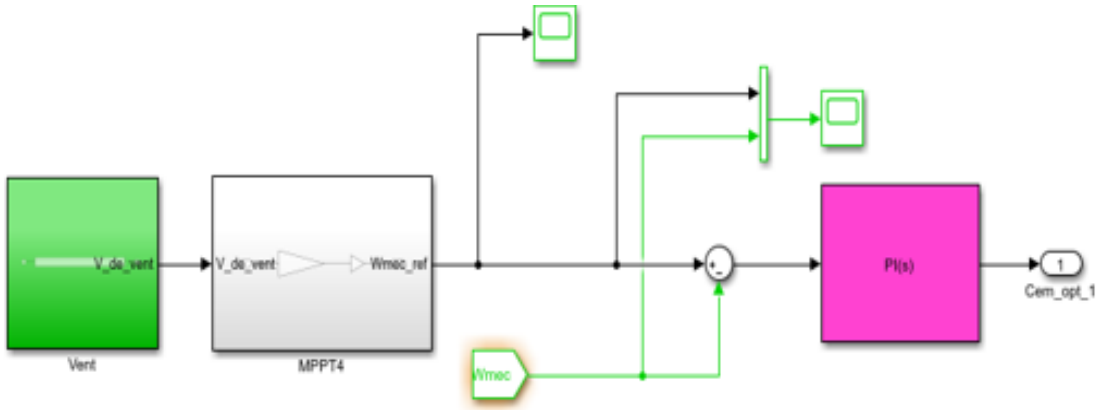


Fig. IV.12. WECS using MPPT based on PI controller

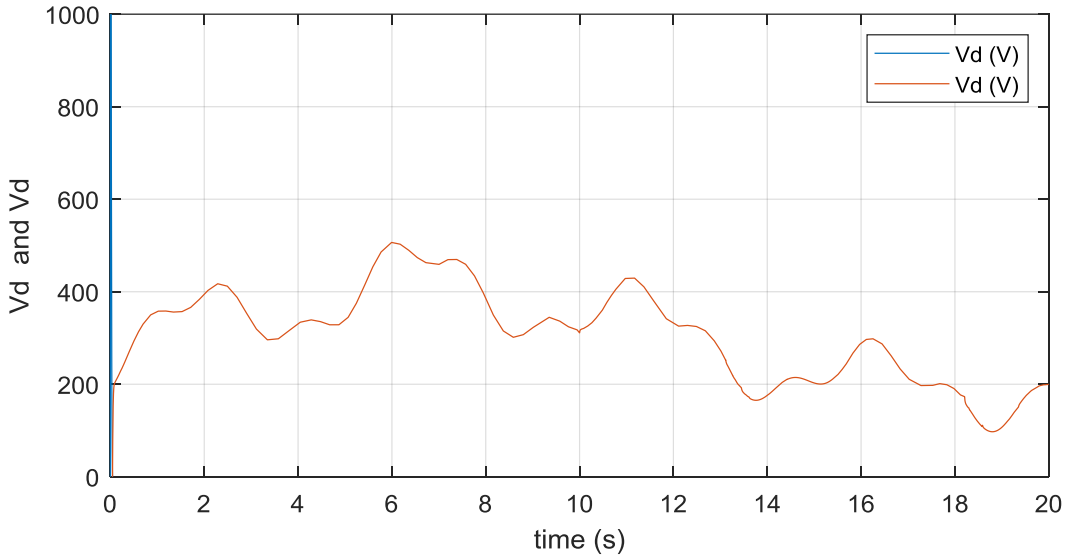


Fig. IV.13. *Vd and Vq* of PMSG with MPPT based on PI controller

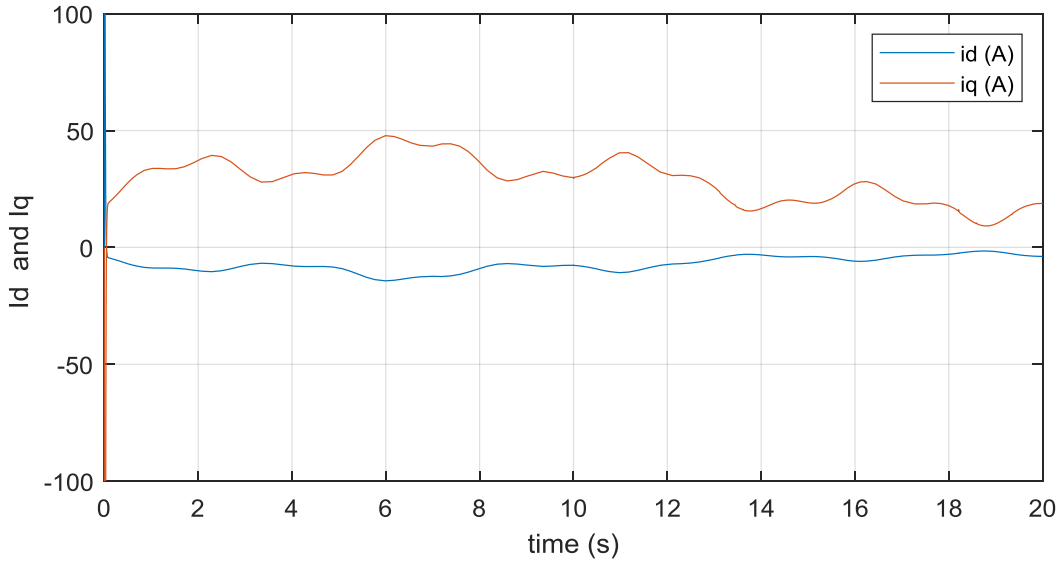


Fig. IV.14. Id and Iq of PMSG based on PI controller with MPPT

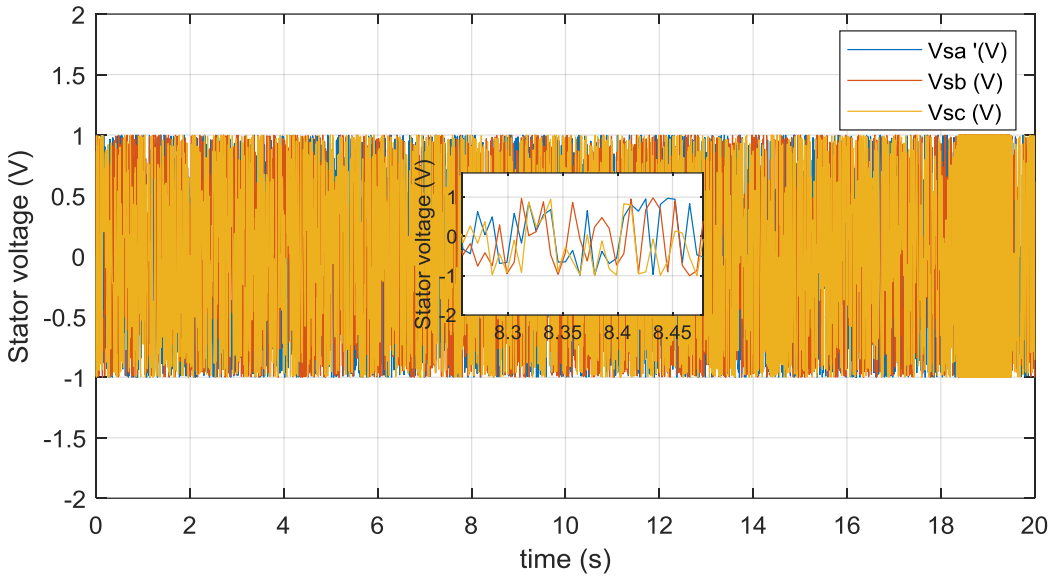


Fig. IV.15. Stator voltage of PMSG with MPPT based on PI controller

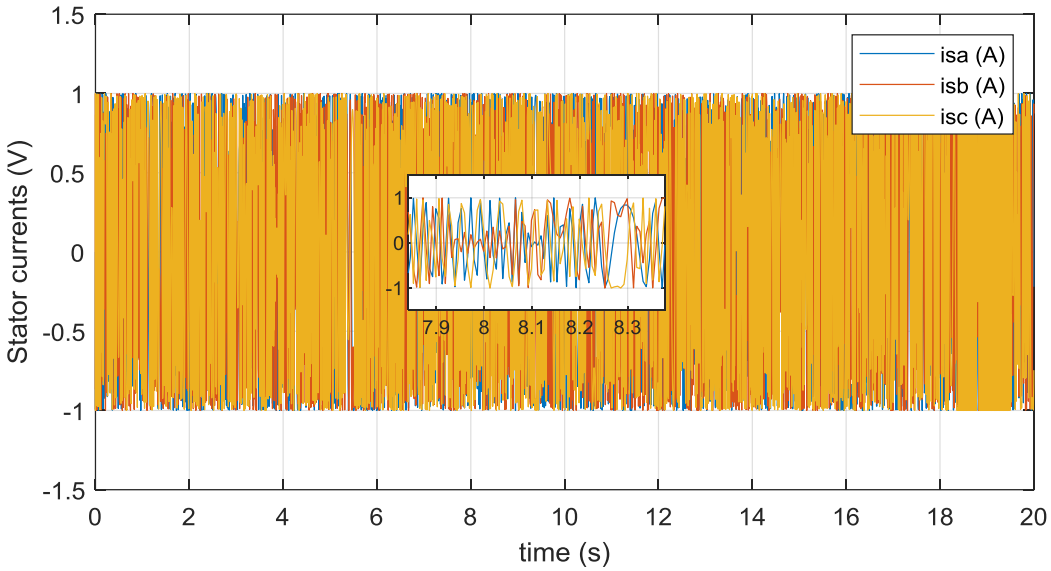


Fig. IV.16. Stator currents of PMSG with MPPT based on PI controller

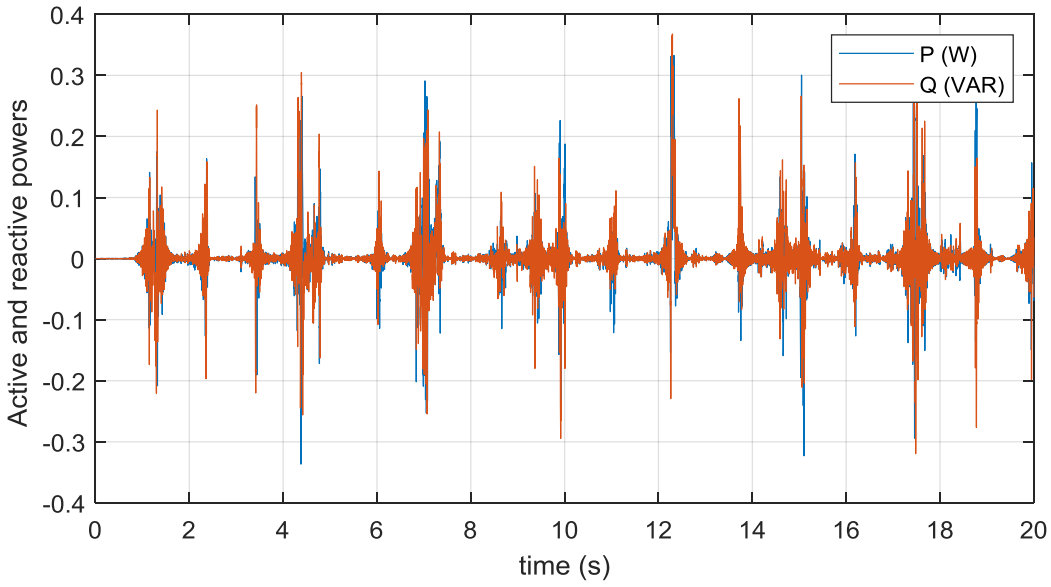


Fig. IV.17. Active and reactive of PMSG with MPPT based on PI controller

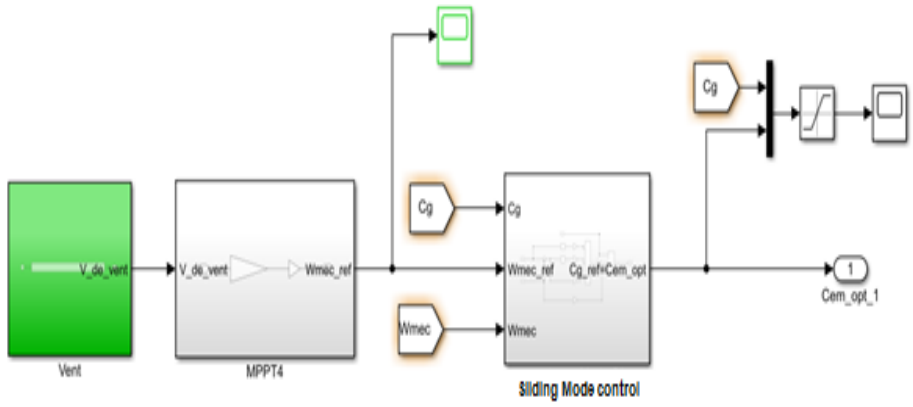
The simulation results of the permanent magnet synchronous generator (PMSG), operating in coupling with a wind turbine and incorporating a maximum power point tracking (MPPT) strategy, are presented in the figures above. The analysis of figures IV.12 and IV.13, present respectively the voltages and currents in the (d,q) coordinate system, and show that the components along the *(q)* axis remain practically zero, while those along the (d) axis maintain significant and nearly constant values. This behavior reflects the effectiveness of the flux-oriented vector control applied to the PMSG, combined with the MPPT strategy.

In the three-phase ((a,b,c)) coordinate system, Figures IV.14 and IV.15 illustrate the generator voltages and currents. The results show that these quantities exhibit balanced sinusoidal waveforms and practically constant amplitudes, confirming the quality of the implemented control. Regarding the active and reactive power of the GSAP (Figure IV.16), The active power generated by the PMSG represents the useful electrical power delivered by the system. The generated power follows the variations of wind speed and turbine mechanical power. An increase in wind speed leads to higher electrical power production, while a decrease in wind speed results in reduced output power.

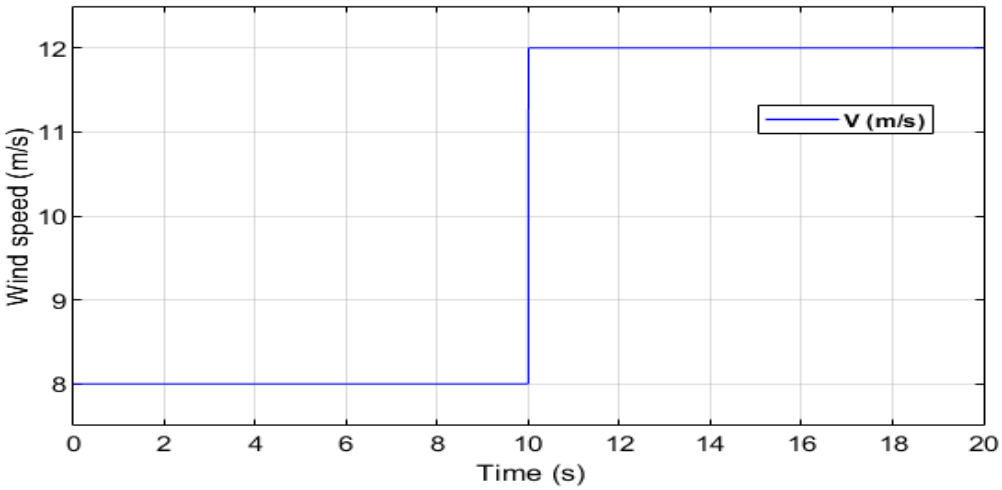
The simulation results confirm the ability of the generator to effectively convert mechanical energy into electrical energy over a wide operating range.

The results indicate that their values remain generally low. However, more pronounced fluctuations in reactive power can be observed. These are mainly due to the switching of the power switches of the converters associated with the machine, as well as to variations in wind speed imposed by the wind turbine system.These results highlight the good stability of the generator and the satisfactory performance of the MPPT strategy associated with the vector control.

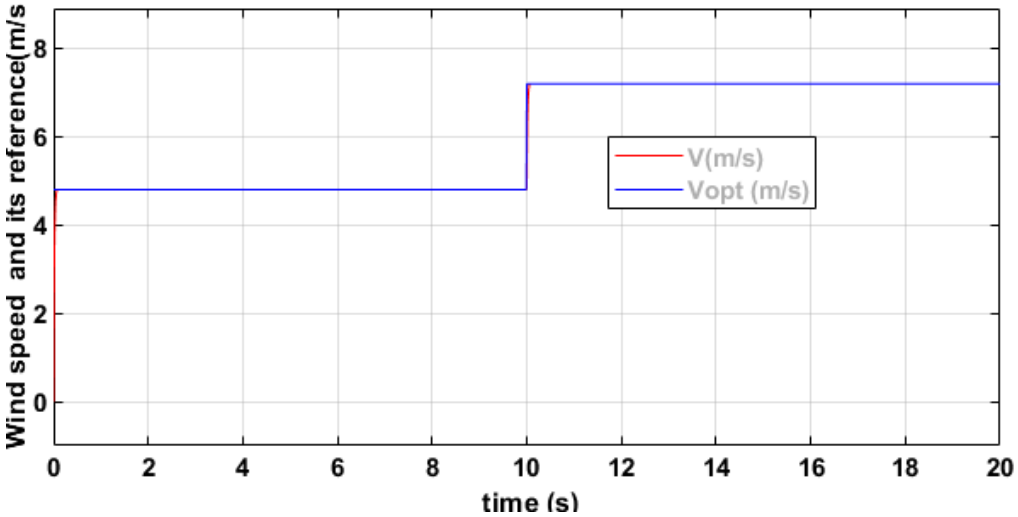
IV.6. Simulation of the PMSG connected to the wind turbine with MPPT using SMC controller



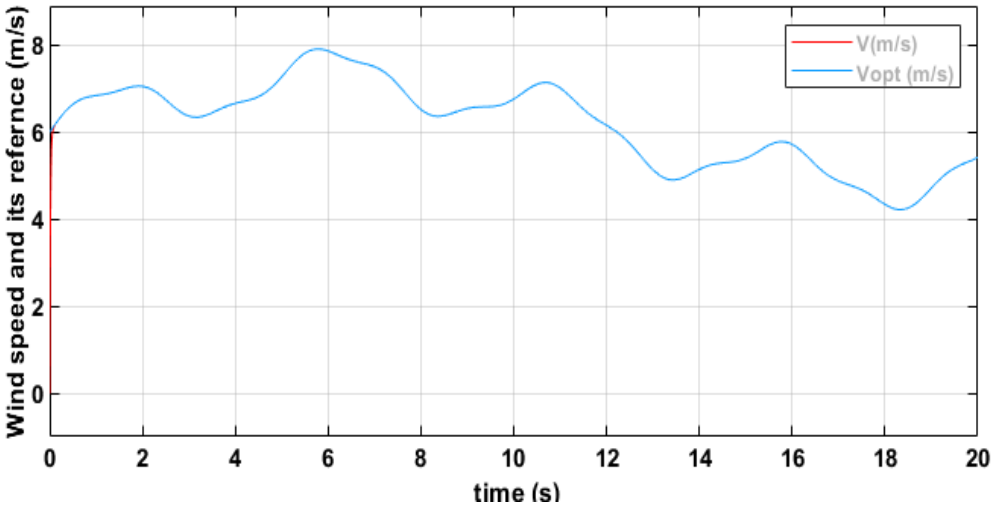
FigIV.18. WECS using MPPT based on SMC controller



FigIV.19. Wind Speed step (between 8 and 12m/s) with MPPT based on SMC

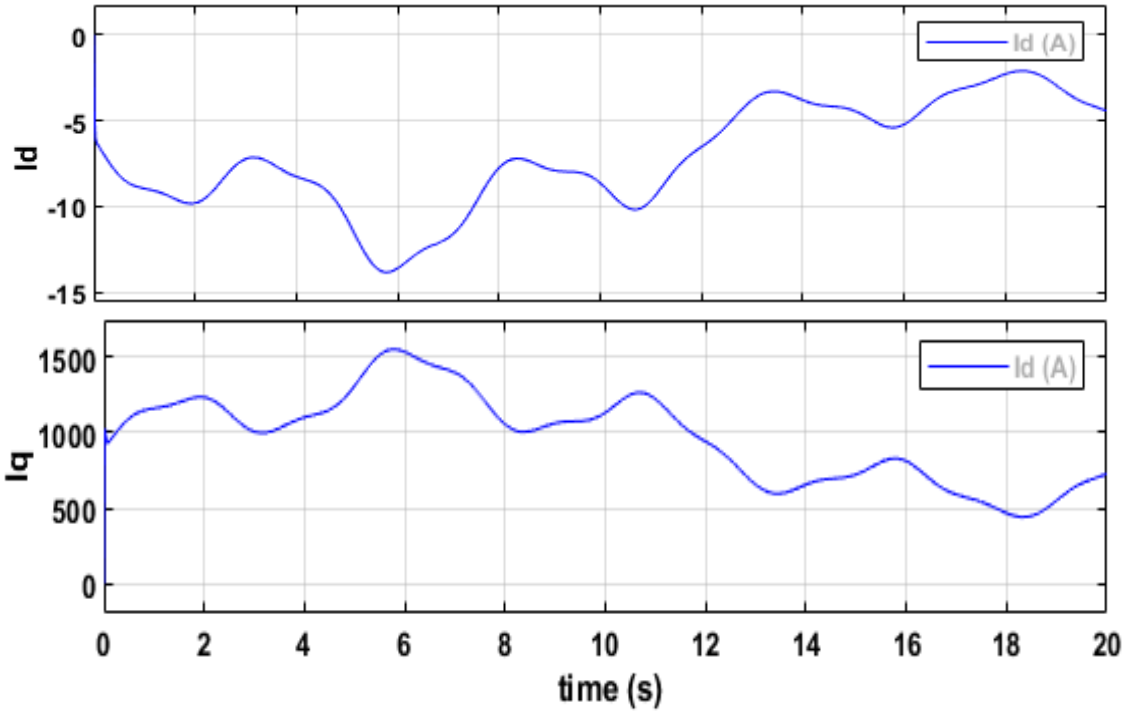


FigIV.20. Wind Speed step and its references (between 8 and 12m/s) with MPPT based on SMC

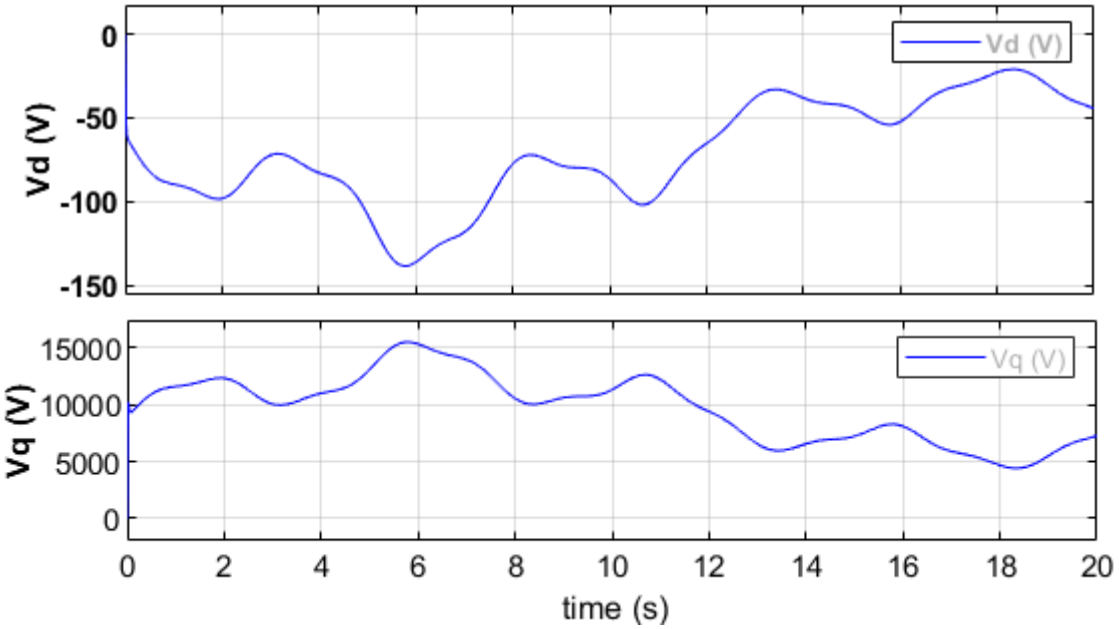


FigIV.21. Variable wind Speed and its references with MPPT based on SMC

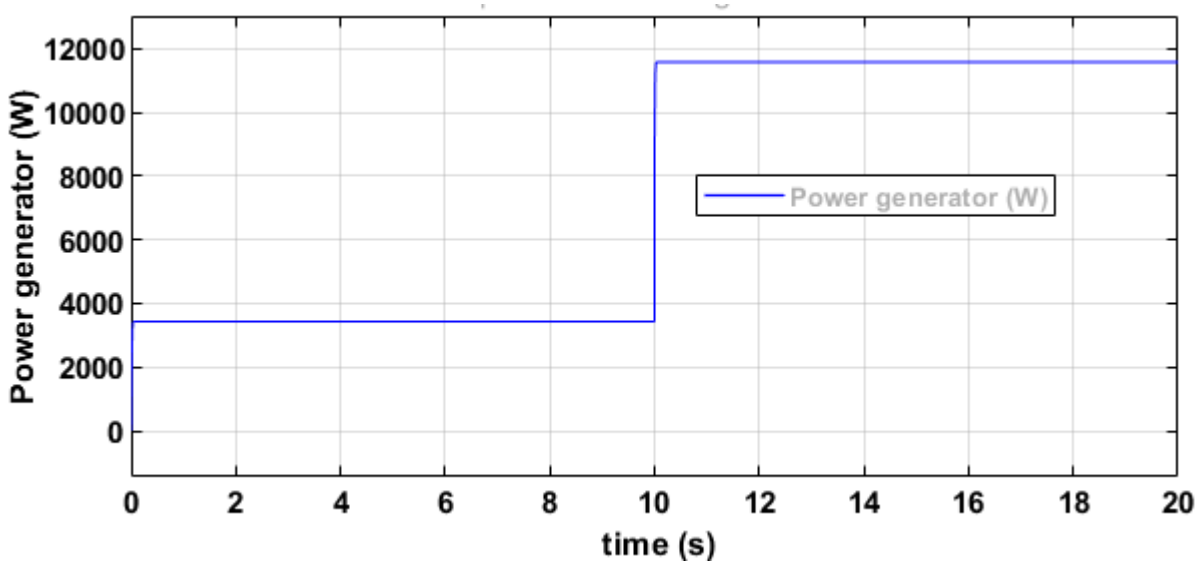
The simulation results show that the wind speed is initially 8 m/s, then gradually increases to reach a value of 12 m/s.



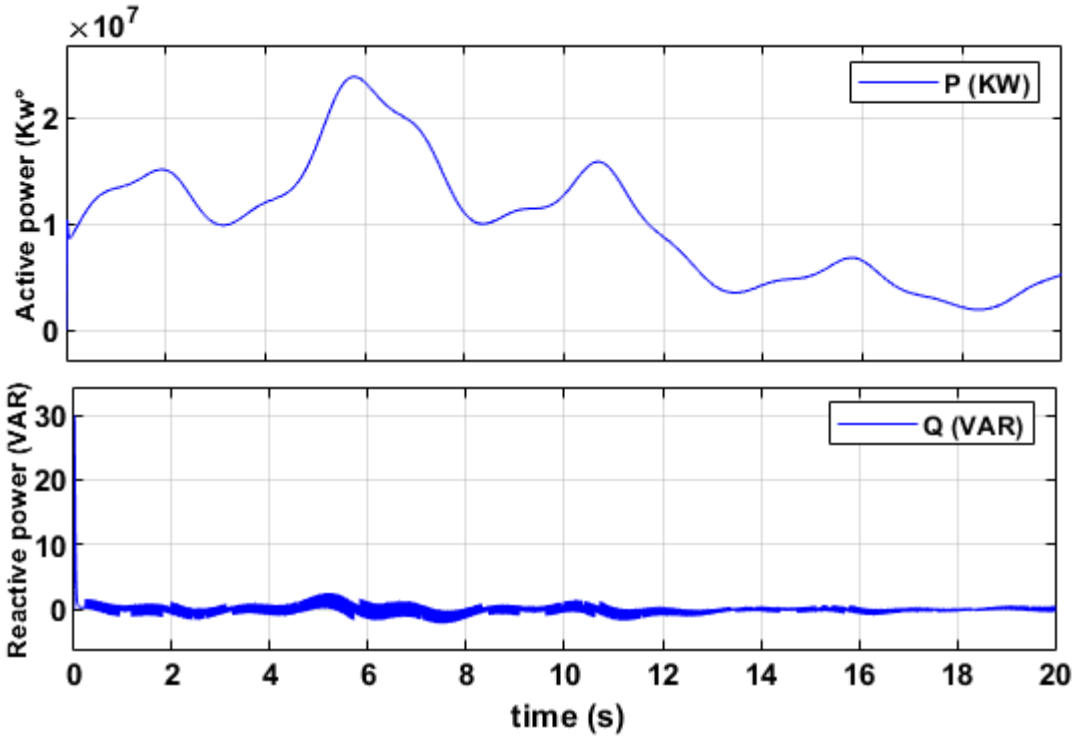
FigIV.22. Id and Iq currents of PMSG with MPPT based on SMC



FigIV.23. Vd and Vq voltages of PMSG with MPPT based on SMC



FigIV.24. Power generator of PMSG with MPPT based on SMC



FigIV.25. Active and reactive power of PMSG with MPPT based on SMC

IV.7. Parameters used for the wind turbine model

J=0.21 kg.m2; Moment Of Inertia
F=0.0001 KG;M2/s; Viscous friction
R=3 m; Blade radius
G=6;% ; Transmission ratio
ro=1.22;
Cp_{Max}*=0.39;* Maximum Power Coefficient
$Lamd_{Opt}$*=10;* Optimal specific speed
$S=pi.R^2.m^2$ *:* Surface swept by the blades
p=4;% ; Number of pole pairs
Phif=0.6 Wb; Nominal flux
$_{fpor}$*=5000 Hz ;* Carrier frequency
R_{ch}*=10 Ohm;* Load resistance
L_{ch}*=0.0002 H;* Load inductance
Rs=10.6 Ohm; Stator resistance
Ld=1.402e-3 H; Direct Inductance of the GS
Lq=2.802e-3 H; Indirect Inductance of the of GS

- Simulation Conditions

The simulation was conducted under the following operating conditions:

* Initial wind speed: 12 m/s

* Wind speed variation: 10-13 m/s

* Simulation duration: 20 s

* Sampling time: 1 µs

* Load type: Three-phase balanced resistive-inductive load

IV.7. Discussion of Results

The simulation results of the Permanent Magnet Synchronous Generator (PMSG) driven by a wind turbine and controlled using a Maximum Power Point Tracking (MPPT) strategy based on Sliding Mode Control (SMC) are presented in the figures above. Figures 17 and 18 illustrate the wind speed variation and its reference value under a step change condition, where the wind speed is initially 8 m/s and then gradually increases to 12 m/s. Figure 19 shows the system response under random wind speed variations. An excellent agreement can be observed between the actual wind speed and its optimal reference value generated by the MPPT algorithm. This demonstrates the effectiveness of the MPPT strategy combined with Sliding Mode Control in tracking the maximum power point. Figures 20 and 21 present the evolution of the direct-axis and quadrature-axis currents ((Id) and (Iq)), as well as the corresponding voltages ((Vd) and (Vq)) in the Park reference frame. It can be observed that the direct-axis components remain practically zero, whereas the quadrature-axis components exhibit significant values. This behavior is consistent with the principles of vector control, which generally impose (Id = 0) to ensure effective decoupling between the magnetic flux and the

electromagnetic torque. Figure 22 depicts the evolution of the active power as the wind speed varies from 8 m/s to 12 m/s. Figure 23 illustrates both active and reactive power under random wind speed variations. The results indicate that the reactive power remains nearly zero, while the active power closely follows the wind speed variations and reaches significant values. These observations confirm the satisfactory performance of the proposed control strategy in terms of maximum power extraction and power factor regulation.

The simulation results indicate high conversion efficiency throughout the operating range. The absence of rotor copper losses contributes significantly to the superior performance of the PMSG compared with conventional generator technologies. The dynamic response of the generator was evaluated under varying wind conditions and the results demonstrate:

- Rapid adaptation to wind speed changes.
-Stable electromagnetic torque production.
-Balanced and sinusoidal voltage and current waveforms.
-Efficient energy conversion.
-Smooth transition between operating points.

These characteristics confirm the robustness and reliability of the PMSG for wind energy applications. The simulation results validate the developed PMSG model and confirm its suitability for variable speed wind energy conversion systems. The generator exhibits stable operation and maintains high efficiency under changing wind conditions. The main observations include:

- Effective conversion of mechanical power into electrical power.
- Stable rotor speed response.
-High-quality voltage and current waveforms.
- Efficient torque production.
- Reliable power generation under variable operating conditions.

These findings demonstrate the advantages of PMSG technology in improving the performance and efficiency of modern wind energy conversion systems

.IV.8. Conclusion

This section presented the simulation environment and the parameters used for the implementation of the Wind Energy Conversion System in MATLAB/Simulink. The selected parameters describe the aerodynamic, mechanical, electrical, and control subsystems of the WECS. These values provide a realistic framework for evaluating system performance and validating the mathematical models developed in the previous chapter. The following sections present and analyze the simulation results obtained under the specified operating conditions.

The performance analysis of the Permanent Magnet Synchronous Generator confirms its effectiveness as an electrical energy conversion device within the proposed wind energy conversion system. The simulation results demonstrate stable dynamic behaviour, efficient power conversion, and high-quality electrical output under varying wind conditions. The obtained results validate the mathematical model of the PMSG and provide a solid basis for the subsequent analysis of the power electronic converter and inverter control strategy

The analysis of the wind profile and aerodynamic results demonstrates the ability of the proposed wind turbine model to accurately capture the dynamic behaviour of the aerodynamic conversion process. The turbine successfully converts the available wind energy into mechanical power while maintaining high aerodynamic efficiency under varying wind conditions. The obtained results validate the theoretical model and confirm its suitability for further analysis of the electrical generator and power electronic conversion stages presented in the following sections.

General Conclusion

The increasing demand for clean and sustainable energy has led to significant interest in wind energy conversion systems (WECSs) in modern power generation as a viable solution for reducing dependence on fossil fuels and mitigating environmental impacts. Among the various generator technologies used in wind power applications, the Permanent Magnet Synchronous Generator (PMSG) has gained considerable attention due to its high efficiency, reliability, and suitability for variable-speed operation.

This dissertation investigated the modeling, control, and performance enhancement of a PMSG-based wind energy conversion system. The study focused on the development and evaluation of advanced control strategies aimed at improving system efficiency, stability, robustness, and power quality under varying wind conditions. Two control approaches are considered: the conventional Proportional–Integral (PI) controller and the nonlinear Sliding Mode Controller (SMC). Mathematical models of the wind turbine, PMSG, and associated power electronic converters are developed to accurately represent the dynamic behavior of the overall system.

A comprehensive comparative analysis is carried out through simulation studies to assess the performance of the proposed control techniques in terms of maximum power extraction, reference tracking capability, disturbance rejection, and dynamic response. Simulation studies are carried out to evaluate and compare the performance of the proposed controllers in terms of reference tracking, dynamic response, robustness, and maximum power extraction.

The obtained results demonstrate the effectiveness of both control approaches in ensuring stable system operation while highlighting the superior robustness and performance characteristics of the Sliding Mode Controller. Furthermore, the Sliding Mode Controller exhibits improved robustness and dynamic performance compared with the conventional PI controller, particularly under variable operating conditions. The results presented in this work confirm the potential of advanced control techniques for enhancing the efficiency and reliability of wind energy conversion systems, thereby contributing to the integration of renewable energy sources into modern electrical power networks.

The findings of this research contribute to the development of efficient and reliable control solutions for modern wind energy conversion systems and provide valuable insights for the integration of renewable energy sources into future power systems.

Perspectives

The work presented in this dissertation has focused on the modeling, control, and performance enhancement of a Permanent Magnet Synchronous Generator (PMSG)-based wind energy conversion system. The developed models and control strategies, namely the Proportional–Integral (PI) controller and the Sliding Mode Controller (SMC), have demonstrated their effectiveness in improving system performance under varying wind conditions.

Despite the encouraging results obtained through simulation, several research directions can be explored in future work.

- First, the proposed control strategies can be validated experimentally using a real-time test bench or hardware-in-the-loop (HIL) platform to assess their practical feasibility and performance under real operating conditions.
- Second, advanced nonlinear and intelligent control techniques, such as fuzzy logic control, neural networks, adaptive control, or model predictive control, may be investigated to further enhance system robustness and energy capture efficiency.

In addition, future studies may consider the integration of energy storage systems to improve power quality and ensure a more reliable energy supply. The impact of grid disturbances, parameter uncertainties, and fault conditions on system performance can also be analyzed to develop more resilient control schemes. Furthermore, extending the proposed approach to offshore wind energy systems and large-scale wind farm applications represents an interesting area for future research.

Overall, these perspectives provide promising opportunities for improving the efficiency, reliability, and grid integration capability of modern wind energy conversion systems.