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Fault Tolerant Control of a Wind Energy Conversion System

**Commande Tolérante aux Défaits d'un Système
de Conversion de l'Énergie Éolienne**

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ملخص

الهدف من هذه الأطروحة هو اقتراح نهج جديد يعتمد على التحكم المتسامح مع الخطأ ومخطط تشخيص واكتشاف الخطأ، وذلك لاكتشاف، عزل وتعويض الأخطاء التي تحدث في المولد الحثي ذي التغذية المزدوجة المدمج في نظام تحويل طاقة الرياح. تمت دراسة سيناريوهين للخطأ على وجه التحديد: خطأ الدارة القصيرة في الجزء الثابت وعطل مستشعر التيارات، تحت تأثير سرعة الرياح الثابتة والعشوائية. يعتمد النهج المقترح على مراقب الوضع الانزلاقي المصمم من نموذج معيب لمولد حثي مزدوج التغذية ذي 3 أطوار. مراقب الوضع الانزلاقي فعال للغاية ومشتق لتوليد مجموعة من البقايا التي لا تسمح فقط باكتشاف الخطأ بل وحتى عزل المرحلة المعيبة أيضاً وقد تم فحصه لضمان التشغيل الدائم للمولد الخاضع للخطأ. تظهر نتائج المحاكاة فعالية النهج المقترح.

الكلمات المفتاحية: المولد الحثي ذو التغذية المزدوجة، تشخيص وكشف الأعطال، التحكم المتسامح مع الخطأ، دارة قصيرة بين اللفات، مراقب الوضع المنزلق، نظام تحويل طاقة الرياح.

Abstract

The aim of this thesis is to propose a new approach based on Fault Tolerant Control and Fault Diagnosis and Detection schemes to detect, isolate and compensate the faults that can occur in Doubly-Fed Induction Generator-Based Wind Energy Conversion Systems. Under fixed and random wind speeds, two fault scenarios are specifically discussed, Doubly-Fed Induction Generator with stator Inter-Turn Short-Circuit fault and current sensor fault. The approach proposed is based on the Sliding Mode Observer designed from a three-phase faulty model of the Doubly-Fed Induction Generator. A Sliding Mode Observer scheme has been developed and tested to ensure the non-stop operation of a Doubly-Fed Induction Generator-Based Wind Energy Conversion System subject to fault. The simulation results show the effectiveness of the proposed approach.

Keywords: Doubly-Fed Induction Generator (DFIG); Fault Diagnosis and Detection (FDD); Fault Tolerant Control (FTC); Inter-Turn Short-Circuit (ITSC); Sliding Mode Observer (SMO); Wind Energy Conversion System (WECS).

Résumé

L'objectif de cette thèse est de proposer une nouvelle approche basée sur des schémas de Commande Tolérante aux Défauts et de Diagnostic et Détection de Défauts pour détecter, isoler et compenser les défauts qui peuvent survenir dans une Génératrice Asynchrone à Double Alimentation intégrée dans un Système de Conversion d'énergie Éolienne. Sous vitesse du vent fixes et aléatoires, deux scénarios de défaut sont spécifiquement discutés, Génératrice Asynchrone à Double Alimentation avec défaut de Court-Circuit entre spires du stator et défaut de capteur du courant. L'approche proposée est basée sur l'observateur à mode glissant conçu à partir d'un modèle défectueux triphasé du Génératrice Asynchrone à Double Alimentation. Un schéma d'observateur en mode glissant a été développé et testé pour assurer le fonctionnement continu d'un système de conversion d'énergie éolienne basé sur un Génératrice Asynchrone à Double Alimentation soumis à un défaut. Les résultats de la simulation montrent l'efficacité de l'approche proposée.

Mots-clés : Génératrice Asynchrone à Double Alimentation, Diagnostic et Détection de Défauts, Commande Tolérante aux Défauts, Court-Circuit entre Spires, Observateur à Mode Glissant, Système de Conversion d'énergie Éolienne.

DEDICATION

I dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents whose words of encouragement and push for tenacity ring in my ears. Also, I dedicate this work to all those who have contributed directly or indirectly to the success and the successful completion of this work. That they find traces in this memory of my deep gratitude.

Amina

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LIST OF SYMBOLS AND ABBREVIATIONS

WECS	Wind Energy Conversation System
DFIG	Doubly Fed Induction Generator
IM	Induction Machine
ITSC	Inter-Turn Short-Circuit
FDD	Fault Diagnosis and Detection
FDI	Fault Diagnosis and Isolation
FTC	Fault Tolerant Control
FOC	Stator Field-Oriented Control
PI	Proportional Integral
SMC	Sliding Mode Control
SMO	Sliding Mode Observer
HOSM	High Order Sliding Mode Observer
UIO	Unknown Input Output
VFC	Variable Frequency Converter
V_{Wind}	Wind turbine speed
ρ	Air density
C_p	Power coefficient
λ	Tip-speed ratio
β	Blade pitch angle
G	Drive train gear ratio
abc	Three-phase reference frame
dq	dq reference frame
s, r	Stator and rotor index
P_s	Active power
Q_s	Reactive power
f	Frequency
l_s	Stator's self-inductance
l_r	Rotor's self-inductance
$l_{\sigma s}$	Stator leakage inductance
$l_{\sigma r}$	rotor leakage inductance
M_s	Mutual inductance between two stator phases
M_r	Mutual inductance between two rotor phases
m_{sr}	Mutual inductance between stator and rotor phase

J	Moment of inertia of the low-speed shaft
f_{vis}	Viscous friction coefficient
T_{em}	Electromagnetic torque
T_{vis}	Viscous friction torque
T_g	Generator torque
Ω_{mec}	Mechanical speed
p	Number of pole pairs
ω_s	stator speed
ω_r	rotor speed
θ_s	Angle between stator phase and Park's axis
θ_r	Angle between rotor phase and Park's axis
A	State matrix
B	Control matrix
$x(t)$	State vector
u	Control vector
$\hat{x}(t)$	Estimate of state vector
γ	Fault level parameter (percentage of the shorted turns)
E_x	Fault position vector
r_f	Fault resistance
I_f	Fault current
T_{32}	Transformation matrix (from abc to dq)
T_{23}	Inverse transformation matrix (from dq to abc)
$I_{n \times n}$	Identity matrix with dimension n
$0_{n \times m}$	Zero matrix with dimension $n \times m$
R	Space of real numbers
$R^{n \times n}$	$n \times n$ dimensional real space
A^T	Transpose of vector or matrix A
A^{-1}	Inverse of matrix A
$ \cdot $	Absolute value
$\lambda_{max}(A)$	Maximum eigenvalue of matrix A
$\lambda_{min}(A)$	Minimum eigenvalue of matrix
A_i	i^{th} element of vector A
$\frac{\partial(\cdot)}{\partial \theta}$	Partial differential operator
$\times$	Cross product
$+, -$	Positive and negative sequence components
$*$	Reference value

GENERAL INTRODUCTION

The availability of conventional energy sources is limited, and they contaminate the environment. As a result, increasing emphasis has been placed on the use of renewable energy sources. Due to its economic feasibility, wind energy is the fastest growing and most promising renewable energy source. Wind turbine generator systems are now widely available, and their number is steadily increasing. There are different generator technologies adopted in wind turbine generator systems, but the most promising type of wind turbine for the future market is the Doubly-Fed Induction Generator (DFIG) wind turbine [1,2].

Newly, DFIG, as a variable speed generator, has generated considerable interest in the application of wind energy. The use of DFIG could provide many advantages, such as operating over a wide range of rotor speeds and reducing the amount of power recovered by the converter with an essential rarity in the cost of the converter, less mechanical complexity, easy maintenance; in addition, this machine can operate either in grid-connected or standalone mode [3-5].

Nevertheless, DFIG-based Wind Energy Conversion System (WECS) is usually affected by diverse disturbances and faults scenarios as described in [6-9], such as short circuit in ‘abc’ phases, current sensor faults ... etc. Thus, stator windings are subject to insulation failure, machine bearings are subject to excessive wear and damage, etc. This is caused by a combination of thermal, electrical, mechanical, magnetic and environmental stresses [10-12]. These disturbances and faults have many adverse effects on the normal behavior of the real system [13-15], so the possibility of DFIG failures is unavoidable because many of its components are sensitive to failure [16,17].

In fact, there are many publications about stator Inter-Turn Short-Circuit faults (ITSC) of DFIG that confirm the danger of these faults, (see [18-22]), which can cause phase-to-phase or phase-to-ground faults. As a result, this may cause the system performance’s decrease as well as the complete system failure. Accordingly, fault detection and isolation of stator ITSC faults are necessary since control systems rely on information provided by measured signals [23-27]. Fault Diagnosis and Detection (FDD) of DFIG defects has been the subject of considerable research interest, [28-33], due to its great influence on the operational continuation of certain industrial processes. Correct diagnosis and early detection of emerging defects result in rapid unplanned maintenance and short downtime for the process under consideration. It also avoids harmful, sometimes devastating consequences, and helps to reduce financial loss.

The FDD of stator ITSC and current sensor faults is possible by means of several methods,

that can be classified into external methods (approach without model) based on measured inputs and outputs, such as intelligent systems [34–36], statistical analysis systems [37, 38], Fast Fourier Transform (FFT) [39, 40], and internal methods (approach with model), such as the observational approach [26, 41, 42]. Using these techniques, the faulty current is detected by analyzing the residual between the measured and estimated currents. In these studies, different state observers have been used to estimate the current that was already measured.

In recent years Guezmil A., et al. In [43], have designed an active FTC for ITSC fault on Induction Machine (IM) based on sliding mode, by using the Lyapunov stability theory. An online diagnosis using a High Order Sliding Mode Observer (HOSM) allows the fault detection and phase identification on the one hand and provides signal alarm on the other. Another method is presented in [44], authors use banks of Unknown Input Output (UIO) in the model-based fault detection and isolation schemes in order to detect and isolate the ITSC fault and reduce or almost eliminate unknown disturbances' effect. A fault diagnosis method for IM is designed and implemented on the d-Space DS1103 platform. It is worth pointing out that this technique has a characteristic of being low cost.

Yu, W., et al. In [45], in this paper, a fault detection method of novel sliding mode observer is proposed, without a velocity sensor. In addition to better elimination of chattering for the new sliding mode observer (SMO), at the same time, it has better stability and faster convergence speed than the traditional sliding mode observer.

Tegui, J. B., et al. In [46] proposes an alternative strategy to the use of a speed sensor in the implementation of active and reactive power-based model reference adaptive system estimator in order to calculate the rotor and stator resistances of an IM and the use of these parameters for the detection of ITSC faults in the stator of this motor. Compared to existing works in the literature [43–46]. The main goal in this doctorate thesis is focused on the proposed new and easy approach based of Fault Tolerant Control (FTC) and FDD schemes to detect isolate and compensate the faults that occurs in DFIG-based WECS, under fixed and random wind speed. This approach is based on the Sliding Mode Observer designed from a three-phases faulty model of the DFIG.

Generally, the principal faults can broadly be classified as sensor faults, actuator faults, and system faults [47]. In particular, this work focuses on two fault scenarios, DFIG with ITSC fault as an actuator fault and current sensor fault. The aim of choosing these two fault scenarios is because the ITSC of the stator winding and the current sensor faults are the most common faults in induction machines, and it is a typical electrical fault of DFIG [48]. Moreover, a significant number of authors studied these faults [10, 12, 16, 18], but they focused on other types of Induction Machines, mainly squirrel cage induction machines [49]

or induction machines in 'dq' coordinate [21,26], but in this work, we studied these types of faults for DFIG-based WECS in three-phases coordinate. Furthermore, in DFIG, the methods for diagnosis, identification, and isolation of these types of defects are primarily dependent on external methods such as artificial intelligence and Fast Fourier Transform [35,37], whereas in this work we concentrated on internal methods (approach with model), particularly the Sliding Mode Observer.

The main contributions of this doctoral thesis are summarized as follows

1. DFIG modeling with ITSC faults is analyzed. This model is used to represent the fault in a single phase (namely a single-phase short circuit fault). By using this model, the short circuit faults at any level and in any phase can be quantitatively represented. This proposed model provides a basis for studies of model-based FDD and FTC approaches, and also provides a model test bench for evaluating other approaches.

2. A SMO Scheme is very effective and derived to generate a set of residuals that are used not only to detect the faults but also to isolate the fault that occurs, and it has been examined to ensure the non-stop operation of DFIG-based WECS subject to fault.

3. Diagnosis and compensation of ITSC faults.

4. The proposed FTC scheme of DFIG-based WECS is subject to current sensor fault. It can ensure perfect reference tracking of the torque and reactive power in the presence of a current sensor fault. In addition, a robust control algorithm is proposed, which can ensure desired control performance against model uncertainties.

The outline of this doctorate thesis is given as follows :

General Introduction as already noted gives general background and describes the general structure of the work.

Chapter 1 gives an overview and a brief introduction to the field of fault diagnosis and FTC. Additionally, their applications to DFIG-based WECS are investigated. Furthermore, we present the three-phase dynamic model (in the natural 'abc' coordinate) of the DFIG-based WECS with stator ITSC fault.

Chapter 2 in this chapter, a traditional control strategy (vector control with field-oriented control) is implemented to control of stator active and reactive power of DFIG-based WECS in order to maximize the power developed by the stator windings. This control is tested and synthesizing firstly by conventional Proportional - Integral type regulators and compared to Sliding Mode Controller.

Chapter 3 proposed a FDD approach based on Sliding Mode Observer to generate a

residuals signal to detect and isolate Single-Phase Short Circuit Fault in DFIG-based WECS. Meanwhile.

Chapter 4 develop a FDD method based on the observer for DFIG with current sensor fault, then generate residuals from the actual and estimated currents obtained by SMO to isolate the fault and correct it thereafter.

Finally, a general conclusion that summarizes the research outcomes of this thesis and some perspectives will be introduced.

CHAPTER 1

GENERALITIES

1.1 Introduction

This chapter will carry out a bibliographical synthesis of the field of fault diagnosis and Fault Tolerant Control (FTC) as well ; its application to wind turbine systems is investigated. It starts with Section 1.2 a general description of wind turbine conversion systems by presenting their components. Section 1.3 introduces the current faults in the DFIG-Based Wind Energy Conversion System. Section 1.4 summarizes the available methods used in the field of fault diagnosis and FTC in wind turbine systems. Section 1.5 presents a model of DFIG-based WECS.

1.2 Wind Turbine Conversion Systems

The demand of energy over the globe is unremittingly growing owing to the growing of population, energy consumption per capita and huge industrialization. The availability of conventional fossil fuels is limited. Thus, energy crises in the future will be increasing more. Therefore, the use of renewable energy sources, such as solar, wind [50], biogas [51], ocean [52], tidal [53], and so on is emerging at tremendous rate. Among these, wind energy is one of the most promising and fastest growing renewable energy sources in recent years [54].

The wind turbine includes several components, which contribute, with their specific function, to the energy conversion process. Figure 1.1 illustrates the main components of a modern wind turbine. which are, to a greater or lesser extent, common for all wind turbine concepts. From left to right, there are the aerodynamical and mechanical part of the wind turbine (aerodynamic rotor and gearbox), the electrical system (generator, power electronic interface and transformer) and finally its connection to the grid. An interaction with the control system is indicated as well [55].

1.2.1 Doubly Fed Induction Generator (DFIG)

The DFIG is broadly employed in wind turbines. It is commonly composed of an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with different brushes that make it easily to approach the varied rotor windings (Figure 1.2) [8].

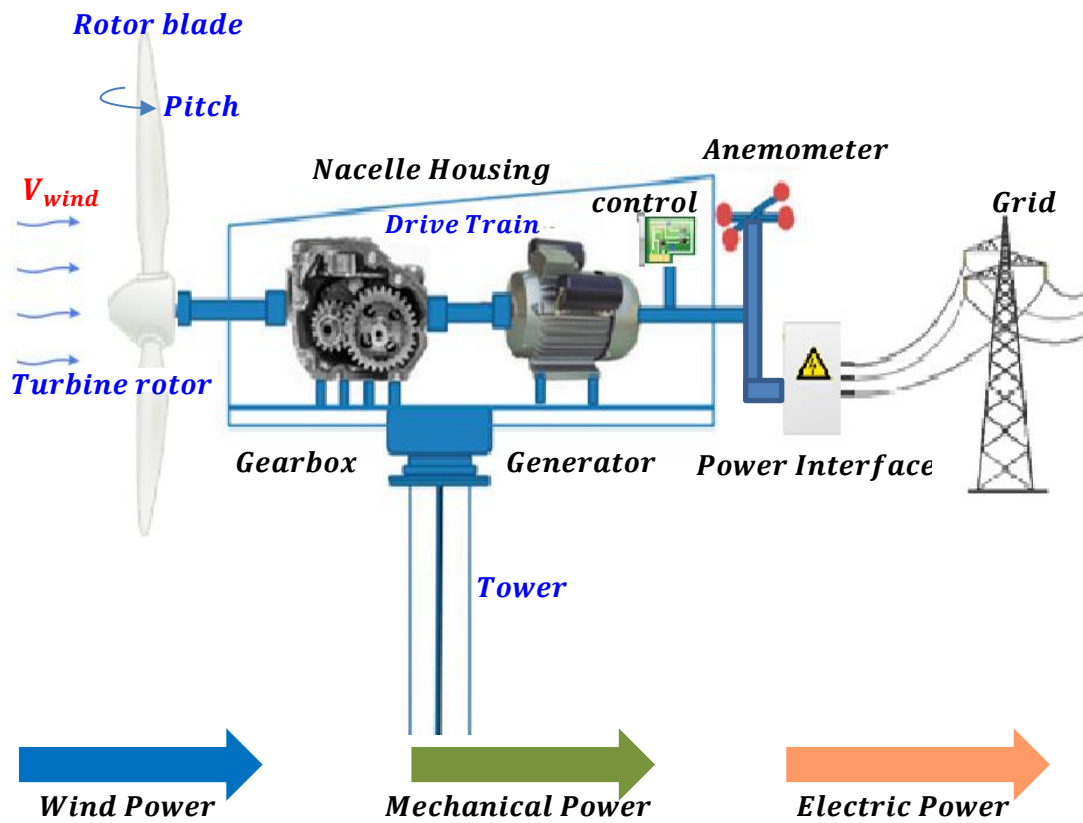


FIGURE 1.1 Wind turbine components

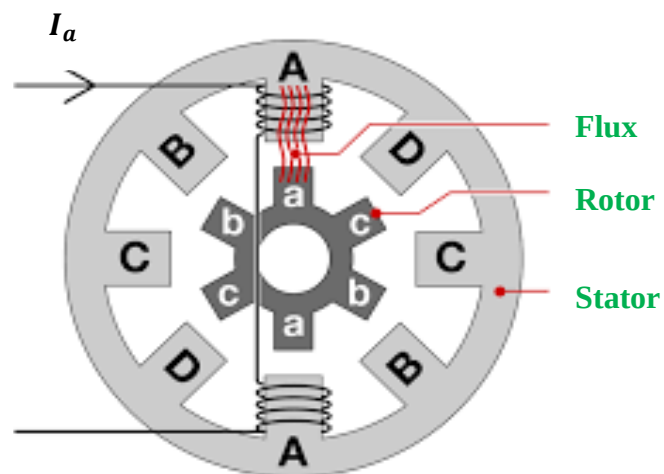


FIGURE 1.2 Doubly Fed Induction Generator (DFIG)

For wind power applications, this type of machine has distinct advantages over the conven-

tional type of machines [56].

- Wide range of variable speed operation is possible.
- Stator is never been fully loaded and stress on the windings is also less and hence heat generation is also less. This leads to the reliability and ruggedness of the generator.
- Highly capable of low wind sites in order to capture the maximum power available in the wind.
- Cost of the system is less when compared to fully fed wind turbines since rating of the required power converter is just even less than the 1/3 of the nominal power.
- Robust and well proven technology.

1.3 Fault Versus Failure

Wind power plants are commonly found in multifaceted terrain and bad climates. The WECS are considered an essential part. It is characterized by its high fault rate, in its sensor and actuator in particular. Its impact on the performance of the system can be highly noticed, resulting in the system's breakdown and innumerable damages. Therefore, realizing the fault tolerant control of WECS is an important guarantee for improving the operation reliability of wind power generation systems [57]. A brief review of fault-diagnosis concepts containing basic definitions and classifications which is essential to the reader is covered in this section.

- **Fault** a fault in dynamical systems is a deviation of the system structure or the system parameters from the nominal situation [58].
- **Failure** inability of a system or a component to accomplish its function [60] [?, ?].
- **Disturbances** an unknown input included in the system's model. It can be incertitude, noise or a nonlinearity term. It has a considerable affect in process's performances. It is an event that occurs when the delivered service deviates from correct service. A service fails either because it does not comply with the functional specification, or because this specification did not adequately describe the system function [59].

An important note is worth mentioning, here, regarding the relevant connotation and the accurate usage in the engineering terminology of both failure and fault, a fault causes a change in the characteristics of a component such that the mode of operation or performance of the component is changed in an undesired way. Hence the required specifications on the system performance are no longer met. Compared to the word fault, the failure indicates the fact that a component or a system is not capable of successfully accomplishing its role and task, taking into account that the failure is an irretrievable incidence and then the system or the component should be switched off.

1.3.1 Different Types of Faults

The faults are often classified as follows (Figure 1.3)

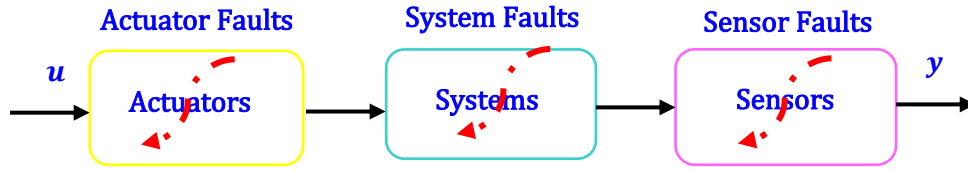


FIGURE 1.3 Different types of faults

- **Sensor faults** the sensor readings have substantial errors.
- **Actuator faults** the influence of the controller on the plant is interrupted or modified.
- **System faults** dynamical properties of the plant are changed. Note that faults can occur both in component level and overall system level.

The effects of a fault in a single component may be of minor importance to the component itself. However, due to fault propagation throughout the overall system, the fault may eventually cause system failure. It would be very beneficial if fault-tolerant control is applied in component level wherever is possible [60].

1.4 Fault in DFIG-based Wind Energy Conversion System

DFIG has a fixed part called a stator which consists of a three-phase winding placed in the notches of the magnetic circuit and a moving part called a rotor (Figure 1.2). There are, in fact, a lot of faults that can occur in the DFIG, but the common faults are current sensor fault, bearing faults, stator and rotor winding insulation failures. They lead to the short circuits as well as turn-to-turn faults in the rotor and stator windings [61, 62]. In this doctoral thesis, we focus on investigating the behaviors of DFIG-based WECS in the presence of a common electrical fault (i.e., stator ITSC and current sensor fault).

1.4.1 Stator Faults

Stator windings may have different types of faults. However, there are mainly four typical stator faults : turn to-turn fault, Phase-to-Phase short fault, Phase-to-Ground short fault and open circuit coil fault (Figure 1.4). These are asymmetric faults, which are typically associated to insulation failures, caused by various reasons such as ; poor connection, overloading and

overheating, Figure 1.4 shows these main four faults. An open circuit in the stator winding will affect the distribution of the stator Magneto-Motive Force (MMF) in the air gap [63].

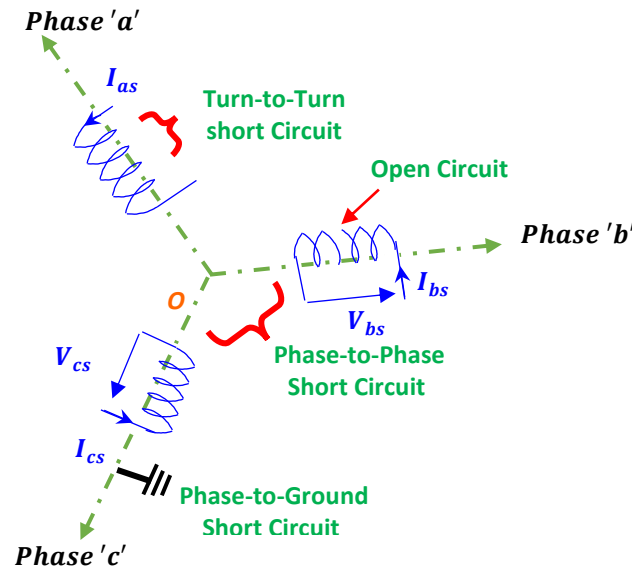


FIGURE 1.4 Different three-phase stator winding faults

1.4.2 Inter Turn Short-Circuit Fault

Short-circuited turns affect the DFIG operation and cause high levels of vibration. Knowing that the three-phase winding of the rotor is similar to that of the stator; therefore, the faults which can affect the rotor winding are of the same type as the stator faults such as short-circuits between turns of windings of the same phase, or of different phases, phase-to-ground short-circuits, or phase opening, which cause asymmetry in the rotor [64].

1.4.3 Current Sensor Fault

Sensor is used to measure the electrical or mechanical variables of the machine. There are types of sensors that are used in DFIG, current sensors and a speed sensor. The failure of one of the sensors leads to serious operating problems [65].

1.5 Fault Diagnosis and Fault Tolerant Control of the DFIG-based WECS

In recent years, many works have been proposed on the topics of fault diagnosis of wind turbines to detect and isolate the possible particular faults [30-32,66]. Fault diagnosis applied to safety-critical systems such as wind turbines has been proven to be a challenging issue

[67]. A brief review of Fault Diagnosis and Fault Tolerant Control concepts containing basic definitions which is essential to the reader is covered in this section.

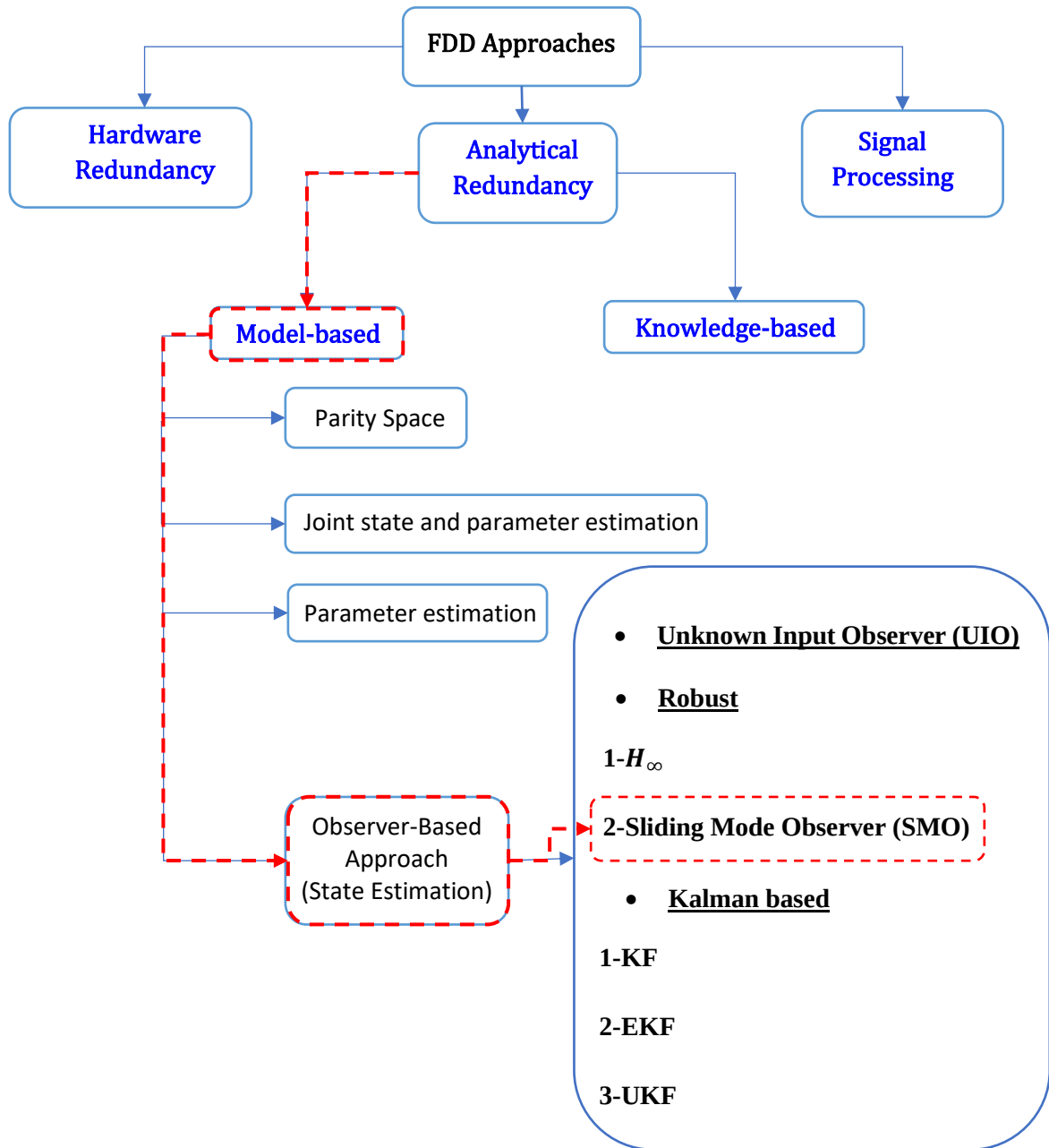


FIGURE 1.5 Classification of the model-based FDD approaches.

1.5.1 Fault Diagnosis Detection Approaches

The main tasks of the FDD algorithm consist of :

- **Fault Detection** (indicate whether a fault occurs in the monitored system).
- **Fault Isolation** (determine the exact location of the fault).
- **Fault Identification** (determine the size of the fault).

Many different FDD approaches have been developed, which are summarized in some survey literature [38, 68, 69]. These approaches can be classified according to the diagram of the Figure 1.5.

1.5.2 Analytical Redundancy

Analytical redundancy employs mathematical model of the system under examination. Frequently, researchers of previous studies in fault diagnosis refer to analytical redundancy as model-based fault diagnosis. Comparing measured signals (from the actual system) and generated signals (estimated from a mathematical model of the process) can help achieve fault diagnosis, making use of analytical redundancy. As stated previously, the difference between the measured signals and the signals generated by the mathematical model forms the residual. The decision whether or not an alarm signal should be identified is taken after the use of a diagnostic logic that helps to evaluate this residual. Some problems may occur when using analytical redundancy as there can be a false alarm rise due to poor mathematical model of the process, high system noise and modelling errors [?].

1.5.3 Observer Based Approach

Observers are dynamic systems that can be used to estimate the state of a system using its input-output measurements. The use of observers for fault detection is based on the total or partial reconstruction of the output vector, through an estimate of the state vector, due to the measurable signals of the monitored system. The difference between the reconstructed outputs and the actual outputs, optionally followed by a filter, allows the generation of residues (Figure 1.6). However, there is a basic distinction between the use of the observer to reconstruct the states vector and the observer to detect the fault [70].

When the fault appears, these inputs become non-zero. The role of the observer, realized on the basis of the system without fault, is that it must then react very rapidly. It is also required of this indicator not to confuse fault and disturbance. So, to achieve a reliable detection system, the observer synthesis must be performed to detect faults and eliminate the effect of disturbances [71].

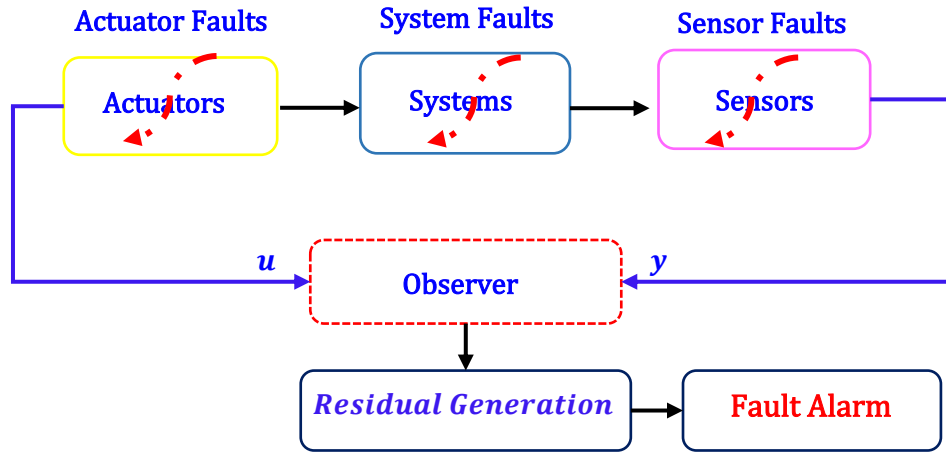


FIGURE 1.6 Generation of residuals by observer-based approach

1.5.4 Generation of Residuals

The residuals, noted by the vector r , are the signals indicating the presence of fault. They reflect the inconsistency between the behavior obtained and that expected of the monitored process. They must be sensitive only to faults [72].

The structuring of residues represents a way to reinforce their performance. A subset of residues is then intended for a particular defect. The advantage of structuring the sets of residues is to simplify their analysis, to determine which of them has become zero. The threshold test can be carried out separately for each residue, leading to a Boolean decision, (a '1' corresponds an active residual); thus, making it possible to structure a signature table, also called incidence matrix. Distinguishing three cases for a signature table (an example is given in Figure 1.7 by a '0', an interesting case, for the isolation of multiple faults, corresponds to a diagonal structure [73].

	f_1	f_2	f_3
r_1	1	1	1
r_2	1	1	1
r_3	1	0	0

Not insulating

	f_1	f_2	f_3
r_1	1	1	1
r_2	1	0	1
r_3	1	1	0

Weakly insulating

	f_1	f_2	f_3
r_1	1	1	0
r_2	1	0	1
r_3	0	1	0

Highly insulating

FIGURE 1.7 Different situations for an incidence matrix

1.5.5 Fault Location

To solve the fault localization problem, the idea is to build a bank of q observer, each one excited by a carefully selected set of system inputs and outputs. Each vector of residues $r_1(t) \dots r_q(t)$ is sensitive to a set of the fault. There are two strategies

- **The DOS Strategy** (Dedicated Observer Scheme) when the fault influences only one residue vector.
- **The GOS Strategy** (Generalized Observer Scheme) when the fault influences all vectors of residues except one [74].

1.5.6 Detection and Problem of Threshold

The main detection difficulty lies in the calculation of the residual threshold. A threshold can be risky to generate a non-detection. A too small threshold would result in false alarms. The problem is therefore to find an optimal threshold that would be the ideal compromise between the rate of false alarms and the rate of non-detection; this is called thresholding problem [75]. So, the assessment of the residues will become a problem of determining a threshold ε such that

$$r(t) \geq \varepsilon : \text{there is fault in the system. } r(t) < \varepsilon : \text{no fault in the system.}$$

1.6 Fault Tolerant Control (FTC)

FTC is an advanced control technique that can accommodate system faults, assure system stability, and maintain acceptable performance, not only under normal condition but also in the presence of faults. Several survey papers present a comprehensive review on development of FTC system [43, 65, 76]. The FTC can be generally divided into two approaches : the passive and active approaches. The general structure of FTC system is shown in Figure 1.8.

1.6.1 Passive FTC

In this approach, the same controller is used throughout the normal condition as well as the fault condition. Since only one fixed controller is used in the entire control process, the passive FTC is easily to be implemented. However, it can only tolerate a limited number of faults, which are assumed known prior to the controller design. Besides, as the number and level of the faults increase, this approach becomes very conservative, and attainable performance may become unsatisfactory. Most passive FTC algorithms are based on robust control techniques by treating the faults as model uncertainties or disturbances [77].

1.6.2 Active FTC

In this approach, the controller reacts to the system fault actively and allows online fault accommodation. An active FTC system can reduce the fault effects by online changing the parameter or the structure of the controller [78].

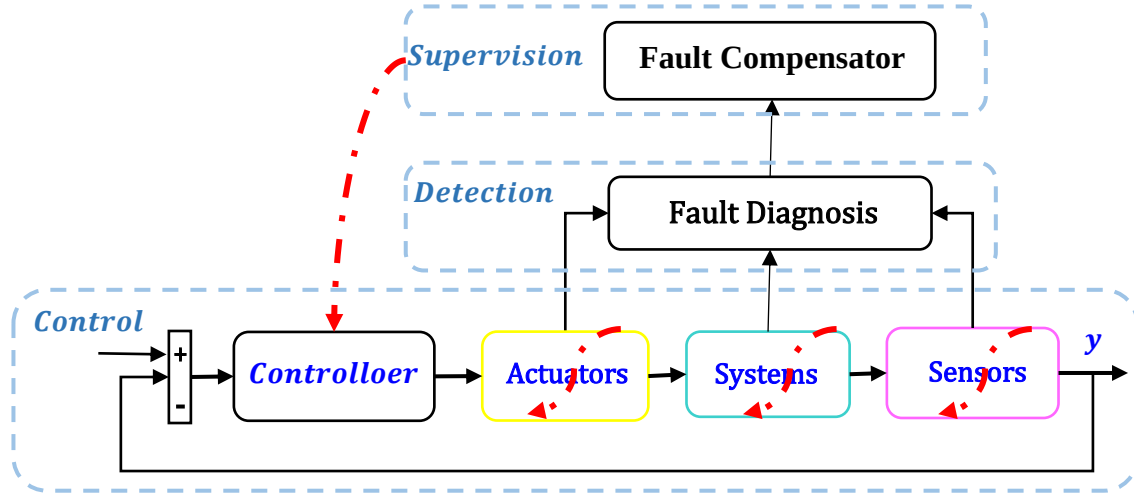


FIGURE 1.8 General structure of FTC system

1.7 Modeling of DFIG-based WECS with ITSC

The mathematical modelling of the DFIG-based WECS with ITSC is the first step in the development of the fault diagnosis scheme. It can be easily obtained by representing the electrical and magnetic relationships among these phase windings using circuit theory [79]. This idea is firstly brought by Tallam [80], where a simple model of induction motor was developed. A similar work for DFIG is presented in [81]. Both modeling results are supported by experimental data, whereas both of the work considers a special case that the short circuit only occurs at the stator phase 'a'.

In this chapter, general mathematical model of DFIG for single-phase is proposed. The model is developed in the natural 'abc' coordinate. The DFIG model presented below assumes that the stator and rotor consist of the three sinusoidal windings displaced by an electrical angle of 120° with respect to the single-phase short circuit fault. In this model, the short circuit fault is represented by two parameters, fault level parameter γ (as in eq. (1.1)) and fault position parameter E_x (as in eq. (1.2)). γ represents the percentage of the shorted turns which is used to quantify the severity of the fault. It is calculated by the following formula [82].

$$\gamma = \frac{\text{Number of shorted turns}}{\text{Total number of turns in a healthy phase}} \quad (1.1)$$

Where $0 \leq \gamma \leq 1$. $\gamma = 0$ corresponds to the healthy condition. E_x :represents the fault position parameter, which is defined as follows for three cases, where fault occurs in phase a, b and c , respectively with :

$$E_a = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}; E_b = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}; E_c = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}; \quad (1.2)$$

1.7.1 Model of DFIG with Single-Phase ITSC Fault in ‘abc’ Coordinate

The winding configuration of a DFIG with a stator ITSC fault in stator phase ‘a’ is shown in Figure 1.9 In natural reference frame and based on the notation of Figure 1.8, it can be seen that the fault splits the faulty phase into two parts, the shorted turns (a_1s) and un-shortcd turns(a_2s).The shorted turns (a_2s) form a closed-loop circuit, which can be modelled as a new phase of the stator. As well, it is known that the rotor of DFIG has three phase windings. Therefore, this faulty DFIG can be interpreted as a multi-phase induction machine with 4 stator phase windings and three rotor phase windings. Using this strategy, the mathematical model of the faulty DFIG can be easily obtained by representing the electrical and magnetic relationships among these phase windings using circuit theory. In this subsection, we developed the model for a special case where the fault only occurs at stator phase ‘a’. In the next, this model is generalized to represent the fault in any single phase of the stator. However, this model neglects several factors that influence the behavior of an actual wind turbine with DFIG configuration (which many would argue makes this model simplified).

The following assumptions have been made for this detailed model [83,84]

- Each stator phase of the machine has the same number of turns and uniform spatial displacement (The machine is symmetrical).
- The three-phase stator and rotor windings are sinusoidally distributed.
- The machine is operating at an unsaturated point.
- The skin or slot effect is not considered.
- Iron losses are neglected.
- Insulation break resistance r_f is negligible.

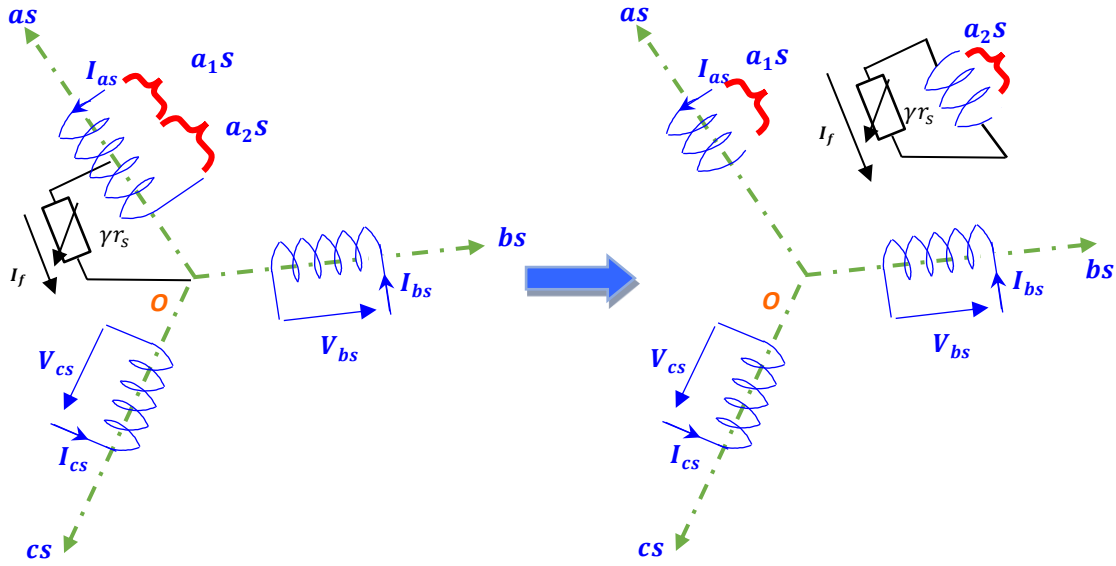


FIGURE 1.9 Stator winding configuration with a short circuit fault in stator phase 'a'.

1.7.2 Generalized DFIG Model

As described earlier, a DFIG with a single-phase short circuit fault can be interpreted as a multi-phase induction machine with four stator phases and three rotor phases. By taking the case that fault in stator phase 'a' as an example [82], a general model of DFIG is given as follows : Voltage equation

$$\begin{bmatrix} V_{abcs} \\ V_{abcr} \\ \dots \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0_{3 \times 3} & \vdots & -\gamma r_s E_x \\ 0_{3 \times 3} & R_r & \vdots & 0_{3 \times 1} \\ \dots & \dots & \vdots & \dots \\ \gamma r_s E_x^T & 0_{1 \times 3} & \vdots & -\gamma r_s \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \\ \dots \\ I_f \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{abcs} \\ \varphi_{abcr} \\ \dots \\ \varphi_{a_2s} \end{bmatrix} \quad (1.3)$$

Flux equation :

$$\begin{bmatrix} \varphi_{abcs} \\ \varphi_{abcr} \\ \dots \\ \varphi_{a_2s} \end{bmatrix} = \begin{bmatrix} L_{ss} & M_{sr} & \vdots & -\gamma L_{ss} E_x \\ M_{rs} & L_{rr} & \vdots & -\gamma M_{sr} E_x \\ \dots & \dots & \vdots & \dots \\ \gamma E_x^T L_{ss}^T & \gamma E_x^T M_{sr}^T & \vdots & -\gamma L_{DD} \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \\ \dots \\ I_f \end{bmatrix} \quad (1.4)$$

This is a general model for the single-phase short circuit fault, which can represent the stator ITSC fault at any level in any stator phase, by setting appropriate values of parameters

γ and E_x according to eq. (1.1) and eq. (1.2). where the subscripts 's' and 'r' denote stator and rotor, and the subscripts 'a', 'b' and 'c' denote phase 'a', 'b' and 'c'; V_{abs} and V_{abcr} represent the voltages of stator and rotor phases; I_{abs} and I_{abcr} represent the currents of stator and rotor phases; I_f is the short circuit current. φ_{abcs} and φ_{abcr} are the magnetic fluxes for the stator and rotor phases. Therefore, the variable vectors are given as :

$$\begin{aligned} V_{abs} &= \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}; V_{abcr} = \begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix}; I_{abs} = \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix}; \\ I_{abcr} &= \begin{bmatrix} I_{ar} \\ I_{br} \\ I_{cr} \end{bmatrix}; \varphi_{abs} = \begin{bmatrix} \varphi_{as} \\ \varphi_{bs} \\ \varphi_{cs} \end{bmatrix}; \varphi_{abcr} = \begin{bmatrix} \varphi_{ar} \\ \varphi_{br} \\ \varphi_{cr} \end{bmatrix}; \end{aligned}$$

The parameter matrices of model of eq. (1.3) and (1.4) are given as :

$$R_s = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix}; R_r = \begin{bmatrix} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{bmatrix}; \quad (1.5)$$

$$L_{ss} = \begin{bmatrix} L_{\sigma s} + M_s & \frac{-M_s}{2} & \frac{-M_s}{2} \\ \frac{-M_s}{2} & L_{\sigma s} + M_s & \frac{-M_s}{2} \\ \frac{-M_s}{2} & \frac{-M_s}{2} & L_{\sigma s} + M_s \end{bmatrix}; L_{rr} = \begin{bmatrix} L_{\sigma r} + M_r & \frac{-M_r}{2} & \frac{-M_r}{2} \\ \frac{-M_r}{2} & L_{\sigma r} + M_r & \frac{-M_r}{2} \\ \frac{-M_r}{2} & \frac{-M_r}{2} & L_{\sigma r} + M_r \end{bmatrix}; \quad (1.6)$$

$$M_{sr} = m_{sr} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r) & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r) \end{bmatrix}. \quad (1.7)$$

With r_s and r_r represent the stator and rotor resistances. $L_{\sigma s}$ and $L_{\sigma r}$ represent the stator and rotor leakage inductances. θ_r represents the electrical angle between the stator and rotor. M_s and M_r represent the mutual inductances of the stator and rotor. m_{sr} represents the stator-rotor mutual inductance. By referring the rotor parameters to stator side, these mutual inductances are equal :

$$L_{DD} = L_{\sigma s} + M_s \quad (1.8)$$

$$M_{rs} = M_{sr}^T \quad (1.9)$$

1.7.3 The Mechanical Equation

The mechanical equation of DFIG is written as [82] :

$$\left\{ \begin{array}{l} J \cdot \frac{d\omega_r}{dt} = T_{em} - T_g - f_r \omega_r \\ T_{em} = p(I_{abcs}^T \frac{\partial M_{sr}}{\partial \theta_r} I_{abcr} + \gamma E_x^T I_f \frac{\partial M_{sr}}{\partial \theta_r} I_{abcr}) \\ \frac{d\theta_r}{dt} = \omega_r \end{array} \right. \quad (1.10)$$

1.8 Summary

This chapter presents an overview on the DFIG-based WECS concepts and emphasizes their different characteristics. The first part is devoted to general information on wind turbines, accompanied by a state of the art on electromechanical conversion. Then, we showed that the DFIG-based WECS can present failures which lead, for most of them, to an untimely shutdown of the generator, or even of the process. For overcome this problem the fault detection has become important. Wherefore, in the second part we summarized the available methods used in the field of fault diagnosis and FTC. In Section 1.7 a mathematical model of DFIG-based WTCS with stator ITSC fault was proposed, where a set of new parameters were introduced to quantitatively represent the fault.

CHAPTER 2

Control of DFIG-based WECS

2.1 Introduction

Control systems technology is significant and undeniable for wind turbine operation. As for DFIG, the main function is to sustain magnitudes of the high-speed shaft torque, active and reactive power of the generator, and grid side converter magnitude such as the DC bus voltage and the reactive power, close to their optimum values, so as to accomplish an effective energy generation [85].

In this chapter, vector control-based Field Oriented Control (FOC) is implemented to control the stator active and reactive power of the DFIG-based WECS in order to maximize the active power developed by the stator windings. This control is developed and tested by synthesizing firstly by conventional Proportional - Integral type regulators and compared with Sliding mode controller. Then in a MATLAB / Simulink environment, we will present the results which make it possible to analyze the behavior of the variables of the DFIG-based WECS with ITSC fault.

2.2 Control of DFIG-based WECS

The control of the DFIG-based WECS has two objectives [86]

- The decoupled output (i.e., electromagnetic and reactive power) control.
- Maximize the active power.

The conventional approach for the first objective is Field Oriented Control, which can be realized by the two independent rotor current regulations on the stator flux-oriented coordinate. For the second objective, a recently proposed method, maximum power point tracking (MPPT) (see more [87]), has been extensively used in the wind power generation context. These two control strategies are always applied simultaneously to DFIG wind turbine systems.

2.2.1 Vector Control with Field Oriented Control

The purpose of the DFIG's variable speed control is to extract the maximum amount of wind power. For this, we need an algorithm acting on the setpoint variables in order to have the best possible performance of the device studied [88].

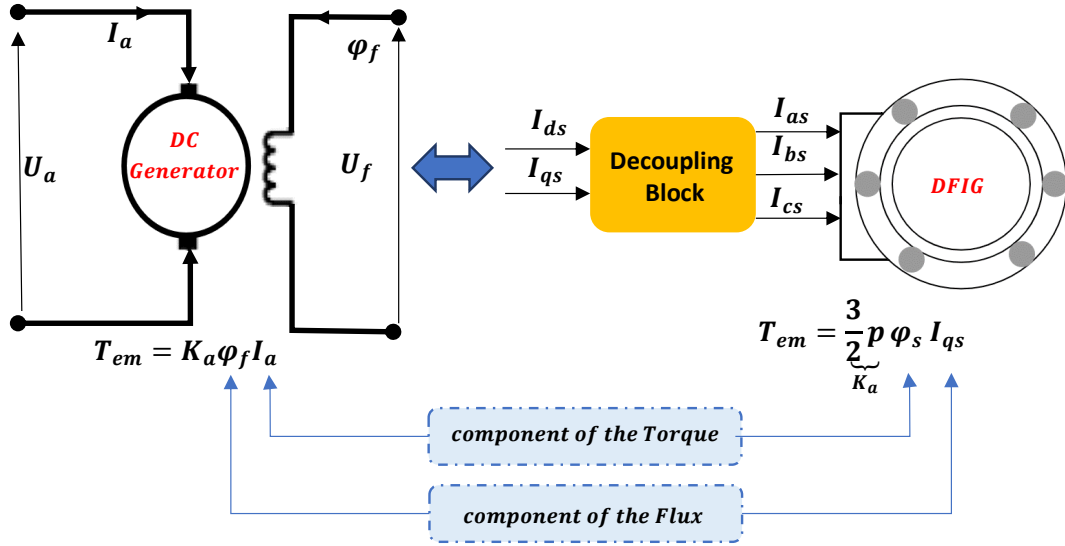


FIGURE 2.1 Analogy between control of the DC-generator and the DFIG

Since the control outputs of the DFIG (i.e., the electromagnetic torque and reactive power) are nonlinear in terms of the state variables (i.e., currents), a challenging task of the controller design is to deal with these output nonlinearities. The vector control is a commonly used approach to solve this problem. Another important advantage of this approach is that it allows the decoupled control of the electromagnetic torque and reactive power. Vector control is a control method that controls an AC machine as a DC machine with independent excitation, implying that the flux and torque can be controlled separately (Figure 2.1) [88].

Different types of vector control schemes have been presented in the literature [89, 90], which can be classified as shown in Figure 2.2.

The field-oriented control (FOC) proposed in 1970 by Blaschke [91] and Hasse [92] is based on an analogy with a mechanically commutated separately excited brushed DC motor. The main noticeable aspects in this motor are the separation of the excitation and armature windings, the control of the flux by the inductor excitation current, and the indirect control of the torque by the armature current regulation. Hence, the currents of the flux and the torque are electrically and magnetically separated. Figure 2.5 represents the principle of Field-Oriented Control.

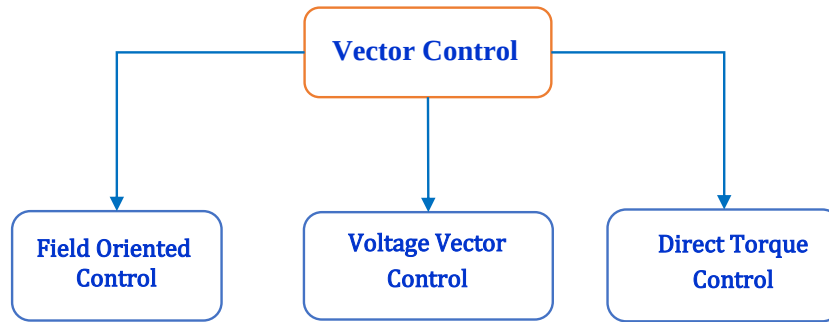


FIGURE 2.2 Different types of vector control schemes

2.2.2 Control of Active and Reactive Powers

In order to achieve the objectives of control, the DFIG is connected directly in the network on the stator side, moreover, the rotor circuit is supplied by a source of assumed constant DC voltage through an inverter controlled by the PWM technique.

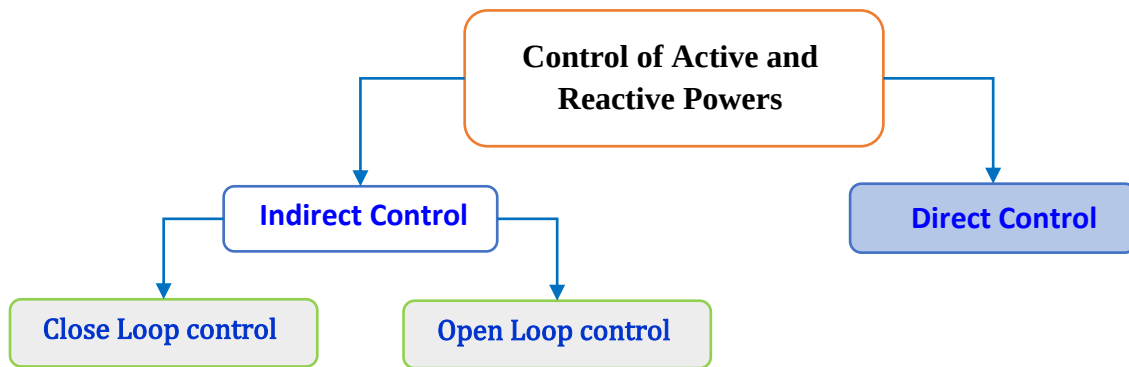


FIGURE 2.3 Control of Active and Reactive Powers

The purpose of vector control with FOC is to control stator active and reactive powers of the DFIG-based WECS with ITSC in order to maximize the active power. This control is developed and tested by synthesizing regulators. The reference values of these regulators will be the active power for the rotor axis q and the reactive power for the rotor axis d . The reactive power setpoint will be kept zero to ensure a unit power factor on the stator side so as to optimize the quality of the energy returned to the network. The active power setpoint should make it possible to keep the power coefficient of the optimum wind turbine. Figure 2.3 represents the different strategy used for controlling the active and reactive powers [93].

2.2.3 Model of DFIG in 'dq' coordinate

Recall that the dynamics of the healthy DFIG ($\gamma = 0$) in 'abc' coordinate is expressed by eq. (1.3) see more chapter 1. To simplify the model in eq. (1.3), the 'dq' transformation is applied to project the model into a two-axis stationary coordinate, known as stationary 'dq' coordinate. In this coordinate, q-axis is 90 degrees ahead of the d-axis, and d-axis coincides with stator phase 'a'. The stationary 'dq' coordinate and its relationship with the stator 'abc' coordinate and rotor 'abc' coordinate is presented in figure 2.4

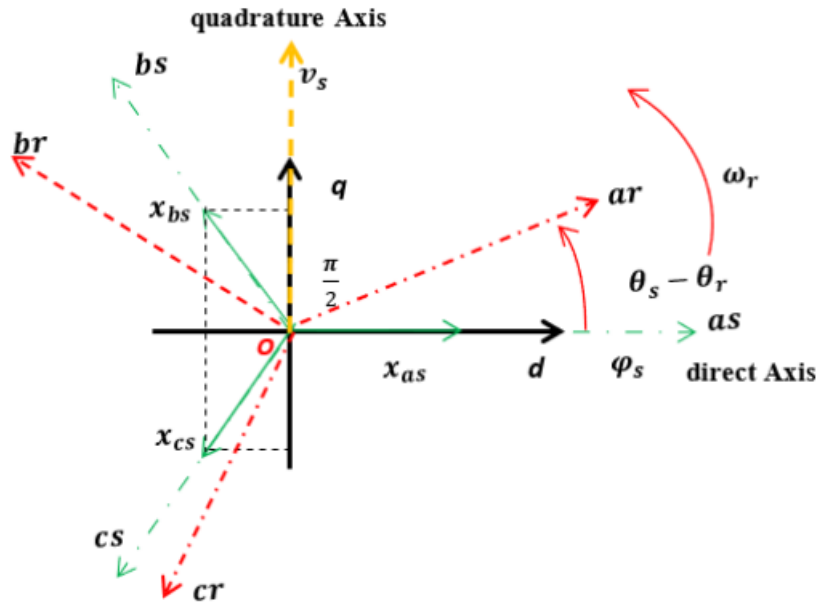


FIGURE 2.4 Principle of Field-Oriented Control

The general dq transformation matrix T_{32} (from 'abc' to 'dq') is given as [93] :

$$T_{32} = \frac{3}{2} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad (2.1)$$

Then the variables in the stationary 'dq' coordinate can be transferred from the variables in the 'abc' coordinate by following equation :

$$X_{dqs} = |T_{32}|_{\theta=0} X_s; \quad X_{dqr} = |T_{32}|_{\theta=-\theta_r} X_r; \quad (2.2)$$

So, the reduced model is written as follows :

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 \\ 0 & 0 & r_r & 0 \\ 0 & 0 & 0 & r_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_s & 0 & 0 \\ \omega_s & 0 & 0 & 0 \\ 0 & 0 & 0 & -\omega \\ 0 & 0 & -\omega & 0 \end{bmatrix} \begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} \quad (2.3)$$

With : $\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} = \begin{bmatrix} l_s & 0 & m_{sr} & 0 \\ 0 & l_s & 0 & m_{sr} \\ m_{sr} & 0 & l_r & 0 \\ 0 & m_{sr} & 0 & l_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix}$. Stator active and reactive powers in 'dq' coordinate given by [94] :

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} V_{ds} & V_{qs} \\ V_{qs} & -V_{ds} \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} \quad (2.4)$$

With stator flux constant and oriented $\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \end{bmatrix} = \begin{bmatrix} \varphi_s \\ 0 \end{bmatrix}$ and $\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} 0 \\ v_s \end{bmatrix}$.

If we neglect the stator resistance of the windings $r_s = 0$, an assumption often accepted for large power machines used for the production of wind energy [95], the DFIG voltage equations are reduced to the following form :

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} 0 & v_s \\ v_s & 0 \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} \quad (2.5)$$

The active and reactive powers are therefore in terms of the stator currents, we have no direct action. We must therefore look for a relation between the rotor currents and the stator currents. From the eq. (2.3) of the direct and quadrature component of the stator currents, we can write the equations relating the stator currents to the rotor currents as follows :

$$\begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} = \begin{bmatrix} \frac{-m_{sr}}{l_s} & 0 \\ 0 & \frac{-m_{sr}}{l_s} \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + \begin{bmatrix} \frac{v_s}{\omega_s l_s} \\ 0 \end{bmatrix} \quad (2.6)$$

By replacing I_{ds} and I_{qs} by their terms given by eq. (2.6), we obtain the following expres-

sions for the active and reactive powers :

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} 0 & \frac{-v_s m_{sr}}{l_s} \\ \frac{-v_s m_{sr}}{l_s} & 0 \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + \begin{bmatrix} 0 \\ v_s^2 \frac{\varphi_s}{\omega_s l_s} \end{bmatrix} \quad (2.7)$$

Taking into account the chosen of benchmark and the approximations, and if we consider the magnetizing inductance m_{sr} as a constant, the system obtained relates proportionally the active power with the rotor current of axis 'q' and the reactive power with the rotor current of axis 'd' at constant $\frac{v_s^2}{l_s \omega_s}$ near imposed by the network.

2.2.4 Rotor Voltages

From the system of eq. (2.3), the expressions of the rotor voltage equations can be written as follows :

$$\begin{aligned} \begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} &= \begin{bmatrix} r_r & 0 \\ 0 & r_r \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + \begin{bmatrix} l_r - \frac{m_{sr}^2}{l_s} & 0 \\ 0 & l_r - \frac{m_{sr}^2}{l_s} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} \\ &+ \begin{bmatrix} 0 & -g\omega_s(l_r - \frac{m_{sr}^2}{l_s}) \\ g\omega_s(l_r - \frac{m_{sr}^2}{l_s}) & 0 \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + \begin{bmatrix} 0 \\ g \frac{v_s m_{sr}}{l_s} \end{bmatrix} \end{aligned} \quad (2.8)$$

where : $g = \frac{\omega_s - \omega_r}{\omega_s}$ is the slip of the machine; $\sigma = (l_r - (m_{sr}^2)/l_s)$ In steady state, the terms involving the derivatives of the two-phase rotor currents disappear, we can therefore write [95] :

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} r_r & -g\omega_s \sigma \\ g\omega_s \sigma & r_r \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + \begin{bmatrix} 0 \\ g \frac{v_s m_{sr}}{l_s} \end{bmatrix} \quad (2.9)$$

V_{dr} and V_{qr} are the 'dq' components of the rotor voltages to be imposed on the DFIG to obtain the desired rotor currents;

$(l_r - \frac{m_{sr}^2}{l_s})$ is the coupling term between the two axes; $g\omega_s \frac{v_s m_{sr}}{\omega_s l_s}$ represents the coupling term between the direct and quadrature axis. For weak slips, this coupling term can be neglected in order to have perfect decoupling between the two axes [95]. However, for certain applications of the DFIG, the variation of the rotation speed can be important and the slip cannot be neglected; In this case, it is necessary to consider compensation terms to have control of each axis independently of the other.

To regulate powers optimally, we will set up two control loops on each axis with proportional integral controller for each, a loop on the power and the other on the current corresponding while compensating the terms of disturbance and couplings appearing on the block diagram model DFIG. We obtain the control structure shown in (Figure 2.6) [93].

$$\begin{bmatrix} V_{dr}^* \\ V_{qr}^* \end{bmatrix} = \begin{bmatrix} 0 & -g\omega_s\sigma \\ g\omega_s\sigma & 0 \end{bmatrix} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} + R(s) \begin{bmatrix} e_{dr} \\ e_{qr} \end{bmatrix} + \begin{bmatrix} 0 \\ g\frac{v_s m_{sr}}{l_s} \end{bmatrix} \quad (2.10)$$

$$\begin{bmatrix} I_{dr}^* \\ I_{qr}^* \end{bmatrix} = \begin{bmatrix} 0 & \frac{-v_s m_{sr}}{l_s} \\ \frac{-v_s m_{sr}}{l_s} & 0 \end{bmatrix} \begin{bmatrix} R_{seP_s} \\ R_{seQ_s} \end{bmatrix} + \begin{bmatrix} \frac{v_s m_{sr}}{\omega_s l_s} \\ 0 \end{bmatrix} \quad (2.11)$$

This structure results in a more complex regulatory system. However, it offers better robustness in the face of possible instabilities on the electrical network. The proportional integral regulator used for the control of currents and powers is simple and easy to set up while offering acceptable performance for use as a generator of the DFIG. In addition, the symmetry of the system after compensation leads to calculate the regulators for a single axis, the other two will be identical to the first [95].

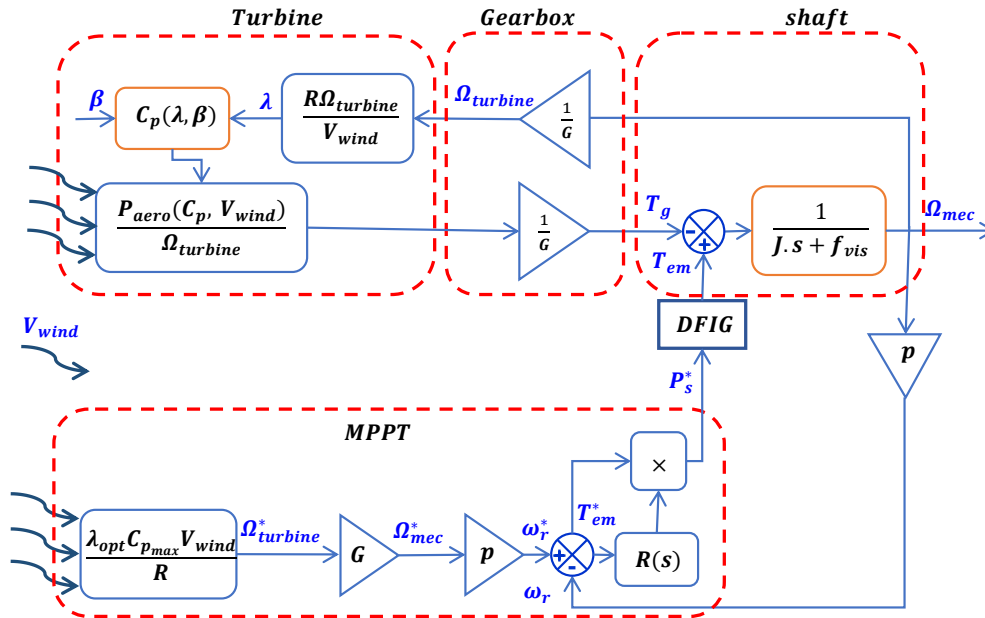


FIGURE 2.5 Diagram bloc of the MPPT

2.2.5 MPPT Control Strategy

The Maximum Power Point Tracking (MPPT) control strategy is mandatory in order to extract the maximum power from the available wind energy. The MPPT control strategy is based on adjusting the rotor speed to track the optimal reference power. The rotor speed can be adjusted by controlling electromagnetic torque of the DFIG rotor. Figure 2.5 shows the model scheme of the MPPT control strategy (for more details see more [96]).

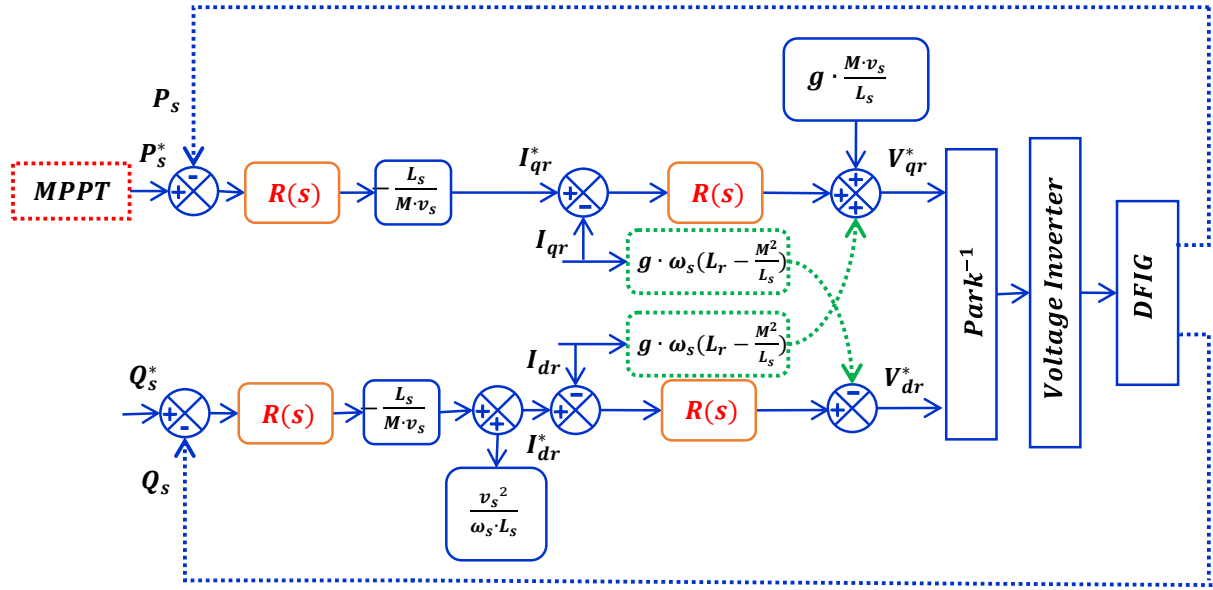


FIGURE 2.6 Block diagram of the proposed control strategy design

2.3 Synthesis of Regulators

The synthesis of regulators is necessary for the realization of the active and reactive power control of the DFIG. This control is developed and tested by synthesizing firstly by conventional Proportional-Integral type regulators and compared with Sliding Mode Controller.

2.3.1 Application of the Proportional Integral (PI) Control to the DFIG

In this section, we will adopt conventional type regulators PI necessary for controlling the active and reactive powers of the DFIG- based WECS. The rotor currents are controlled by Proportional Integral (PI) regulators. This type of regulator remains the most commonly used for controlling the DFIG- based WECS, as well as in many regulation systems. industrial. The regulators of each axis have the role of canceling the difference between the reference of

active and reactive powers and their measured values (Figure. 2.6). DFIG's control strategy uses a proportional integral PI regulator. It is a simple and quick regulator to implement ; it gives a good compromise between complexity and performance. The PI regulator results from the harmonious combination of two actions [97] :

- A proportional action which is used to regulate the speed of the dynamics of the system.
- An integral action which makes it possible to eliminate the difference between the reference variable and that which one wishes to control.

2.3.2 Application of the Sliding Mode (SMC) to the DFIG

Sliding mode control strategy is proposed to improve the effectiveness of the DFIG-based WECS and to achieve high dynamic performance of stator active power and reactive power control [32] and compensate the fault that occurs in DFIG.

Active and reactive powers control surface

The sliding surface proposed by J. SLOTINE [98] is given by :

$$S(x) = \left(\frac{d}{dt} + \delta \right)^{n-1} . e(x) \quad (2.12)$$

To control the active and reactive powers, we take $n = 1$; the expression of the active power control surface is as follows :

$$\begin{cases} S(P_s) = e(P_s) = P_s^* - P_s \\ S(Q_s) = e(Q_s) = Q_s^* - Q_s \end{cases} \quad (2.13)$$

Their derivatives are given by :

$$\begin{cases} \dot{S}(P_s) = \dot{e}(P_s) = \dot{P}_s^* - \dot{P}_s \\ \dot{S}(Q_s) = \dot{e}(Q_s) = \dot{Q}_s^* - \dot{Q}_s \end{cases} \quad (2.14)$$

Recall that $\dot{I}_{qr}$, $\dot{I}_{dr}$ are given by :

$$\begin{cases} \dot{I}_{dr} = -\frac{r_r}{\sigma} I_{dr} + g\omega_s I_{qr} + \frac{1}{\sigma} V_{dr} \\ \dot{I}_{qr} = -\frac{r_r}{\sigma} I_{qr} - g\omega_s I_{dr} - g\frac{m_{sr}v_s}{\sigma l_s} + \frac{1}{\sigma} V_{qr} \end{cases} \quad (2.15)$$

By replacing the expression of $\dot{P}_s$ by its expression as well as $\dot{I}_{qr}$ and $\dot{Q}_s$ by its expression as well as $\dot{I}_{dr}$ which results in :

$$\begin{cases} \dot{S}(P_s) = \dot{P}_s^* + \frac{v_s m_{sr}}{l_s} \left(-\frac{r_r}{\sigma} I_{qr} - g \omega_s I_{dr} - g \frac{m_{sr} v_s}{\sigma l_s} + \frac{1}{\sigma} V_{qr} \right) \\ \dot{S}(Q_s) = \dot{Q}_s^* + \frac{v_s m_{sr}}{l_s} \left(-\frac{r_r}{\sigma} I_{dr} + g \omega_s I_{qr} + \frac{1}{\sigma} V_{dr} \right) \end{cases} \quad (2.16)$$

By replacing the expression of V_{qr} with $V_{qreq} + V_{qrn}$ and V_{dr} with $V_{dreq} + V_{drn}$ the control clearly appears in the following equation :

$$\begin{cases} \dot{S}(P_s) = \dot{P}_s^* + \frac{v_s m_{sr}}{l_s} \left(-\frac{r_r}{\sigma} I_{qr} - g \omega_s I_{dr} - g \frac{m_{sr} v_s}{\sigma l_s} + \frac{V_{qreq} + V_{qrn}}{\sigma} \right) \\ \dot{S}(Q_s) = \dot{Q}_s^* + \frac{v_s m_{sr}}{l_s} \left(-\frac{r_r}{\sigma} I_{dr} + g \omega_s I_{qr} + \frac{V_{dreq} + V_{drn}}{\sigma} \right) \end{cases} \quad (2.17)$$

In sliding and permanent mode :

$$\begin{cases} S(P_s) = 0 \Rightarrow \dot{S}(P_s) = 0, \text{ and } V_{qrn} = 0 \\ S(Q_s) = 0 \Rightarrow \dot{S}(Q_s) = 0, \text{ and } V_{drn} = 0 \end{cases} \quad (2.18)$$

Hence, the formula of V_{qreq} and V_{dreq} becomes as follow :

$$\begin{cases} V_{qreq} = -\frac{\sigma l_s}{m_{sr} v_s} \dot{P}_s^* + r_r I_{qr} + \sigma g \omega_s I_{dr} + g \frac{v_s m_{sr}}{l_s} \\ V_{dreq} = -\frac{\sigma l_s}{m_{sr} v_s} \dot{Q}_s^* + r_r I_{dr} - \sigma g \omega_s I_{qr} \end{cases} \quad (2.19)$$

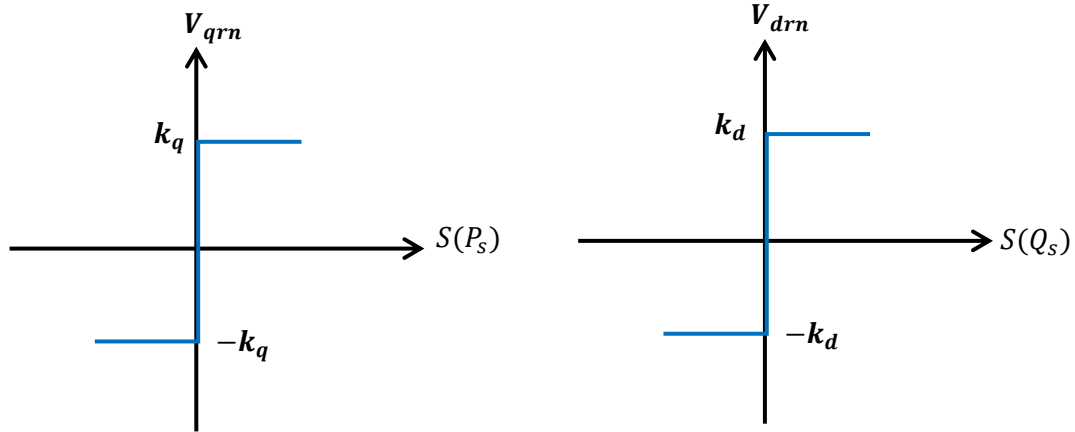


FIGURE 2.7 Sign function

The discontinuous control V_{qr_n} and V_{dr_n} are given by :

$$\begin{cases} V_{qr_n} = k_q \cdot \text{sign}(S(P_s)) \\ V_{dr_n} = k_d \cdot \text{sign}(S(Q_s)) \end{cases} \quad (2.20)$$

Where : k_q, k_d are a positive gains. The controllers V_{dr_n} and V_{qr_n} are given by the basic form, which is that of a relay represented by the function "sign" Figure 2.7

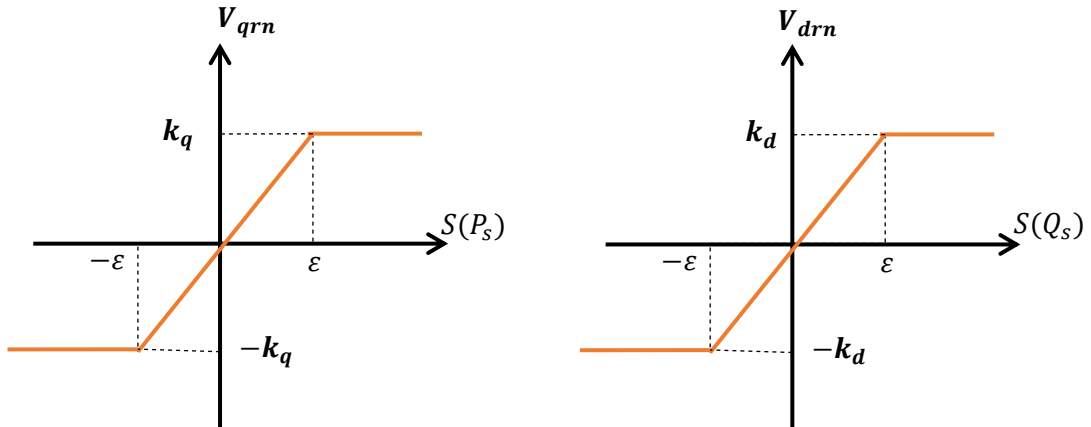


FIGURE 2.8 Soft "sat" control

However, the use of the relay type control can cause undesirable dynamics characterized by the chattering phenomenon. Other methods are proposed to limit this phenomenon. We use for the control by sliding mode regulators so-called "soft control" with a single threshold. It is given by the eq. (2.21), (2.22) and represented in the Figure 2.8.

$$V_{qr_n} = \begin{cases} \frac{1}{\varepsilon} = k_q(S(P_s)) & \text{if } |S(P_s)| < \varepsilon \\ k_q \cdot \text{sign}(S(P_s)) & \text{if } |S(P_s)| \geq \varepsilon \end{cases} \quad (2.21)$$

$$V_{dr_n} = \begin{cases} \frac{1}{\varepsilon} = k_d(S(Q_s)) & \text{if } |S(Q_s)| < \varepsilon \\ k_d \cdot \text{sign}(S(Q_s)) & \text{if } |S(Q_s)| \geq \varepsilon \end{cases} \quad (2.22)$$

This function is also known as the saturation function "sat". The high-frequency oscillations that appear in the responses of the sliding regime can be avoided by making the discontinuous controls V_{qr_n}, V_{dr_n} continuous. To do this, the sign function is replaced by the

sat function.

$$\begin{cases} V_{qr_n} = k_q \cdot \text{sat}(S(P_s)) \\ V_{dr_n} = k_d \cdot \text{sat}(S(Q_s)) \end{cases} \quad (2.23)$$

Where : k_q, k_d are a positive gains. The block diagram of the proposed SMC control strategy design is presented in Figure 2.9.

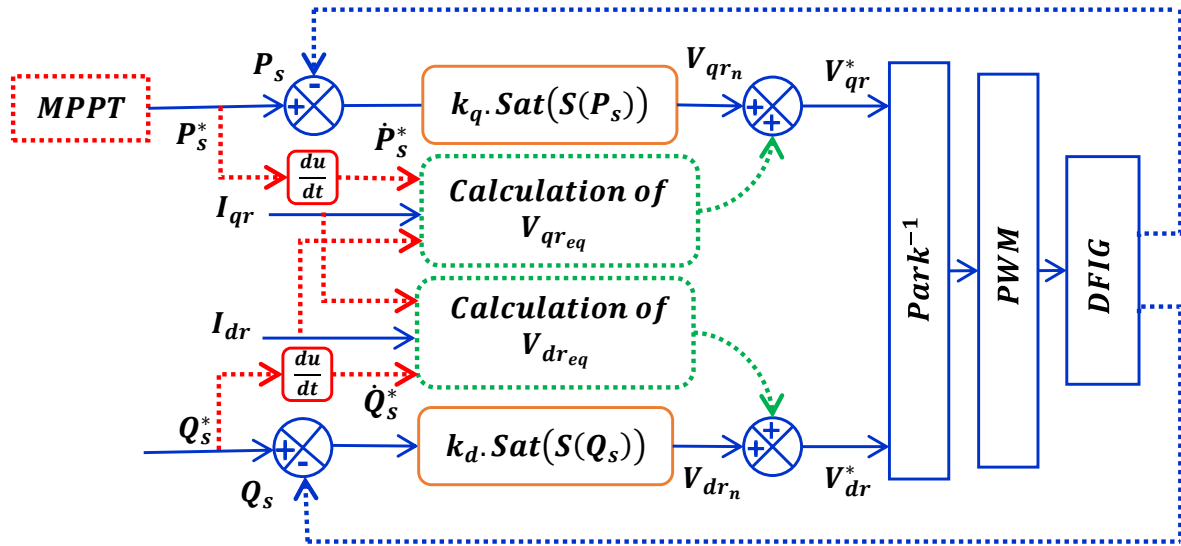


FIGURE 2.9 SMC control strategy

2.4 Results and Discussions

The simulation results presented in this part will make it possible to check the proposed control objectives :

- The decoupled output (i.e., electromagnetic and reactive power) control.
- Maximize the active power.

The results obtained by $Q_s^* = 0 \text{ VAR}$. The control is developed and tested by synthesizing firstly by conventional Proportional-Integral type regulators and compared with Sliding mode controller. The simulation studies in this work are carried out in the MATLAB/Simulink environment, using the « Euler » method with the fixed step size of $0,3 \text{ ms}$ and the schematic diagram of the implemented system is given in Figure 2.6 and 2.9. The DFIG is rated power at 7.5 kW , and its parameters are provided as follows : Rated line voltage = $220/380 \text{ V}$; Rated stator frequency $f = 50 \text{ Hz}$; Inertia of rotor $J = 0.3125 \text{ kg.m}^2$; Coefficient of friction

$f_{vis} = 6,73.10^{-3} N.m.s^{-1}$; Stator resistance $r_s = 0,455\Omega$; Rotor resistance $r_r = 0.62\Omega$; Mutual inductance $m_{sr} = 0,078H$; Stator inductance $M_s = 0,084H$; Rotor inductance $M_r = 0,081H$; Number of pole pairs $p = 2$; Wind Turbine Parameters of $10kW$; Diameter $R = 3m$; Number of blades = 3.

TABLEAU 2.1 Scenarios of stator ITSC fault under fixed wind speed

Time [s]	$0[s] \rightarrow 2[s]$	$2[s] \rightarrow 3.5[s]$	$3.5[s] \rightarrow 5[s]$
γ	$\gamma=0(0\%)$	$\gamma=0.01(1\%)$	$\gamma=0.03(3\%)$
$V_{Wind}[\frac{m}{s}]$	$13[\frac{m}{s}]$		

Figure 2.10 presents the constant wind speed; this curve remains constant at 13 [m/s]. The aim of considering this type of wind speed is that it doesn't make any noise, in addition to being able track and study the fault very well. This is contrary to the real wind speed, which contains a lot of noise that makes the study of faults difficult.

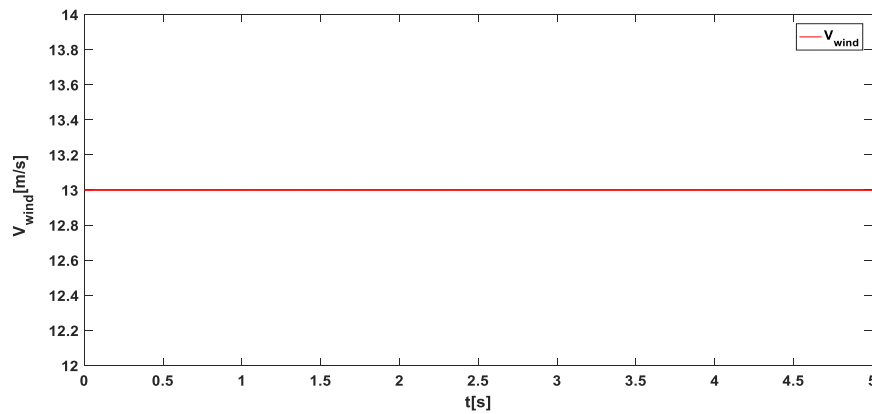


FIGURE 2.10 Fixed wind speed

Figure 2.11 illustrates the variation of measured, and reference values of rotor speed ω_r controlled respectively by PI and SM controllers. It can be seen after starting, that the tow controller provides good tracking of the rotor speed at its reference without any overshoot and with zero steady-state error. When the target rotor speed is $121.68rps$, the rise time of the PI control is $0.15[s]$ and that of the SMC is $0.16[s]$. When the fault occurs at $t = [2, 3.5][s], \gamma = 0.01(1\%)$ the PI and SM controllers maintain the DFIG stable and not too affected by the 1% ITSC fault.

At $(t = [3.5, 6][s], \gamma = 0.03(3\%))$ we remark that the measured rotor speed exceed their reference value and the poor dynamic performance of the PI control in the steady state.

However, the SMC shows good dynamic performance compared with PI, and it is trying to maintain its robustness against the ITSC fault. The SMC avoids the chattering problem because the use of function ‘sat’ as illustrated in eq. (2.23).

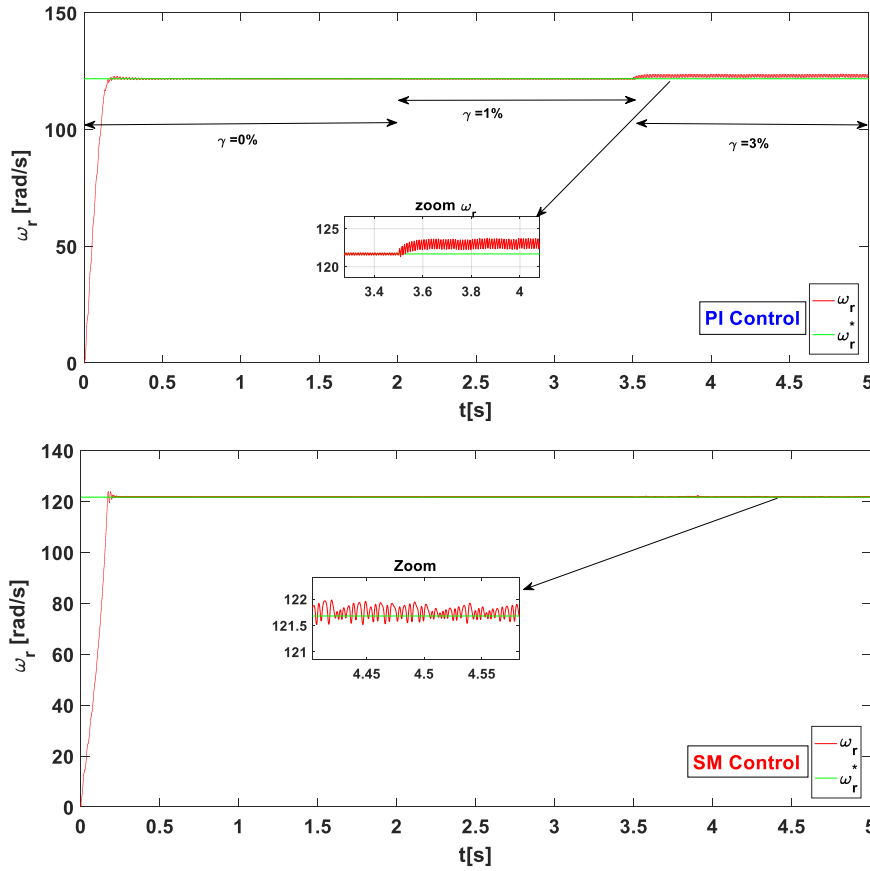


FIGURE 2.11 Variation of rotor speed under fixed wind speed

The active power P_s response regulated by two control methods PI and SM under a fixed wind speed condition is shown in Figure 2.12. We remark (at $t = [0, 2][s]$, $\gamma = 0\%$) when using PI control, during the starting period, the active power had overshoot (approximately 50%) lasted until 0.15[s].

When using SMC, the active power could basically achieve a poor overshoot (approximately 10%) and last until 0.5[s]. The presence of oscillations generated by the inverter is also noticeable; at $t = [0.5, 2][s]$ the measured value of active power P_s dynamic is fast, follow, and converge perfectly to their reference value without any overshoot and with zero steady-state error for both types of control. When ($t = [2, 3.5][s]$, $\gamma = 1\%$ and $t = [3.5, 5][s]$, $\gamma = 3\%$), for PI control, it is remarkable that there is an increase in oscillations in measured value of active power when the fault occurs, in contrast to the SMC, which remains robust and not

affected by fault.

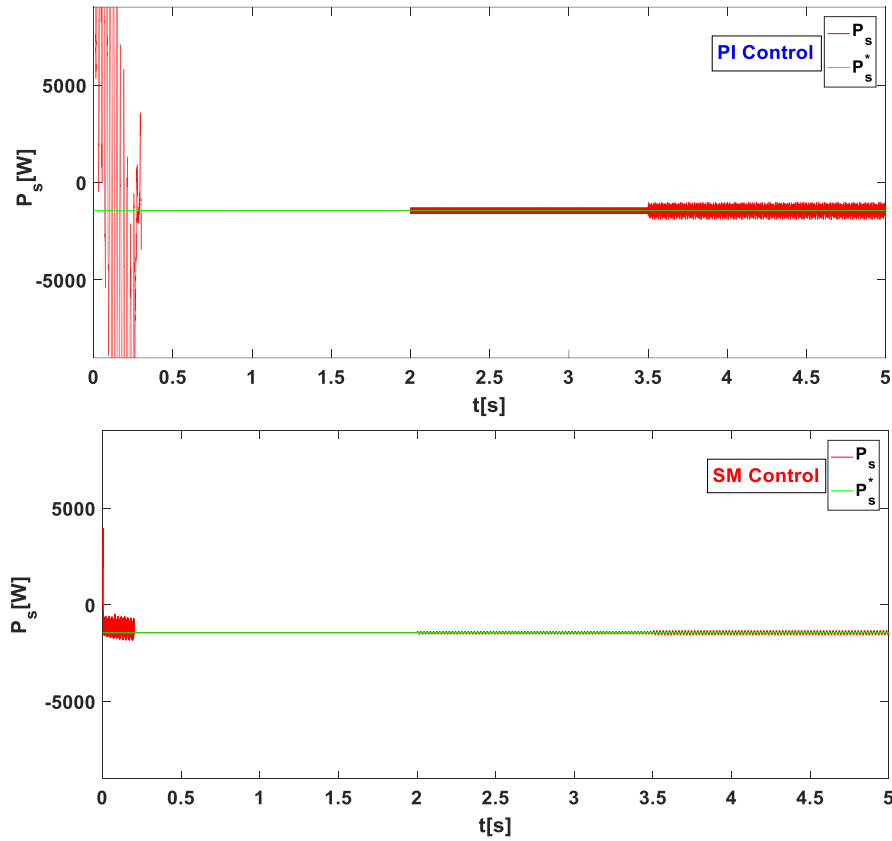


FIGURE 2.12 Variation of stator active power under fixed wind speed

Figure 2.13 presents the variation of reactive power Q_s controlled by PI and SM. We remark that when the target reactive power is $Q_s^* = 0 \text{ VAR}$, the rise time of the PI control is $0.15[s]$ and the SMC is $0.15[s]$. However, the speed response time of SMC was slightly faster than that of PI control. During the starting period, the reactive power had overshoot (approximately 60%) for both kinds of control. The presence of oscillations generated by the inverter is also noticeable; it was especially noticeable in the PI controller, which lasted until $0.9[s]$ compared to the SMC, which lasted until $0.15[s]$. The measured value of reactive power Q_s dynamic is fast, follow, and converge perfectly to their reference value at $t = [0.9, 2][s]$ for both types of control, with no overshoot and zero steady-state error.

When $t = [2, 3.5][s]$, $\gamma = 1\%$, for PI control, there is an increase in oscillations in measured reactive power value when the fault occurs in contravention of the SMC, which remained robust and was unaffected by the 1% fault. When $t = [3.5, 5][s]$, $\gamma = 3\%$ for PI control, we remark an increase of oscillations in measured value of reactive power. This oscillation is bigger than when $\gamma = 1\%$. However, for SMC control, we remark a slight increase of

oscillations in reactive power compared with when it is controlled by PI.

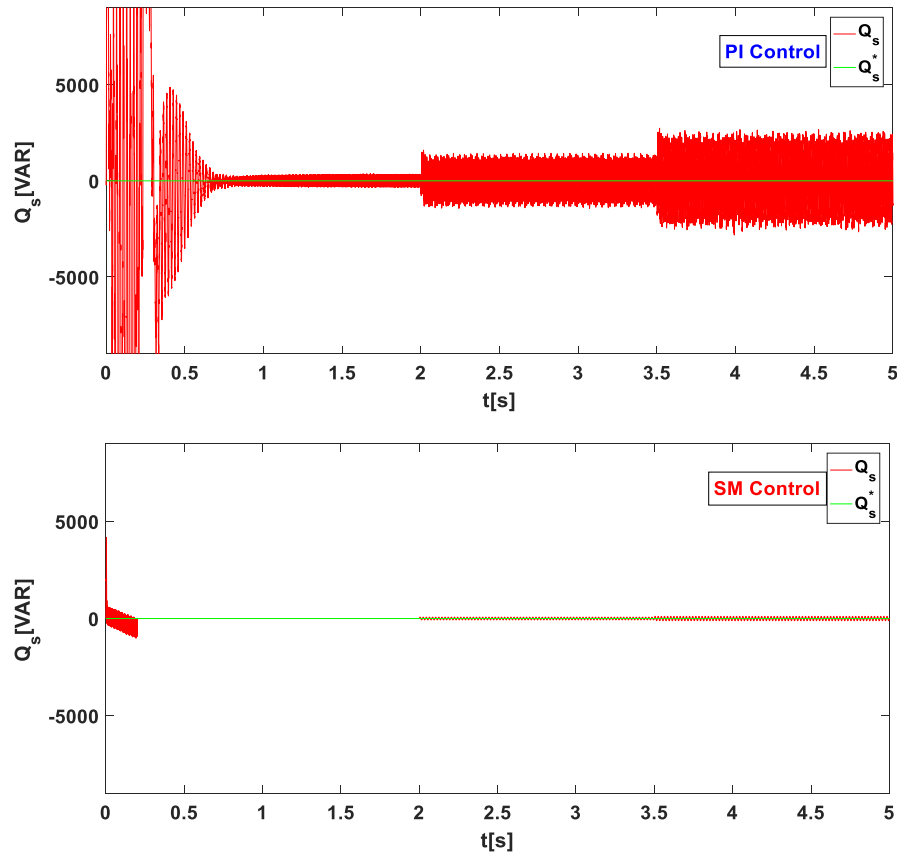


FIGURE 2.13 Variation of stator reactive power under fixed wind speed

It can be seen that the results of Figure 2.13 agree with the simulation results displayed in Figure 2.12 (stator active power) show a perfect decoupling between the active power (electromagnetic torque) and the stator reactive power.

2.4.1 Performance of the PI and SMC for DFIG Operating under random Wind Speed

In order to see the effect of the variation of the wind speed and fault on the rotor speed, active and reactive powers, the DFIG-based WECS was tested and simulated in a faulty operation under random wind speed. The results obtained by $Q_s^* = 0 \text{ VAR}$.

TABLEAU 2.2 Scenarios of stator ITSC fault under random wind speed

Time [s]	$0[s] \rightarrow 2[s]$	$2[s] \rightarrow 3.5[s]$	$3.5[s] \rightarrow 5[s]$
γ	$\gamma=0(0\%)$	$\gamma=0.01(1\%)$	$\gamma=0.03(3\%)$
$V_{Wind}[\frac{m}{s}]$	Random wind speed		

Figure 2.14 represents the random wind speed ; the aim of choosing this profile is to contain noise and correspond with the real wind speed.

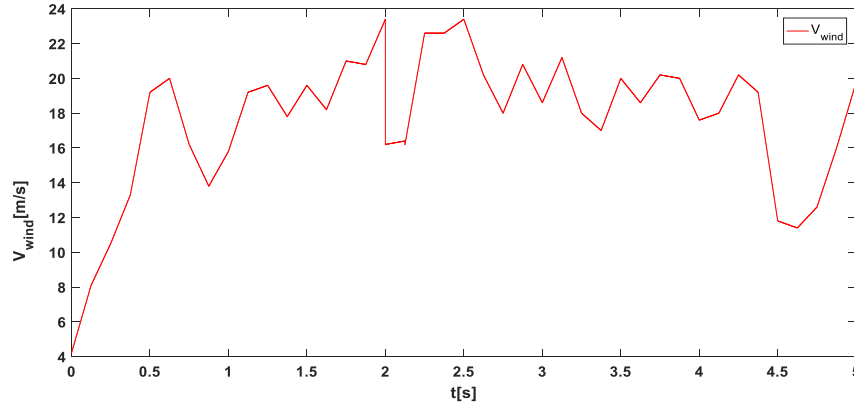


FIGURE 2.14 Random wind speed

Figure 2.15 shows the variation of measured and reference value of rotor speed controlled by PI and SM controllers. It can be seen after starting that there is an overshoot that has remained until 0.15[s] for PI and until 0.16[s] for SMC. When $(t = [0.15, 2][s], \gamma = 0\%)$ the SMC provides good tracking of the rotor speed at its reference values coming from the MPPT of the wind turbine, without any overshoot and with zero steady-state error, the PI controller provides poor tracking of the rotor speed reference, and we note there is steady-state error. When the fault occurs (at $t = [2, 3.5][s], \gamma = 0.01(1\%)$) for PI it is remarkable that it is sensitive to the variation of the wind speed and of fault, there is a large error between the desired and measured values. For SMC increase in oscillations in measured value of rotor speed, the SMC provides good tracking of the rotor speed reference values.

At $(t = [3.5, 5][s], \gamma = 0.03(3\%))$ we remark that the measured rotor speed exceed their reference values and the poor dynamic performance of the PI control. However, the SMC shows good dynamic performance compared with PI, and it is trying to maintain its robustness against the ITSC fault.

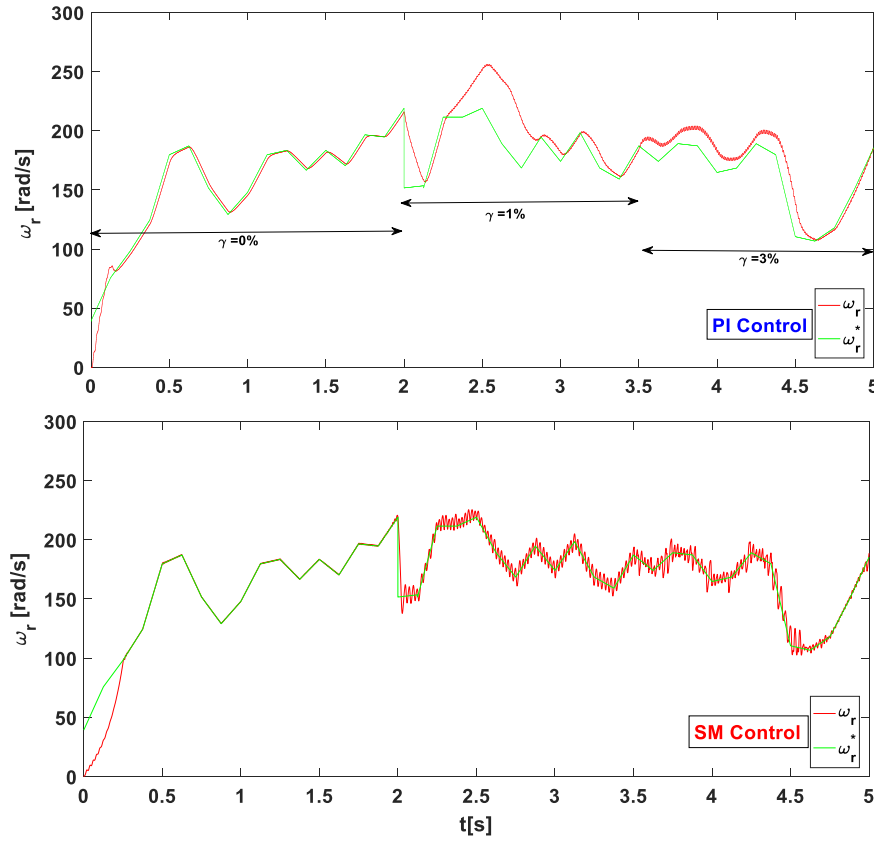


FIGURE 2.15 Variation of rotor speed under random wind speed

The active power P_s response controlled by PI and SM controller under random wind speed condition is illustrated in Figure 2.16. We remark after starting that for PI there is an overshoot (approximately 50%) that has remained until 0.15[s] for PI and there is no overshoot for SMC. Also, in order to achieve the maximum wind energy capture, the rotor speed changes accordingly, and the optimal power curve is tracked. When $(t = [0.5, 2][s], \gamma = 0\%)$ the SMC provides good tracking of the active power at its reference values coming from the MPPT of the wind turbine, the PI controller provides poor tracking of the active power reference values, and we note there is steady-state error.

When the fault occurs (at $t = [2, 3.5][s], \gamma = 0.01(1\%)$ and $(t = [3.5, 5][s], \gamma = 0.03(3\%))$ for PI, it is notable that it is sensitive to variations in wind speed and an increase in oscillations in measured value of active power, with a large error between the desired and measured values, in contrast to the SMC, which remained robust and was unaffected by the fault and wind speed disturbance.

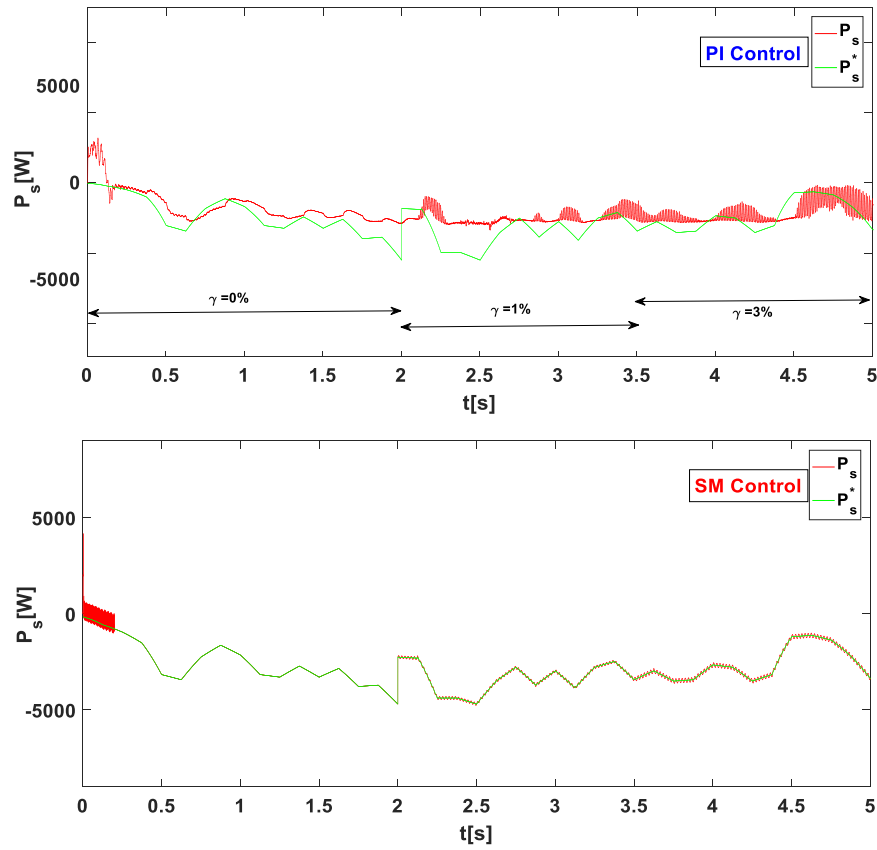


FIGURE 2.16 Variation of active power under random wind speed

Figure 2.17 presents the variation of reactive power Q_s controlled by PI and SM. We remark that when the target reactive power is $Q_s^* = 0[\text{VAR}]$, the rise time of the PI control is $0.15[\text{s}]$ and the SMC is $0.15[\text{s}]$. However, the speed response time of SMC was slightly faster than that of PI control. During the starting period, the reactive power had overshoot (approximately 60%) for both kinds of control. The presence of oscillations generated by the inverter is also noticeable; it was especially remarkable in the PI controller, which lasted until $0.9[\text{s}]$ compared to the SMC, which lasted until $0.15[\text{s}]$.

At $t = [0.9, 2][\text{s}]$ for PI, we notice that the Q_s changes with the change of wind speed and is affected by disturbance of wind speed. We also note a poor performance for dynamic tracking for PI compared with SMC. For SMC, the measured value of reactive power Q_s dynamic are fast, follow, and converge perfectly to their reference value without any overshoot and with zero steady-state error and are not affected by disturbance of wind speed.

When the fault occurs (at $t = [2, 3.5][\text{s}]$, $\gamma = 0.01(1\%)$ and $t = [3.5, 5][\text{s}]$, $\gamma = 0.03(3\%)$), for PI it is remarkable that it is sensitive to the variation of the wind speed and increases in

oscillations in measured value of active power. There is a large error between the desired and measured values, for SMC we observe an increase in oscillations in reactive power because it is affected by 1% and 3% ITSC faults but it is not affected by disturbance of wind speed.

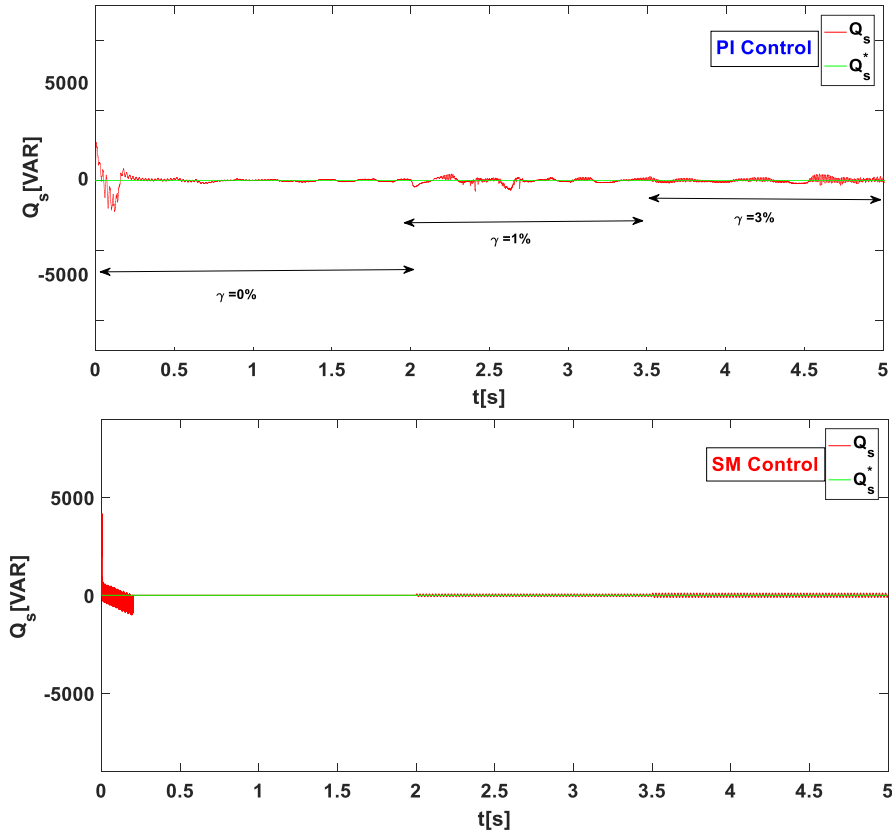


FIGURE 2.17 Variation of reactive power under random wind speed

It can be seen that the results of Figure 2.17 agree with the simulation results displayed in Figure 2.16 (stator active power), a perfect decoupling between the electromagnetic torque and the stator reactive power.

2.5 Summary

This chapter has allowed us to study and apply the vector control in stator active and reactive powers of the DFIG-based WECS. The choice of the Field Oriented Control (FOC) was made by orienting the stator flux along the axis d. Indeed, this choice allows us not only to simplify the model of the machine but also to decouple the control of the torque and the flux.

The simulation results show that the SMC strategy has shorter regulation time, less overshoot, stronger immunity, and adaptability for the given value change compared with PI control strategy.

Furthermore, SMC can adjust the active power output with the change of the external wind speed and the reactive power can also be adjusted according to the needs of the system, which realizes the active power and reactive power decoupling control well and verifies the effectiveness of the control method applied to the DFIG-based WECS.

CHAPTER 3

FDD of ITSC Fault in DFIG-based WECS

3.1 Introduction

In this chapter, we propose an approach to detect and isolate the stator ITSC fault in DFIG-based WECS. We focus on diagnosing the first fault (i.e. single-phase ITSC fault). The single-phase fault can be formulated as an additive term in the state space model (i.e. the additive fault); in this state-space form, the single-phase ITSC fault is represented by unknown parameter (i.e. γ), which can be considered as the additive fault. To estimate this unknown parameter, a SMO-based on residual generation is firstly designed. Residual signals are generated by taking measured three-phase stator currents and those reconstructed by SMO from a faulty model of the DFIG, from which a decision system is developed to isolate the ITSC fault.

In addition, the influence of model uncertainties is considered. The condition that DFIG operates under varying of wind speed is also discussed in this chapter. To ensure the stability of the SMO in the presence of wind speed variation, a SMO is developed based on the Lyapunov theory to assure stability condition.

The FDD approach explained in this chapter has been selected for the purpose of fault-tolerant control. Emphasis is laid on approach that does not only detect, but also isolate or identify fault.

3.2 Stator ITSC Fault Diagnosis

Generally, a model-based fault diagnosis approach consists of three main steps, which are the fault detection, the fault isolation and the fault identification. Firstly, the fault detection aims to decide if there is a fault in the system or not. Secondly, the fault isolation enables the determination of the fault position and its occurrence time. Finally, the fault identification permits the fault level estimation, its type and nature [99]. The fundamental problem of fault detection method is concerned with designing a residual generator which yields residuals that allow a reliable decision between two cases : healthy or faulty DFIG [100]. The Observer plays the main role in model-based fault diagnosis for monitored systems ; the idea of using a SMO-based approach for the DFIG with stator ITSC fault diagnosis consists of using an estimated

three-phase stator current to generate a residual [101].

3.2.1 State Space Model Representation

The model of the single-phase ITSC fault as presented in chapter 1 Section 1.7 is given by two equations : the voltage and flux equations, which can be written in a compact form as. There are usually two methods to transform this model into a state-space representation. One is to select the currents as the state variables, and the other is to select the fluxes as the state variables. In this work, the first method is utilized and the fault is formulated into an additive fault represented by two unknown variables. The state-space representation can be obtained as :

$$\frac{d}{dt} \begin{bmatrix} I_{abcs} \\ I_{abcr} \\ I_f \end{bmatrix} = -L^{-1} \underbrace{\begin{bmatrix} R_s & \omega_r \frac{dM_{sr}}{d\theta_r} & -\gamma r_s E_x \\ \omega_r \frac{dM_{rs}}{d\theta_r} & R_r & -\gamma \omega_r \frac{dM_{sr}}{d\theta_r} E_x \\ \gamma r_s E_x^T & -\gamma E_x^T \omega_r \frac{dM_{rs}}{d\theta_r} & -\gamma r_s \end{bmatrix}}_{A_{\omega_r}} \begin{bmatrix} I_{abcs} \\ I_{abcr} \\ I_f \end{bmatrix} + L^{-1} \begin{bmatrix} V_{abcs} \\ V_{abcr} \\ 0 \end{bmatrix} \quad (3.1)$$

where : $L^{-1} = \begin{bmatrix} L_{ss} & M_{sr} & -\gamma L_{ss} E_x \\ M_{rs} & L_{rr} & -\gamma M_{sr} E_x \\ \gamma E_x^T L_{ss}^T & -\gamma E_x^T M_{sr}^T & -\gamma r_s \end{bmatrix}$; the matrices R_s, R_r, L_{ss}, L_{rr} and M_{sr} are given in (1.5) and eq. (1.6).

The general state-space representation of state variables of eq. (3.1), is writing in the following form :

$$\begin{cases} \dot{\tilde{x}} = \tilde{A}(\omega_r, \theta_r) \tilde{x} + \tilde{B} \tilde{u} \\ y = x \end{cases} \quad (3.2)$$

with : $\tilde{x} \in R^7$; $\tilde{u} \in R^7$; $\tilde{A} \in R^{7 \times 7}$; $\tilde{B} \in R^{7 \times 7}$;

$$\tilde{x} = \begin{bmatrix} x \\ I_f \end{bmatrix} \in R^7; ; y = x = \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \in R^6; \tilde{u} = \begin{bmatrix} u \\ 0 \end{bmatrix} \in R^7; u = \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} \in R^6; I_f \in R;$$

The Partial decomposition of the matrix $\tilde{A}(\omega_r, \theta_r)$ and $\tilde{B}$ is given as follows :

$$\tilde{A}(\omega_r, \theta_r) = \begin{bmatrix} A(\omega_r, \theta_r) & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = L^{-1} A_{\omega_r} \quad ; \tilde{B} = \begin{bmatrix} B & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = L^{-1} \quad (3.3)$$

With : $A(\omega_r, \theta_r), B \in R^{6 \times 6}; A_{12}, B_{12} \in R^{6 \times 1}; A_{22}, B_{22} \in R; A_{21}, B_{21} \in R^{1 \times 6}; C = I_{6 \times 6}$. The model of eq. (3.1) is defined through the following structure :

$$\begin{cases} \dot{x} = A(\omega_r, \theta_r) + Bu + \underbrace{A_{12}I_f}_{\hat{f}(t)} \\ y = x \end{cases} \quad (3.4)$$

So, we can rewrite the eq. (3.1) as follows :

$$\frac{d}{dt} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} = A(\omega_r, \theta_r) \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} + B \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} + \hat{f}(t) \quad (3.5)$$

The general model of the DFIG with single-phase ITSC fault written by the derivate of the currents, given as follows :

$$\begin{aligned} \frac{d}{dt} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} = & - \begin{bmatrix} L_{ss} & M_{sr} \\ M_{rs} & L_{rr} \end{bmatrix}^{-1} \begin{bmatrix} R_s & \omega_r \frac{dM_{sr}}{d\theta_r} \\ \omega_r \frac{dM_{rs}}{d\theta_r} & R_r \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \\ & + \begin{bmatrix} L_{ss} & M_{sr} \\ M_{rs} & L_{rr} \end{bmatrix}^{-1} \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} + \hat{f}(t) \end{aligned} \quad (3.6)$$

3.2.2 Sliding Mode Observer

The main advantage of using sliding-mode observers over their linear counterparts is that, while in sliding, they are insensitive to the matched unknown inputs. Moreover, they can be used to reconstruct unknown inputs which could be a combination of system disturbances, faults or non-linearities. The reconstruction of unknown inputs has found useful applications in fault detection and isolation [70].

It is obvious that the analysis of the observability of nonlinear systems is complex because the observability can depend on the input of the system and there can be observability singularities in the state space [102]. DFIG is strongly nonlinear and the analysis of its observability is rather difficult if we consider the rotor speed ω_r as one of the state spaces. But, in practice, DFIG is predominantly running under slowly varying speed conditions. In eq. (3.7), the rotor speed ω_r can be considered as a time-varying parameter while can be measured in real time. Therefore, this model is a MIMO line time-varying system. According to the dynamic model, given in eq. (3.6), the ITSC is considered as an actuator fault. The sliding mode observer is defined through the following structure [103] :

$$\begin{cases} \dot{\hat{x}} = A(\omega_r, \theta_r)\hat{x} + Bu + k.sign(e_x) \\ \hat{y} = \hat{x} \end{cases} \quad (3.7)$$

where, estimated states, input signals and prediction outputs are defined respectively as :

$$\hat{y} = \hat{x} = \begin{bmatrix} \hat{I}_{abcs} \\ \hat{I}_{abcr} \end{bmatrix} \in R^6; u = \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} \in R^6;$$

So, the model of the observer is defined as follows :

$$\frac{d}{dt} \begin{bmatrix} \hat{I}_{abcs} \\ \hat{I}_{abcr} \end{bmatrix} = A(\omega_r, \theta_r) \begin{bmatrix} \hat{I}_{abcs} \\ \hat{I}_{abcr} \end{bmatrix} + B \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} + k.sign(e_x) \quad (3.8)$$

where : $k \in R_+^*$: is the gains of observer. We define a sliding surface $sign(e_x) = \begin{bmatrix} sign(e_{abcs}) \\ sign(e_{abcr}) \end{bmatrix}$.

As to converge to zero the two sliding variables $\begin{bmatrix} sign(e_{abcs}) \\ sign(e_{abcr}) \end{bmatrix} = 0$ [104].

3.3 Fault Detection and Isolation Approach

Accurate and fast fault detection and isolation in DFIG-based WECS minimize the downtime of the units as further damages can be prevented and determine the occurrence of a fault in the system, by using dependencies between different measurable signals [105]. To detect the fault in DFIG with ITSC, consider the estimation error e_x generated by SMO and given by the following equation :

$$e_x = x - \hat{x} \Rightarrow \dot{e}_x = \dot{x} - \dot{\hat{x}} \quad (3.9)$$

$$\text{with : } e_x = \begin{bmatrix} e_{abcs} \\ e_{abcr} \end{bmatrix} \in R^6; .$$

The dynamic of the derivative error estimation is given by :

$$\dot{e}_x = A(\omega_r, \theta_r)e_x + \hat{f}(t) - k.sign(e_x) \quad (3.10)$$

We choose the Lyapunov candidate function $V(e_x)$ associated to the state system error, such as :

$$V(e_x) = \frac{1}{2} e_x^T e_x \quad (3.11)$$

Using eq. (3.6), (3.9) and the derivative of eq. (3.11) is written as follows :

$$\dot{V}(e_x) = e_x^T \dot{e}_x \quad (3.12)$$

This can be rewritten as follows :

$$\dot{V}(e_x) = e_x^T [A(\omega_r, \theta_r) e_x + \hat{f}(t) - k \cdot \text{sign}(e_x)] \quad (3.13)$$

so :

$$\dot{V}(e_x) = e_x^T A(\omega_r, \theta_r) e_x + e_x^T \hat{f}(t) - e_x^T k \text{sign}(e_x) \quad (3.14)$$

We have : $e_x^T A(\omega_r, \theta_r) e_x < 0$, because $A(\omega_r, \theta_r)$ is Hurwitz (the eigenvalues of the $A(\omega_r, \theta_r)$ have strictly negative real parts).

So : $e_x^T \hat{f}(t) - e_x^T k \text{sign}(e_x)$ should be negative to guarantee $\dot{V}(e_x) < 0$. We have :

$$e_x^T \hat{f}(t) - e_x^T k \text{sign}(e_x) = \sum_{i=1}^6 e_i (\hat{f}_i(t) - k \cdot \text{sign}(e_i)) \quad (3.15)$$

where : k is selected to ensure the asymptotic convergence of errors estimation and satisfy the eq. (3.15) If we chose : $k > |\hat{f}_i|_{\max}$, then :

$$\text{sign}(\hat{f}_i(t) - k \cdot \text{sign}(e_i)) = -\text{sign}(e_i) \quad (3.16)$$

because :

$$\begin{cases} \text{If } e_i < 0 \Rightarrow \hat{f}_i(t) + k > 0; \text{sign}(\hat{f}_i(t) + k) = 1 = -\text{sign}(e_i) \\ \text{If } e_i > 0 \Rightarrow \hat{f}_i(t) - k < 0; \text{sign}(\hat{f}_i(t) - k) = -\text{sign}(e_i) \end{cases} \quad (3.17)$$

thus : $\dot{V}(e_x) < 0$, else : $\lim_{t \rightarrow \infty} e_x \rightarrow 0$. As a consequence, $\dot{e}_x = 0$. This latter means that :

$$\hat{f}_i(t) = k \cdot \text{sign}(e_i) \quad (3.18)$$

3.3.1 Extraction of Fault Indicators (Residual Generation)

The residual generation goals are to reconstruct faults indicators using inputs and outputs taken from the system [44]. When the sliding surface estimated by SMO is attained, the fault detection can be easily executed by observing the stator current residuals e_{abc} , and it is presented as follows :

$$\begin{aligned} \|e_{abc}(t)\| &< \varepsilon; \text{No fault occurs} \\ \|e_{abc}(t)\| &\geq \varepsilon; \text{fault has occurred} \end{aligned} \quad (3.19)$$

with : ε or what is called (threshold) is a very small number and achieves $\varepsilon > 0$. $\lim_{t \rightarrow \infty} e_x \rightarrow 0$ only when $\gamma = 0$, that means no fault occurs. Thus, the residuals e_{abc} can provide reliable fault detection in all cases where the fault occurs. Generated residuals in the condition of the fault absence and parametric variations are established in the aim to determine the threshold. The highest value of I_{as} , I_{bs} and I_{cs} , registered, respectively, by fault indicator e_{as} , e_{bs} and e_{cs} , agree to the stator phase affected by the ITSC. If one or all fault indicators overcome the ε , the ITSC fault is detected.

3.3.2 Faulty Phase Isolation

To be able to isolate a faulty phase for stator ITSC in DFIG-based WECS, the following steps must be respected :

- A fault in a phase will affect a stator current. Its residual signal is going to be different from zero, i.e. if :

$$\left\{ \begin{array}{l} |e_{as}(t)| > \varepsilon \Rightarrow |\hat{f}_a(t)| > 0 \\ |e_{bs}(t)| < \varepsilon \Rightarrow |\hat{f}_b(t)| \simeq 0 \\ |e_{cs}(t)| < \varepsilon \Rightarrow |\hat{f}_c(t)| \simeq 0 \end{array} \right. \quad (3.20)$$

- A fault in b phase will influence b stator current and its residual signal exceeds their threshold, i.e. if :

$$\begin{cases} |e_{as}(t)| < \varepsilon \Rightarrow |\hat{f}_a(t)| \simeq 0 \\ |e_{bs}(t)| > \varepsilon \Rightarrow |\hat{f}_b(t)| > 0 \\ |e_{cs}(t)| < \varepsilon \Rightarrow |\hat{f}_c(t)| \simeq 0 \end{cases} \quad (3.21)$$

- A fault in c phase will influence c stator currents and its associated residuals exceed the threshold, i.e. if :

$$\begin{cases} |e_{as}(t)| < \varepsilon \Rightarrow |\hat{f}_a(t)| \simeq 0 \\ |e_{bs}(t)| < \varepsilon \Rightarrow |\hat{f}_b(t)| \simeq 0 \\ |e_{cs}(t)| > \varepsilon \Rightarrow |\hat{f}_c(t)| > 0 \end{cases} \quad (3.22)$$

This technique can isolate the faulty phase whether is a or b or c phase. Simulation tests are investigated in Figures (3.4, 3.7).

3.4 Fault Compensator

Although the control algorithm mentioned in chapter 2 is effective for a healthy DFIG-based WECS, its control performance can degrade in the presence of short circuit faults. In order to maintain a normal and continued operation, a fault compensator is designed to compensate the impacts of ITSC faults on the closed-loop controlled DFIG-based WECS. (Figures 3.1) represents conventional closed-loop control of DFIG-based WECS with ITSC fault compensator.

in order to keep a normal and continuous operation, a compensator is proposed and combined with the conventional controller in order to compensate the harmful effects of stator ITSC defects. The construction of the compensator is established based on the estimated defect current components I_{dr}^*, I_{qr}^* supplied by the use of SMO. Thus, the relationship between the healthy current and the derived faulty current is given as follows :

$$new I_{dr} = I_{dr} - \hat{I}_{dr}; new I_{qr} = I_{qr} - \hat{I}_{qr} \quad (3.23)$$

$\hat{I}_{dr}$ and $\hat{I}_{qr}$ represent the estimate currents components, I_{dr} and I_{qr} represent the defective currents components. The current flawless can in this way supplied by the difference between the estimated defective currents components and the measured currents. Then utilized for the closed-loop control. The fault compensator configuration is illustrated in Figures 3.1

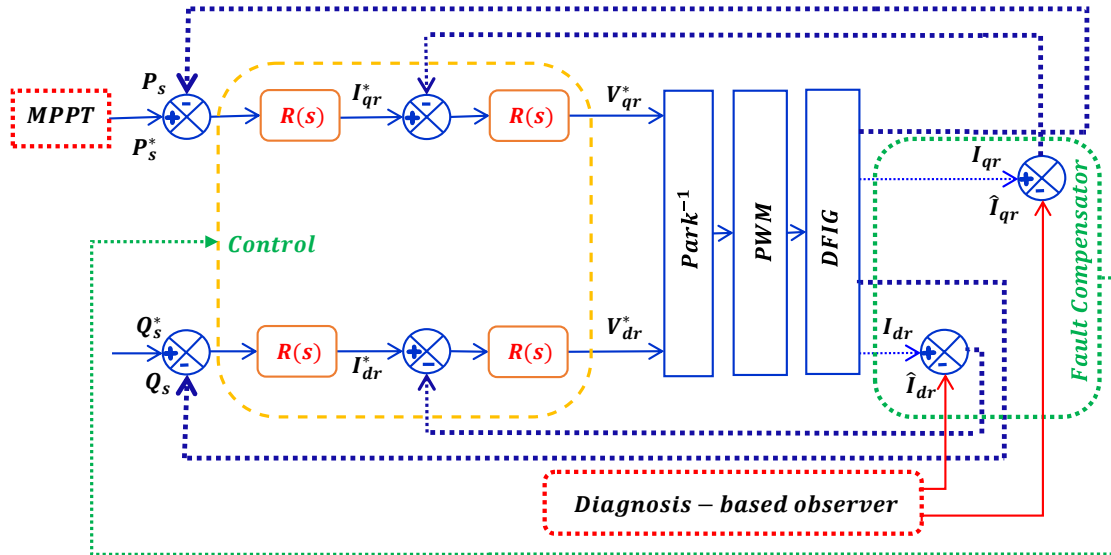


FIGURE 3.1 Closed-loop control of DFIG-based WECS with ITSC fault compensator

3.5 Results and Discussions

In order to validate the correct and precise operation of the proposed FDD approach, a sliding mode observer is developed based on the Lyapunov theory for the diagnosis (detection and isolation) of the single-phase short circuit fault that occurs in DFIG-based WECS. Firstly, the models presented in eq. (3.6) section are simulated in order to analyze and evaluate the behaviors of DFIG-based WECS in the presence of ITSC fault occurring in the stator phase 'a', then the proposed FDD approach performances under various conditions (i.e., wind speed variation) are evaluated through simulations. In these simulations, the DFIG-based WECS operates under closed-loop conditions. Two scenarios are considered :

3.5.1 Performance of the Proposed FDD Approach for DFIG Operating under Fixed Wind Speed

In this part, the DFIG-based WECS was tested and simulated in a faulty operation under fixed wind speed Figures 2.8. To test the detection and isolation approach for the stator ITSC fault, a fault in phase 'a' is introduced. The results obtained by $Q_s^* = 0[VAR]$.

Figures 3.2 shows simulation result of measured three-phase stator currents I_{abcs} . It is clear that three-phase stator currents when ($\gamma = 0\%$ at $t = [0, 2][s]$) in healthy cases are balanced, when an ITSC fault occurs ($\gamma = 0.01(1\%)$ at $t = [2, 3.5][s]$), I_{abcs} becomes unbalanced due

to the winding asymmetry; this is because the effective impedance of the faulted phase is reduced by the short circuit. The current of the faulted phase has a significant magnitude increase compared to the other two phases and the phase with more serious fault (i.e., higher percentage short circuit) ($\gamma = 0.03(3\%)$ at $t = [3.5, 5][s]$) presents larger increase in its current.

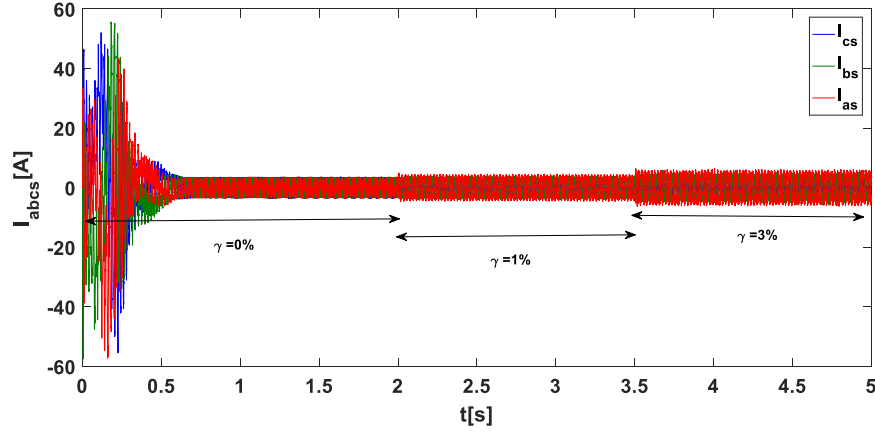


FIGURE 3.2 Evolution of the three -phase stator currents under fixed wind speed

Figures 3.3 present the simulation result of measured three-phase rotor currents I_{abcr} . It is clear that three-phase rotor currents are balanced in healthy cases. However, when an ITSC fault occurs ($\gamma = 0.01(1\%)$ at $t = [2, 3.5][s]$) rotor currents become unbalanced and sensitive to the fault due to the relation between rotor currents I_{abcr} and stator currents I_{abcs} .

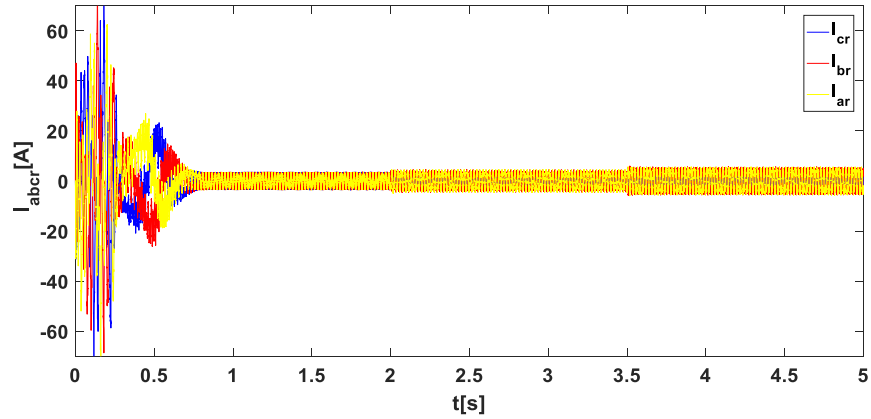


FIGURE 3.3 Evolution of the three -phase rotor currents under fixed wind speed

Figures 3.4 illustrates respectively the measure of three-phase stator currents (I_{as}, I_{bs}, I_{cs}) of the DFIG and their estimated values ($\hat{I}_{as}, \hat{I}_{bs}, \hat{I}_{cs}$) based on the SMO, the dynamic of

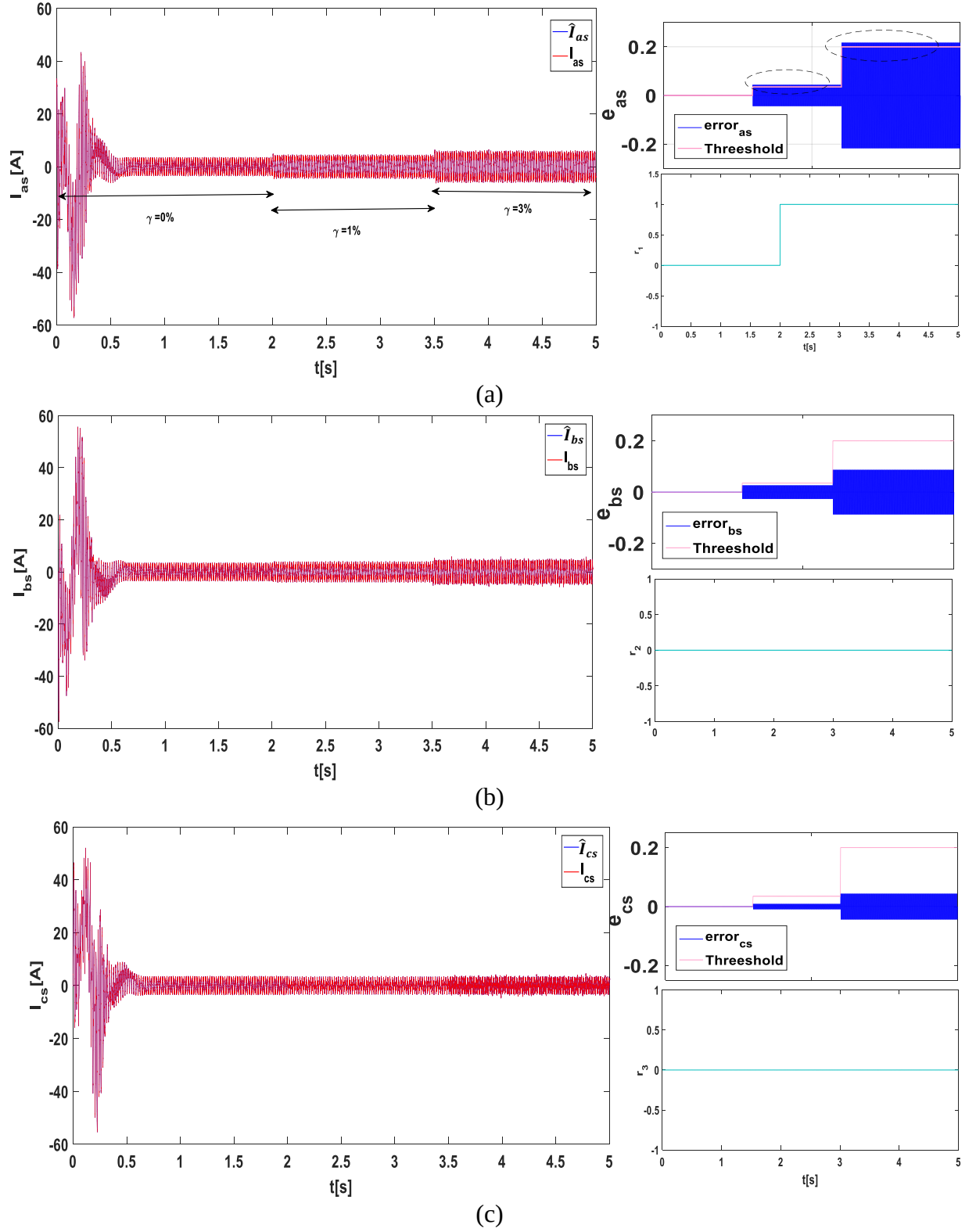


FIGURE 3.4 ITSC fault detection and isolation under fixed wind speed

the steady state errors and the residual signatures generated by proposed SMO. It can be clearly observed from the simulation results that the state's estimation generated from the SMO converges rapidly to those simulated by the real system, especially in healthy operation $\gamma = 0\%$. Furthermore, it can be observed that the estimated errors are very weak, which confirms an ideal estimation by using this observer.

In faulty operation $t = [2, 5][s]$, it is noticeable that the current in phase 'a' presents increase in its amplitude compared with its amplitude in healthy operation, when the stator ITSC fault occurs, with considerable errors of measurement. These errors allow us to detect the fault when it occurs. The residual r_1 , r_2 and r_3 generated from the difference between the estimated currents and the measured one, shown in Figures 3.4, indicates the occurrence of a fault; in the case of ITSC fault in current phase 'a' at $t = [2, 3.5][s]$ and $t = [3.5, 5][s]$, the fault is characterized by fraction of shorted turns of $\gamma = 1\%$ and $\gamma = 3\%$ respectively of the phase and insulation. The analysis of residuals shows that all residuals are affected and exceed their maximum value (threshold). However, only the first residual according to affected current phase 'a' increases more than others' residuals. That allows the isolation of affected phase.

3.5.2 Performance of the Proposed FDD Approach for DFIG Operating during Variations of Wind Speed

In order to see the effect of the variation of the wind speed on the active power, the stator currents and the rotor speed, the DFIG-based WECS is tested and simulated in a faulty operation under random wind speed (Figure 2.12). The results obtained by $Q_s^* = 0VAR$.

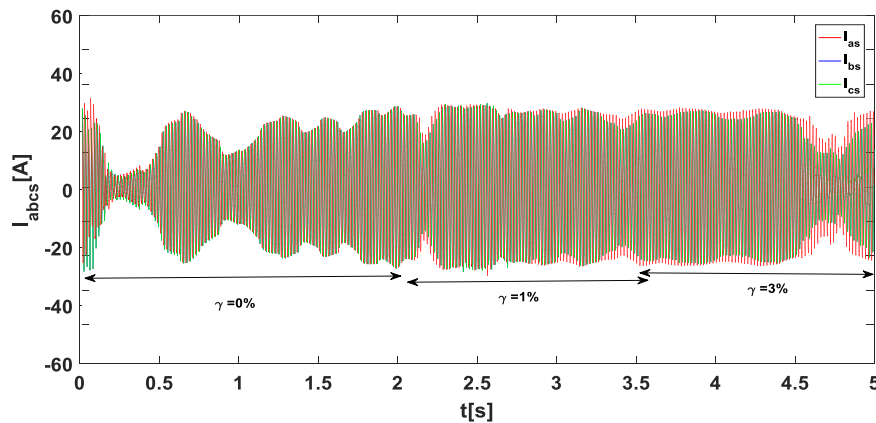


FIGURE 3.5 Evolution of the three -phase stator currents under random wind speed

Figures 3.5 represents the evolution of the measured three-phase stator currents I_{abs} of the DFIG under random wind speed. We remark the increase in the oscillations caused by the application of the random wind speed, we observe also that the three-phase currents become asymmetrical when the fault occurs, and an obvious increase can be observed in the current of the faulted phase, this fault influences in the equilibrium of the three-stator phases and therefore the equilibrium of stator currents which affects the power that is generated.

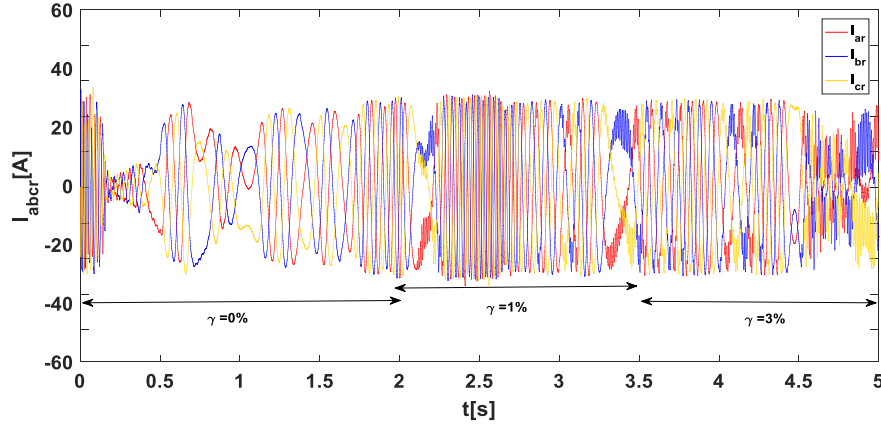


FIGURE 3.6 Evolution of the three -phase rotor currents under random wind speed

Figures 3.6 show the simulation result of measured three-phase rotor currents I_{abcr} . It is clear that three-phase rotor currents are balanced in healthy cases. When an ITSC fault occurs ($\gamma = 0.01(1\%)$ at $t = [2, 3.5][s]$) rotor currents are affected by the fault occurred in the stator currents and it is very sensitive to the disturbance presented by variation of wind turbine.

Figures 3.7 illustrates the measure of three-phase stator currents (I_{as}, I_{bs}, I_{cs}) of the DFIG and their estimated values ($\hat{I}_{as}, \hat{I}_{bs}, \hat{I}_{cs}$), the dynamic of the steady state errors and the residual signatures generated by proposed SMO. Accordingly, the increase in the oscillations caused by the application of the random wind speed can be clearly observed from the simulation results, we also remark an evolution of the stator currents, a distortion after the application of the stator ITSC fault at $t = [2, 5][s]$, for all phases stator current (I_{as}, I_{bs}, I_{cs}). However, the states' estimation generated from the SMO converges rapidly to those simulated by the real system, especially in healthy operation $\gamma = 0\%$. Furthermore, it can be observed that the estimated errors e_{abcs} are very weak, and not affected by the application of random wind speed, while affected by the stator ITSC fault applied at $t = [2, 5][s]$ which confirms an ideal estimation and robustness by using this observer.

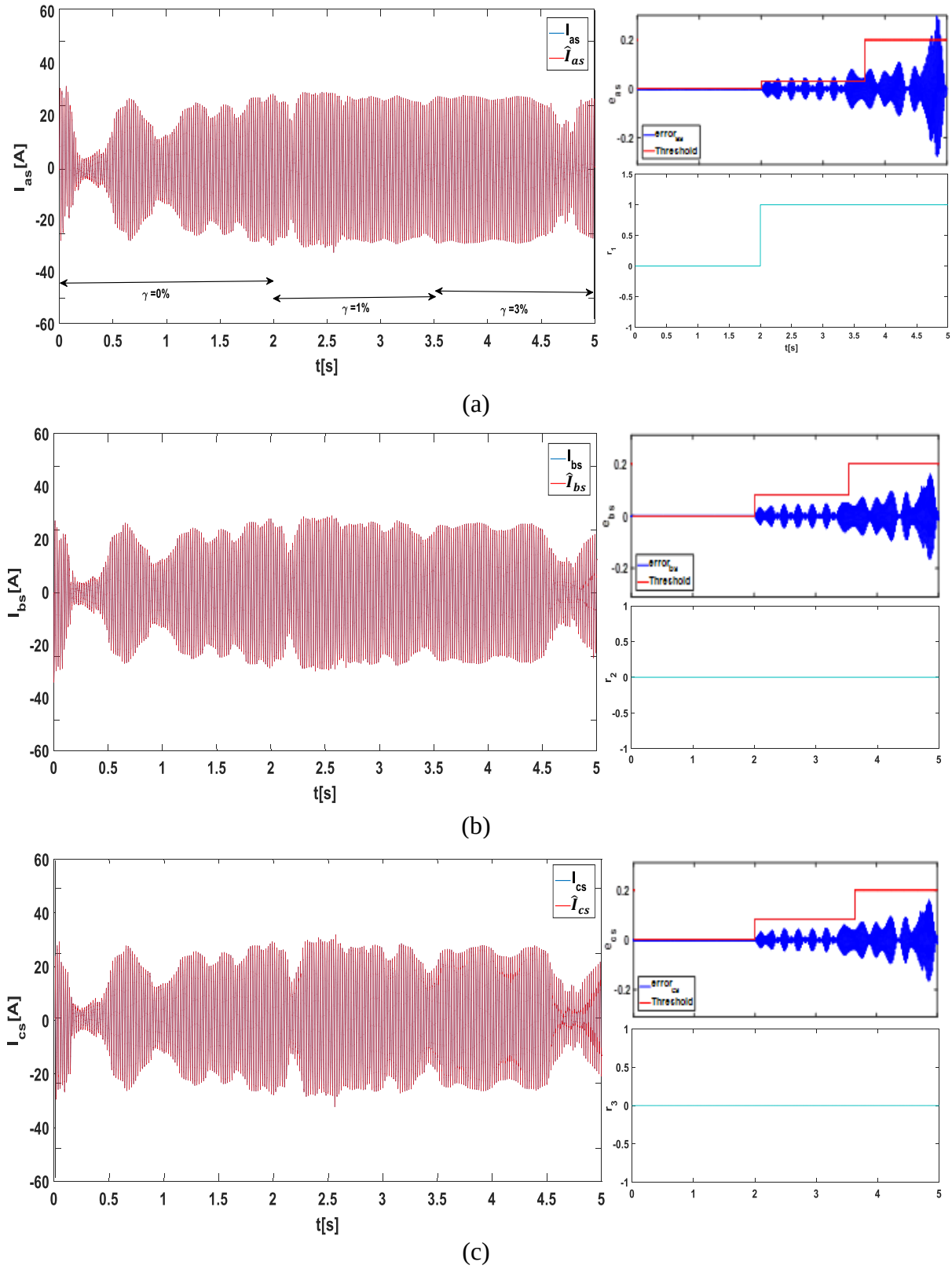


FIGURE 3.7 ITSC fault detection and isolation under random wind speed

We remark that the residual generated from the difference between the estimated currents and the measured one shown in Figures 3.7, indicates the occurrence of a fault ; and always allows to isolate the fault, whatever their type and location are. The presented results are obtained for the ITSC modeled in a-phase of the DFIG. However, due to the symmetry of the DFIG, the results of ITSC fault occurrence in the remaining phases are similar.

3.5.3 Fault Compensator

The obtained estimation results of the defect current are then used by the fault compensator in order to eliminate the harmful effects that the stator ITSC single phase may cause to some crucial electrical within the system.

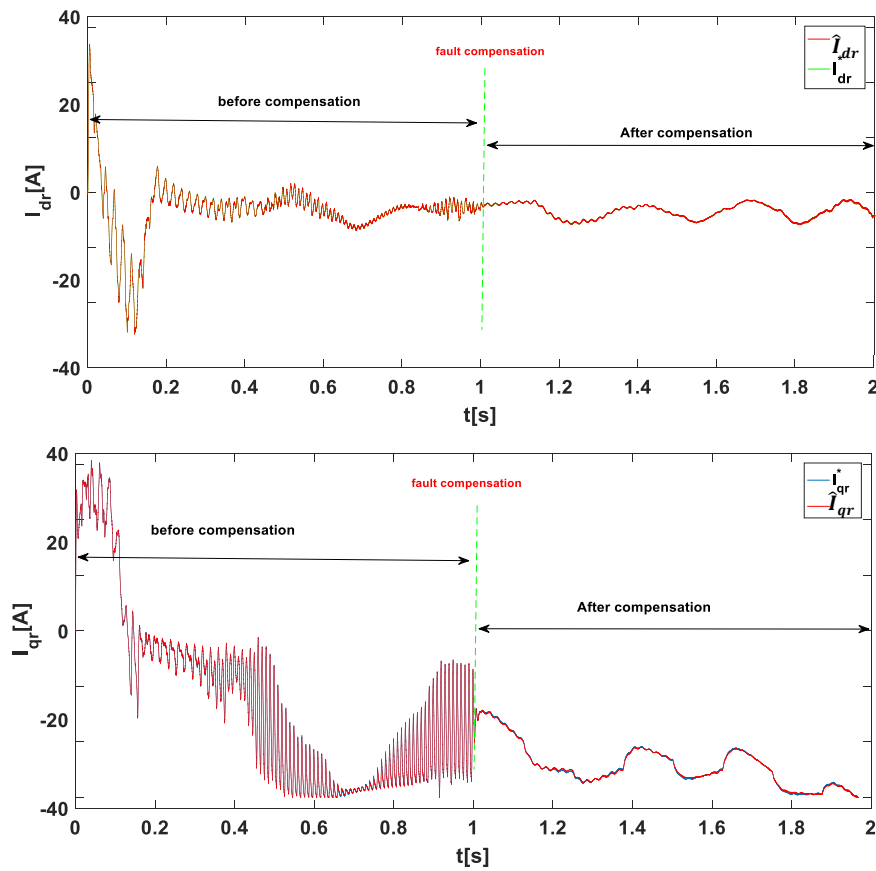


FIGURE 3.8 Fault compensation

The proposed fault compensation scheme is implemented on a closed-loop controlled DFIG-based WECS. The sliding mode observer-based fault diagnosis scheme is firstly employed to provide online diagnosis for the short circuit faults, and meanwhile estimate faulty

current components (i.e., I_{dr} , I_{qr}). These components are then utilized in the fault compensator to remove the influences of the fault. To compare the performance of the DFIG-based WECS before and after the fault compensation, a single 3% short circuit fault is introduced stator phase ‘a’ and the fault compensator is activated at $t = 1[s]$. The simulation results are given in Figures 3.8.

Figures 3.8 presents the simulation results of fault compensation. 3% short circuit fault is applied to stator phase ‘a’, and the fault compensator is activated at $t = 1[s]$. When the fault occurs, the torque active and reactive power are still able to track their reference values but with strong oscillations. These oscillations are significantly reduced when the fault compensator is applied. Simulation results obtained reinforce and assert the effectiveness of the proposed control FTC and observer. It has been observed that the control synthesized SMC rejects the effect of the disturbance which comes from the variation in wind speed. Indeed, the effects of the short circuit fault on a closed-loop controlled DFIG-based WECS are highly reduced and the system performance is recovered by using the proposed fault compensation scheme.

3.6 Summary

In this chapter we have proposed an adapted FDD approach for a DFIG with a stator ITSC fault which is based on SMO. The proposed observer is able to generate specific residuals. These residuals indicate the difference between measured three-phase stator currents and reconstructed ones. Residuals allow to detect and isolate the fault a, b or c faulty phase. However, in order to avoid false alarms, the threshold value must be established after the analysis of the residual level in healthy operating case of the DFIG. Simulation results confirm that the proposed ITSC fault FDD approach offers rapid and precise detection and isolation of fault. Thereafter, based on the block FDD provided by the adaptive observer, a fault compensator is constructed and added to the controller. The simulation studies show that this fault compensator can highly reduce the oscillations in the output power and some other electrical quantities in the presence of short circuit faults.

CHAPTER 4

FDD of Current Sensor Fault in DFIG-based WECS

4.1 Introduction

Accuracy, timeliness and reliability are crucial to the stable operation of DFIG- based WECS. Once a fault occurs, it will affect the overall control performance of the system, and even lead to entire system deficiency. In fact, the early detection and isolation of faults point out the increasing significance of DFIG for Wind Turbines and is beneficial to avoid false alarms due to possible undesired perturbations [105]. The purpose of this chapter is to design an FDD algorithm for DFIG-based WECS with a stator current sensor fault. This FDD algorithm is based on the multiple Dedicated Sliding Mode Observers Scheme (DOS), which generates a set of residuals for detecting and isolating current sensor faults that can affect DFIG behavior. A decision system is employed to accomplish an effective process of the residual vector to detect and isolate of the current sensor fault. Through simulations, it will be demonstrated that the detect and isolate of stator current sensor faults will be correctly achieved, and the diagnosis result will not be affected by disturbances and reference changes.

4.2 Modeling of DFIG with currents sensor Fault

4.2.1 Model in 'abc' coordinate

In natural 'abc' reference frame, the currents model equations in matrix form are given as [106] (Figure 4.1) :

$$\left\{ \begin{array}{l} \frac{d}{dt} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} = \underbrace{\begin{bmatrix} L_{ss} & M_{sr} \\ M_{rs} & L_{rr} \end{bmatrix}^{-1} \begin{bmatrix} R_s & \omega_r \frac{dM_{sr}}{d\theta_r} \\ \omega_r \frac{dM_{rs}}{d\theta_r} & R_r \end{bmatrix}}_{A(\omega_r, \theta_r)} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} + \begin{bmatrix} L_{ss} & M_{sr} \\ M_{rs} & L_{rr} \end{bmatrix}^{-1} \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} \\ y = x + \hat{f}_{sensor_{abcs}}(t) \end{array} \right. \quad (4.1)$$

$$\text{where : } x = \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \in R^6; u = \begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} \in R^6;$$

$\hat{f}_{sensor_{abc}}(t)$:is the stator current fault sensor in ‘abc’ coordinate. Where : The resistance matrices R_s and R_r are given in eq. (1.5) chapter 1, L_{ss}, L_{rr} and M_{sr} are respectively the stator and rotor inductance and mutual inductances matrix given by eq. (1.6) chapter 1.

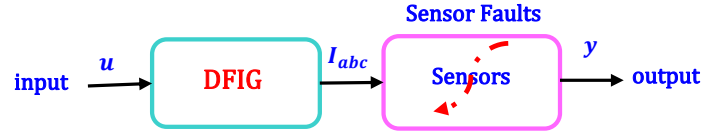


FIGURE 4.1 Current sensor faults

Recall that the model of eq. (4.1) can be write in ‘dq’ coordinate as follows :

$$\frac{d}{dt} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} = L_{dq} \begin{bmatrix} 0 & \omega_s l_s & 0 & \omega_s m_{sr} \\ -\omega_s l_s & 0 & -\omega_s m_{sr} & 0 \\ 0 & g\omega_s m_{sr} & -r_r & g\omega_s l_r \\ -g\omega_s m_{sr} & 0 & -g\omega_s l_r & -r_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} + L_{dq} \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} \quad (4.2)$$

$$\text{With : } L_{dq} = \begin{bmatrix} \frac{l_r}{\sigma l_s} & 0 & -m_{sr} & 0 \\ 0 & \frac{l_r}{\sigma l_s} & 0 & -m_{sr} \\ \frac{-m_{sr}}{\sigma l_s} & 0 & \frac{1}{\sigma} & 0 \\ 0 & \frac{-m_{sr}}{\sigma l_s} & 0 & \frac{1}{\sigma} \end{bmatrix};$$

So, the reduced model is written (106) :

$$\begin{cases} \dot{x}_{dq} = A_{dq}x_{dq} + B_{dq}u_{dq} \\ y_{dq} = x_{dq} + \hat{f}_{sensor}(t) \end{cases} \quad (4.3)$$

Where : $\hat{f}_{sensor}(t)$:is the stator current fault sensor in ‘dq’ coordinate.

$$x_{dq} = \begin{bmatrix} I_{dqs} \\ I_{dqr} \end{bmatrix} \in R^4; u = \begin{bmatrix} V_{dqs} \\ V_{dqr} \end{bmatrix} \in R^4; y = \begin{bmatrix} I_{dqs} \\ I_{dqr} \end{bmatrix} \in R^4; \hat{f}_{sensor}(t) \in R^4.$$

4.3 Fault Diagnosis and Fault-Tolerant Control Strategy

Supper twisting control strategy is proposed to improve the effectiveness of the DFIG-based WECS and to achieve high dynamic performance of stator active and reactive powers

control. The stator active and reactive power given by [107] :

$$\begin{cases} P_s = -\frac{m_{sr}v_s}{l_s}I_{qr} \\ Q_s = -\frac{m_{sr}v_s}{l_s}I_{dr} + \frac{v_s^2}{l_s\omega_s} \end{cases} \quad (4.4)$$

The switching functions are selected as shown in eq. (4.5) :

$$\begin{cases} S(P_s) = (P_s^* - P_s) + c_{P_s} \int (P_s^* - P_s) dt \\ S(Q_s) = (Q_s^* - Q_s) + c_{Q_s} \int (Q_s^* - Q_s) dt \end{cases} \quad (4.5)$$

Where : P_s^* and Q_s^* are the reference values of the stator active and reactive power respectively, the integral terms, weighed by the positive constants c_{P_s} and c_{Q_s} , are added for steady-state errors elimination [108]. Combination of eq. (4.5) with eq. (4.4), the time derivatives of switching variables $S(P_s)$ and $S(Q_s)$ are given as :

$$\begin{cases} \dot{S}(P_s) = \dot{P}_s^* + \frac{v_s m_{sr}}{\sigma l_s} \left(\left(\frac{-r_r}{\sigma} \right) I_{qr} - g\omega_s I_{dr} - g \frac{v_s m_{sr}}{\sigma l_s} \right) + \frac{v_s m_{sr}}{\sigma l_s} V_{qr} + c_{P_s} (P_s^* - P_s) \\ \dot{S}(Q_s) = \dot{Q}_s^* + \frac{v_s m_{sr}}{\sigma l_s} \left(\left(\frac{-r_r}{\sigma} \right) I_{dr} + g\omega_s I_{qr} \right) + \frac{v_s m_{sr}}{\sigma l_s} V_{dr} + c_{Q_s} (Q_s^* - Q_s) \end{cases} \quad (4.6)$$

So the eq. (4.6) can be rewritten as follows :

$$\begin{cases} \dot{S}(P_s) = \dot{P}_s^* + c_{P_s} P_s^* + \frac{v_s m_{sr}}{\sigma l_s} \left(\left(\frac{-r_r}{\sigma} + c_{P_s} \right) I_{qr} - g\omega_s I_{dr} - g \frac{v_s m_{sr}}{\sigma l_s} \right) + \frac{v_s m_{sr}}{\sigma l_s} V_{qr} \\ \dot{S}(Q_s) = \dot{Q}_s^* + c_{Q_s} Q_s^* + \frac{v_s m_{sr}}{\sigma l_s} \left(\left(\frac{-r_r}{\sigma} + c_{Q_s} \right) I_{dr} + g\omega_s I_{qr} - c_{Q_s} \frac{v_s}{\omega_s m_{sr}} \right) + \frac{v_s m_{sr}}{\sigma l_s} V_{dr} \end{cases} \quad (4.7)$$

In this section, the Supper twisting SMC will be replaced by Supper twisting SMC in order to generate the 'dq' components reference voltages V_{dr} and V_{qr} are given by :

$$\begin{cases} \frac{\partial \dot{S}(P_s)}{\partial V_{qr}} = -\frac{v_s m_{sr}}{\sigma l_s} \neq 0 \\ \frac{\partial \dot{S}(Q_s)}{\partial V_{dr}} = -\frac{v_s m_{sr}}{\sigma l_s} \neq 0 \end{cases} \quad (4.8)$$

As far as relative degree is concerned, the sixth equation highlights that the DFIG holds a relative degree of first order. Hence, the application of conventional SMC or Supper twisting SMC can result a control of the DFIG [109], taking into account that the construction, which is determined by Supper twisting SMC, can eliminate the chattering phenomenon as well as stimulate the control's accuracy ; therefore, Supper twisting SMC is selected. Accordingly,

the voltage that is employed is deduced from the control law that follows [108] :

$$\begin{cases} V_{dr} = V_{dr_{eq}} + V_{dr_n} \\ V_{qr} = V_{qr_{eq}} + V_{qr_n} \end{cases} \quad (4.9)$$

Where : V_{dr_n} in addition to V_{qr_n} represent the switching, control terms. The components of the control law in the seventh equation are the switching control terms in addition to the equivalent control terms. In finite time, the switching control terms make the system in any initial state arrive at the sliding manifold.

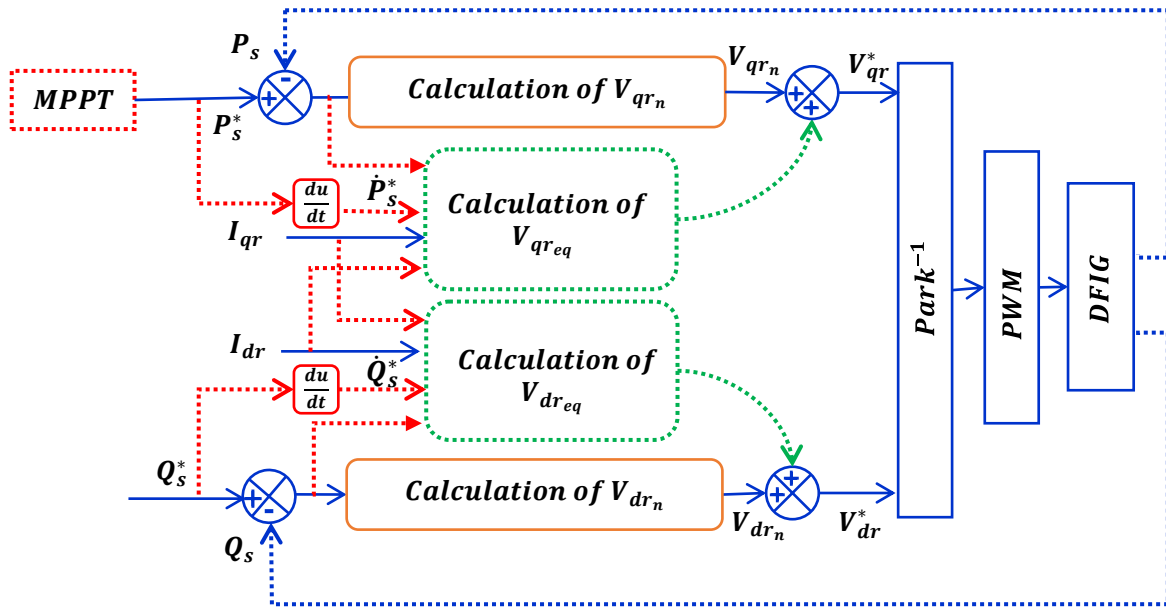


FIGURE 4.2 Super Twisting SM control strategy

The application of the super-twisting algorithm, in this research, can be used to calculate them. Both $V_{dr_{eq}}$ and $V_{qr_{eq}}$ represent the equivalent control terms of the equation as they lead, under typical circumstances, to the movement of the system along the sliding manifold. The system's response can be accelerated by the aforementioned terms which also diminish the steady-state errors. By considering $\dot{S}(P_s) = \dot{S}(Q_s) = 0$ can be a catalyst for derivation of the equivalent control terms, and taking into account the aforementioned method. The

application of the voltage to the rotor is shown as follows :

$$\begin{cases} V_{qr_n} = k_{P_1} \sqrt{|S(P_s)|} \text{sgn}(S(P_s)) + k_{P_2} \int \text{sgn}(S(P_s)) dt \\ V_{dr_n} = k_{Q_1} \sqrt{|S(Q_s)|} \text{sgn}(S(Q_s)) + k_{Q_2} \int \text{sgn}(S(Q_s)) dt \\ V_{qr_{eq}} = -\frac{\sigma l_s}{v_s m_{sr}} [\dot{P}_s^* + c_{P_s}(P_s^* - P_s)] + r_r I_{qr} + \sigma g \omega_s I_{dr} + g \frac{v_s m_{sr}}{l_s} \\ V_{dr_{eq}} = -\frac{\sigma l_s}{v_s m_{sr}} [\dot{Q}_s^* + c_{Q_s}(Q_s^* - Q_s)] + r_r I_{dr} - g \frac{\omega_s}{\sigma} I_{qr} \end{cases} \quad (4.10)$$

where $k_{P_1}, k_{P_2}, k_{Q_1}$ as well as k_{Q_2} represent positive constants to be adjusted. The control diagram is shown in Figure (4.2).

4.4 Current Sensor Fault Diagnosis

Our objective is to develop a method based on the observer of the current sensor fault for the DFIG diagnosis, then generate residuals from the actual and estimated currents obtained by SMO to isolate the fault and correct it thereafter.

4.4.1 Fault Detection Block (Sliding Mode Observer)

The idea of sliding mode observer when the error between the actual and estimated stator currents converges to zero, which guarantees the accuracy of the rotor currents observer [110, 111].

In this section, the purpose is to design a currents sliding observer based on a general class of manifold Θ . The basic sliding mode observer design procedure is performed in two steps. Firstly, an attractive manifold $\Theta(x, t) \in R^p$ is designed so that the output estimation error trajectories restricted to $\Theta(x, t)$, will have a desired stable dynamic. In the second step, the observer gain, to stabilize the equivalent dynamic on $\Theta(x, t)$ is determined. The (x_1, x_2) representing the components current, the rotor speed ω_r and the control input (u_1, u_2) are assumed to be available by measure.

Furthermore, the dynamic of rotor speed ω_r is assumed more slower than the stator and rotor current dynamics. The observer is considered as a copy of the DFIG electric equations where the ω_r speed is taken as a time varying parameter. In the sequel, $(\hat{x}_1, \hat{x}_2)$ denote the observed stator currents and $(\hat{x}_3, \hat{x}_4)$ the observed rotor currents, (e_{ds}, e_{qs}) the stator currents observation error and (e_{dr}, e_{qr}) the rotor currents observation error. Further, we assume that the real rotor currents are bounded as follows : $|x_3| < \rho_3; |x_4| < \rho_4$.

The sliding mode observer of the (4.3) is given by :

$$\left\{ \begin{array}{l} \underbrace{\begin{bmatrix} \dot{\hat{I}}_{dqs} \\ \dot{\hat{I}}_{dqr} \end{bmatrix}}_{\hat{\dot{x}}_{dq}} = A_{dq} \underbrace{\begin{bmatrix} \hat{I}_{dqs} \\ \hat{I}_{dqr} \end{bmatrix}}_{\hat{x}_{dq}} + B_{dq} \underbrace{\begin{bmatrix} V_{dqs} \\ V_{dqr} \end{bmatrix}}_{u_{dq}} + \Delta \text{sign}(e_x) \\ \hat{y}_{dq} = \hat{x}_{dq} \end{array} \right. \quad (4.11)$$

$$\text{Where : } \Delta = \begin{bmatrix} \delta_1 & 0 & 0 & 0 \\ 0 & \delta_2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

where the matrices A_{dq} and B_{dq} are given by :

$$A_{dq} = \left[\begin{array}{cc} \overbrace{\begin{bmatrix} a_1 & a_2 \\ a_5 & a_6 \\ a_9 & a_{10} \\ a_{13} & a_{14} \end{bmatrix}}^{A_1} & \overbrace{\begin{bmatrix} a_3 & a_4 \\ a_7 & a_8 \\ a_{11} & a_{12} \\ a_{15} & a_{16} \end{bmatrix}}^{A_2} \\ \underbrace{\hspace{10em}}_{A_3} & \underbrace{\hspace{10em}}_{A_4} \end{array} \right]; \quad B_{dq} = \left[\begin{array}{cc} \overbrace{\begin{bmatrix} b_1 & b_2 \\ b_5 & b_6 \\ b_9 & b_{10} \\ b_{13} & b_{14} \end{bmatrix}}^{B_1} & \overbrace{\begin{bmatrix} b_3 & b_4 \\ b_7 & b_8 \\ b_{11} & b_{12} \\ b_{15} & b_{16} \end{bmatrix}}^{B_2} \\ \underbrace{\hspace{10em}}_{B_3} & \underbrace{\hspace{10em}}_{B_4} \end{array} \right] \quad (4.12)$$

We propose an observer constituted by this subsystem for (stator currents)

$$\dot{\hat{I}}_{dqs} = A_1 \hat{I}_{dqs} + A_2 \hat{I}_{dqr} + B_1 V_{dqs} + B_2 V_{dqr} + \delta \text{sign}(e_{dqs}) \quad (4.13)$$

and the gain matrices δ is taken as : $\delta = \begin{bmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{bmatrix}$

we define a sliding surfaces error : $\Theta_1 = \begin{bmatrix} \Theta_{11}(e_{ds}) \\ \Theta_{21}(e_{qs}) \end{bmatrix}$; with : $\begin{bmatrix} e_{ds} \\ e_{qs} \end{bmatrix} = \begin{bmatrix} I_{ds} - \hat{I}_{ds} \\ I_{qs} - \hat{I}_{qs} \end{bmatrix}$;
where : $\Theta_{11}(e_{ds})$ and $\Theta_{21}(e_{qs})$ are class C^1 functions characterized by some properties, which will be derived later.

Proposition 1 For the first subsystem (4.13), if the following conditions are fulfilled :

- 1) $\Theta_1(x_{dqs})$ is strictly increasing function satisfying : $\Theta_1(x_{dqs}) = 0$ if and only if $x_{dqs} = 0$.

2) The coefficients δ_1 and δ_2 satisfy :

$$\begin{cases} \delta_1 > a_1|e_{ds}| + a_2|e_{qs}| + a_3(|\hat{I}_{dr}| + \rho_3) + a_4(|\hat{I}_{qr}| + \rho_4) \\ \delta_2 > a_5|e_{ds}| + a_6|e_{qs}| + a_7(|\hat{I}_{dr}| + \rho_3) + a_8(|\hat{I}_{qr}| + \rho_4) \end{cases} \quad (4.14)$$

Then, the manifold $\Psi = \{x_{dqs} \in R^4 / \Theta_1 = 0\}$ is made globally attractive and invariant, moreover the observation errors e_{ds} and e_{qs} converge at least asymptotically to zero.

Proof 1 On the manifold Ψ one has :

$$\Theta_1(e_{dqs}) = 0 \quad (4.15)$$

when $\Theta_1(x_{dqs})$ is chosen among functions that take zero value only at the origin $x_{dqs} = 0$, the condition (4.16) leads to $e_{ds} = e_{qs} = 0$.

In order to determine the gains of the observer, we propose the positive defined Lyapunov function :

$$V = \frac{1}{2} \Theta_1^T \Theta_1 \quad (4.16)$$

The derivative of the Lyapunov function is :

$$\dot{V} = \Theta_1^T \dot{\Theta}_1 \quad (4.17)$$

With $\dot{\Theta}_1 = \begin{bmatrix} \dot{e}_{ds} \frac{d\Theta_{11}}{de_{ds}} \\ \dot{e}_{qs} \frac{d\Theta_{21}}{de_{qs}} \end{bmatrix}$ as the current error dynamic of $\dot{e}_{dqs} = \begin{bmatrix} \dot{e}_{ds} \\ \dot{e}_{qs} \end{bmatrix}$ is given by :

$$\dot{e}_{dqr} = A_1 e_{dqs} + A_2 e_{dqr} - \delta \text{sign}(e_{dqs}) \quad (4.18)$$

with $e_{dqr} = \begin{bmatrix} e_{dr} \\ e_{qr} \end{bmatrix}$, and

$$\begin{cases} \dot{e}_{ds} = a_1 e_{ds} + a_2 e_{qs} + a_3 e_{dr} + a_4 e_{qr} - \delta_1 \text{sign}(e_{ds}) \\ \dot{e}_{qs} = a_5 e_{ds} + a_6 e_{qs} + a_7 e_{dr} + a_8 e_{qr} - \delta_2 \text{sign}(e_{qs}) \end{cases} \quad (4.19)$$

hence $\dot{V}$ can takes the form :

$$\dot{V} = \Theta_{11}^T(e_{ds}) \Theta_{11}(e_{ds}) \frac{d\Theta_{11}(e_{ds})}{de_{ds}} + \Theta_{21}^T(e_{qs}) \Theta_{21}(e_{qs}) \frac{d\Theta_{21}(e_{qs})}{de_{qs}} \quad (4.20)$$

In order to make $\dot{V} < 0$ (negative) $\forall \dot{\Theta}_1 \neq 0$, it is sufficient that the terms $\frac{d\Theta_{11}(e_{ds})}{de_{ds}}$ and $\frac{d\Theta_{21}(e_{qs})}{de_{qs}}$ must be positive $\forall e_{dqs} \neq 0$ and the gains δ_1 and δ_2 are taken as :

$$\begin{aligned} \delta_1 &> \max\{|a_1 e_{ds} + a_2 e_{qs} + a_3 e_{dr} + a_4 e_{qr}|\} = a_1 |e_{ds}| + a_2 |e_{qs}| + a_3 (|\hat{I}_{dr}| + \rho_3) + a_4 (|\hat{I}_{qr}| + \rho_4) \\ \delta_2 &> \max\{|a_5 e_{ds} + a_6 e_{qs} + a_7 e_{dr} + a_8 e_{qr}|\} = a_5 |e_{ds}| + a_6 |e_{qs}| + a_7 (|\hat{I}_{dr}| + \rho_3) + a_8 (|\hat{I}_{qr}| + \rho_4) \end{aligned} \quad (4.21)$$

The manifold Ψ , is then globally attractive and the observation errors e_{ds} and e_{qs} converge at least asymptotically to zero value.

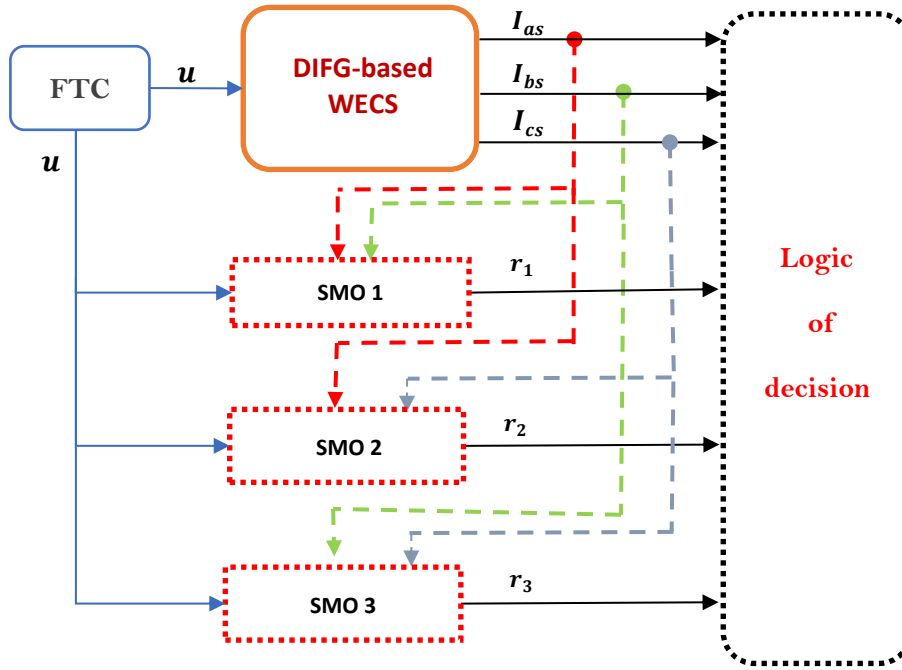


FIGURE 4.3 Detection of sensor faults by the multiple Dedicated Observers Scheme (DOS)

4.4.2 Residual generation block

To isolate the failing phase, we need a block of three observers. Each observer of which has as input two measured currents and the third current is calculated (taking as current value of the missing phase minus the sum of the two phases) this is illustrated in Figure 4.3, then we calculate the residuals :

$$r_1 = \begin{bmatrix} r_{11} \\ r_{21} \end{bmatrix} = \begin{bmatrix} I_{ds} - \hat{I}_{ds1} \\ I_{qs} - \hat{I}_{qs1} \end{bmatrix}; r_2 = \begin{bmatrix} r_{12} \\ r_{22} \end{bmatrix} = \begin{bmatrix} I_{ds} - \hat{I}_{ds2} \\ I_{qs} - \hat{I}_{qs2} \end{bmatrix}; r_3 = \begin{bmatrix} r_{13} \\ r_{23} \end{bmatrix} = \begin{bmatrix} I_{ds} - \hat{I}_{ds3} \\ I_{qs} - \hat{I}_{qs3} \end{bmatrix} \quad (4.22)$$

Theoretically, in the case of three-phase systems balanced to fictitious neutral the sum of the three currents :

$$I = I_{as} + I_{bs} + I_{cs} \text{ is zero.}$$

So : $I = 0 \rightarrow$ Normal operation (no fault).

$I \neq 0 \rightarrow$ Existence of fault (Stator current sensor fault).

While, practically the sum of the three currents is not exactly zero. but it is close to zero. So, we set a threshold ε such that :

$|I| < \varepsilon \rightarrow$ Normal operation (no fault).

$|I| > \varepsilon \rightarrow$ Existence of fault (Stator current sensor fault).

4.4.3 Isolation Block and Fault Correction

From the residual expressions calculated above, Table 4.1 shows the sensitivity of each residue to each defect :

TABLEAU 4.1 Sensitivity of residues to defects.

	Fault in Phase a	Fault in Phase b	Fault in Phase c
Residual r_1	+	+	-
Residual r_2	+	-	+
Residual r_3	-	+	+

(+) sensitive to the fault.

(-) not sensitive.

Thus, if there is a fault (current sensor fault), two residues will necessarily vary (out of the value of the tolerated error). The third remains unchanged, which will make it possible to locate the phase in fault. Table 4.2 summarizes the three cases that can occur when only one of the phases is faulty.

TABLEAU 4.2 Possible cases allowing the detection of a phase

Residual behavior			Phase a	Phase b	Phase c
r_1 Varied	r_2 Varied	r_3 do not vary	+	-	-
r_1 Varied	r_2 do not vary	r_3 Varied	-	+	-
r_1 do not vary	r_2 Varied	r_3 Varied	-	-	+

(+) Presence of fault.

(–) No fault.

In normal operation (without presence of fault), there will be no correction i.e. the two currents represented in the landmark 'dq',

I_{ds} and I_{qs} will be calculated from the three phase currents measured. In the opposite (presence of fault), the two currents I_{ds} and I_{qs} will be obtained according to the fault location, i.e. if the fault is current sensor fault :

a : I_{ds} and I_{qs} will be taken from the third measure i.e. the measure or the current, $I_{as} = -(I_{bs} + I_{cs})$.

b : I_{ds} and I_{qs} will be taken from the second measure i.e. the measure or the current, $I_{bs} = -(I_{as} + I_{cs})$.

c : I_{ds} and I_{qs} will be taken from the first measure i.e. the measure or the current, $I_{cs} = -(I_{as} + I_{bs})$.

4.5 Results and Discussions

In order to show the performance of the proposed diagnostic and isolation scheme we applied a current sensor fault in phase 'a' on DFIG-based WECS. The fault-tolerant control used was developed and tested by synthesizing supper twisting SMC controller, in order of correct and precise operation of the proposed method. The studies were conducted in under MATLAB / Simulink environment, using 'Euler' method with the fixed step size of $0.3ms$, The results obtained by $Q_s^* = 0[VAR]$ in the following variation of wind speed protocol and scenarios of sensor fault :

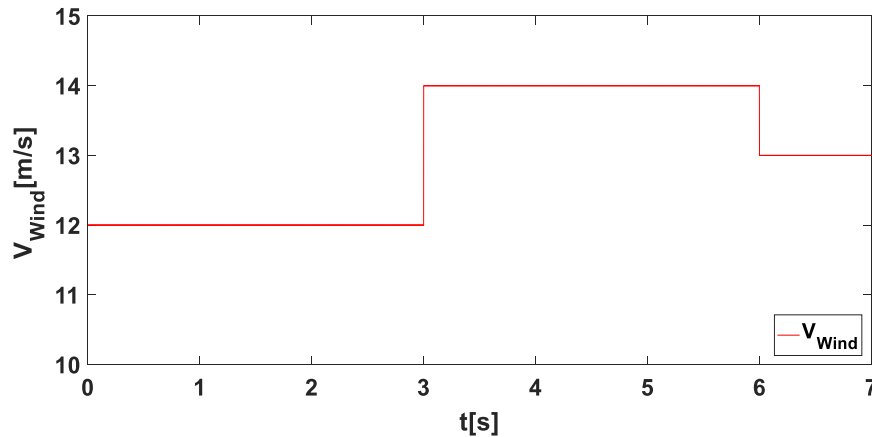


FIGURE 4.4 Variation of wind speed

TABLEAU 4.3 Scenarios of sensor fault

Time[s]	[0;3]	[3;4.5]	[4.5;6]	[6;7]
$V_{wind}[m/s]$	12	14	14	13
$\hat{f}_{sensor}(t)$	Health operation	Health operation	Fault operation	Fault operation

4.5.1 Fault in One Current Sensors

Several tests have been performed to check out the accuracy of the proposed model in the first step; the DFIG-based WECS was tested and simulated in a faulty operation with a rotor speed of $112.32[rad/s]$ and controlled by orientation of the flow stator with reactive power control and adjustment of the speed of rotation to maximize the active power.

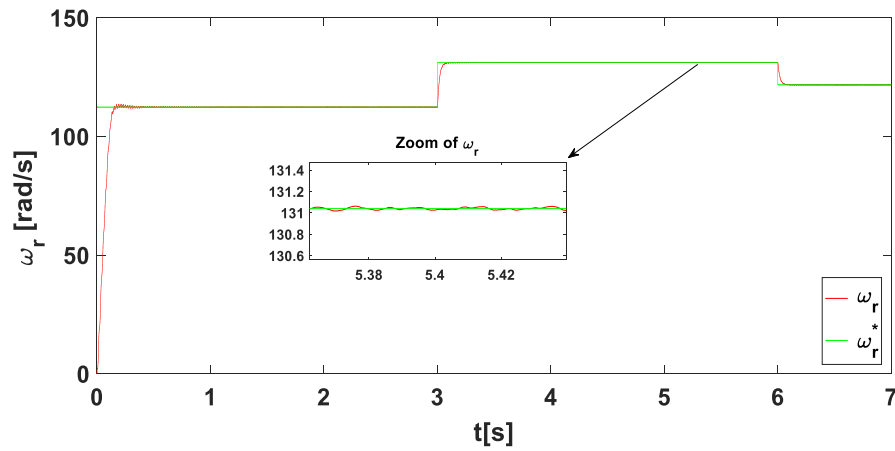


FIGURE 4.5 Variation of rotor speed

Figure 4.5 shows the rotor speed tracking with super twisting control and sliding mode observer. It can be seen after starting, which is done in closed-loop, that the measured and estimated values rotor speed dynamics are fast, follows and converges perfectly to their reference value coming from the control in MPPT operation conditions of the wind turbine, in the steady-state with zero static error. There is a very good speed estimate by the observer over the entire speed range.

The active and reactive power tracking are respectively illustrated in Figure 4.6. It is noticeable that it is present oscillations due to the harmonics injected by rotor inverter. It is also remarkable that it is insensitive to the variation of the wind speed except the increase of the oscillations at the time of the variation of the wind $t=3[s]$ and $t=6[s]$; however, it is noticed that there is an increase in oscillations in estimated value on the active and reactive power when the fault occurred at $t=4.5[s]$. The obtained results reinforce and

assert the effectiveness of the proposed control and observer. It can be observed that the control synthesized super twisting control rejects the effect of the disturbance which comes from the variation in wind speed.

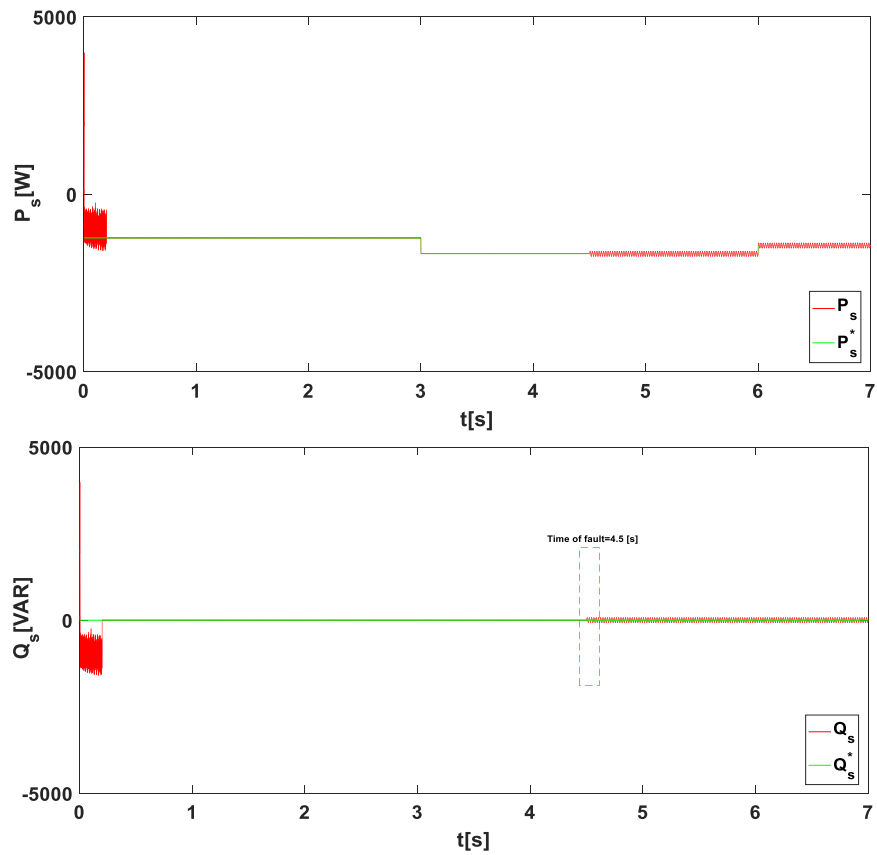


FIGURE 4.6 Variation of active and reactive stator powers

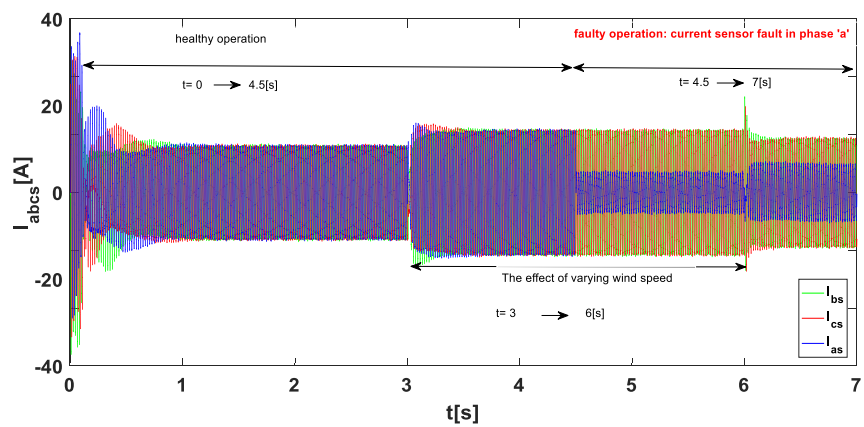


FIGURE 4.7 Three-phase stator currents

Indeed, this fault-tolerant control compensated for the effect of this disturbance introduced at time $t = 3$ [s].

Figure 4.7 presents the evolution of the measure of three-phase stator currents I_{abc} for healthy operation between the times $t = 0$ [s] and 3 [s], as well as in the faulty operation of a current sensor in phase 'a' at $t = [4.5; 7]$ s. In healthy operation, it can be clearly observed that the behaviour of three-phase stator currents is normal and stable and gives high performance. In faulty operation, it is noticed that the current in phase 'a' presents decrease in its amplitude compared with its amplitude in healthy operation when the sensor fault occurs.

Figure 4.8 represents respectively the measure of three-phase stator currents (I_{as}, I_{bs}, I_{cs}) of the DFIG and their estimated values ($\hat{I}_{as}, \hat{I}_{bs}, \hat{I}_{cs}$) based on the use of SMO, and the dynamic of errors of the states, and the residual signatures generated by proposed SMO.

To test the detection and isolation block for the current sensor fault, a fault in phase 'a' is introduced. This phase will reconstruct through the two remaining phases 'b' and 'c'. It can be clearly observed from the simulation results that the state's estimation generated from the SMO converges rapidly to those simulated by the real system (DFIG), especially in healthy operation. Furthermore, it can be observed that the estimated errors are very weak, which confirms an ideal estimation by using this observer.

At $t=3$ [s], we note the increase in the amplitudes of the stator currents Figure 4.8 with the increase in the wind speed which causes the increase in the torque applied to the DFIG and subsequently the active power developed as shown in the Figure 4.6.

In faulty operation $t=[4.5; 7]$ s, it is noticeable that the current in phase 'a' presents decrease in their amplitude compared with their amplitude in healthy operation, when the sensor fault occurs, with considerable errors of measurement. These errors allow us to detect the fault when it occurs. The residual (r_1, r_2 , and r_3) generated from the difference between the estimated currents and the measured one (Boolean variation) shown by Figure 4.8, indicated the occurrence of a fault; it is clear that the residues r_1 and r_2 vary at the moment when the defect appears. Nevertheless, the residue r_3 does not vary, which corresponds to the developed results in table 4.2.

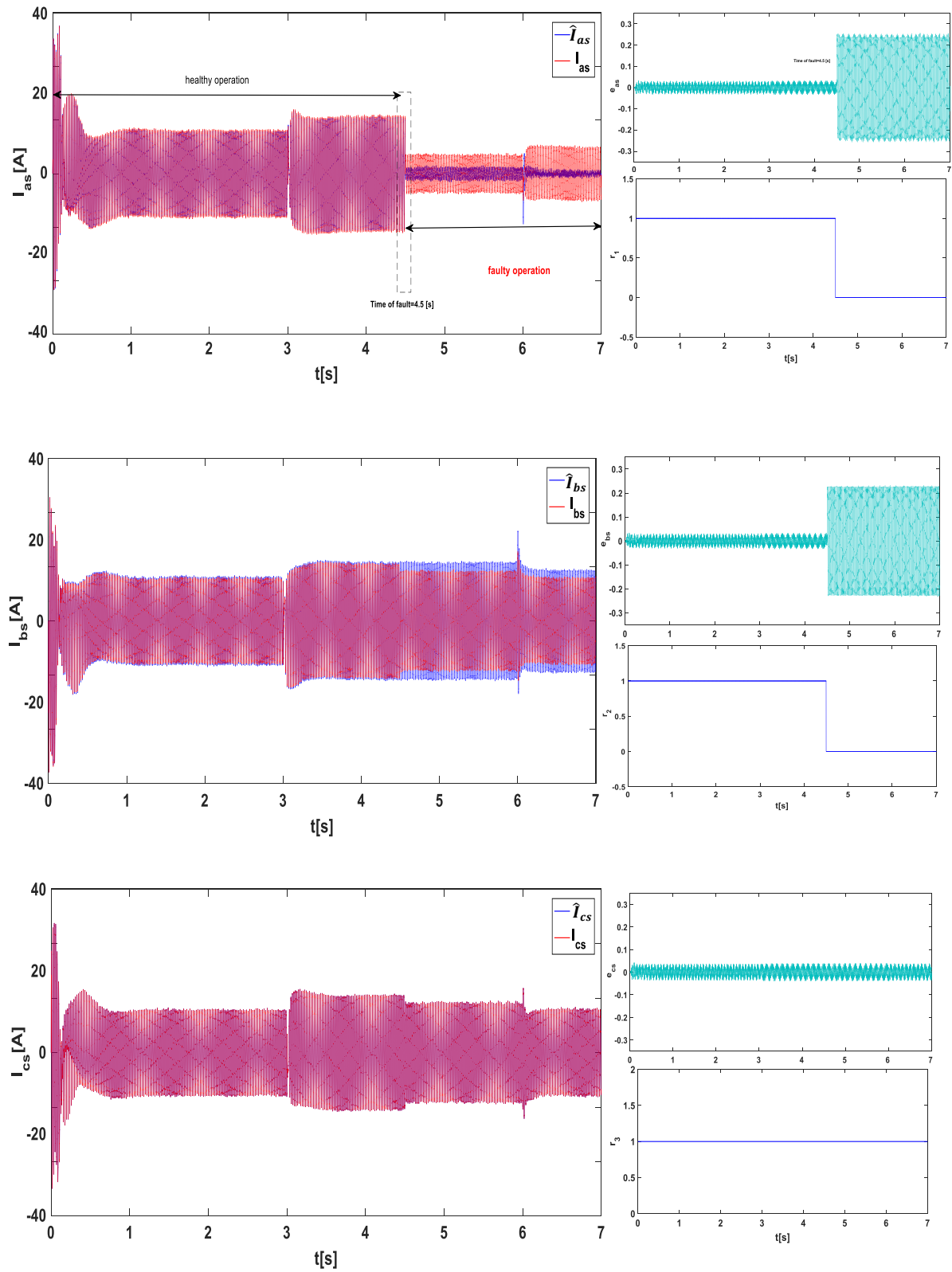


FIGURE 4.8 Three-phase stator currents with sensor fault and their residual signatures

4.5.2 Control with Variation of the Reference Reactive Power

In order to see the effect of the variation of the reactive power on the active power, the stator currents and the adjustment of the rotor speed, we propose to set the reference of the rotor speed of DFIG from the wind speed at a constant value equal to 13 [m/s] Figure 4.9 and the reference of the reactive power is changed as shown in the following table 4.4 :

TABLEAU 4.4 Variation of the reference of reactive power

$Time[s]$	[0 ;2]	[2 ;4.5]	[4.5 ;6]	[6 ;7]
$V_{wind}[m/s]$	13			
$Q_s^*[Var]$	0	-3000	-3000	3000
$\hat{f}_{sensor}(t)$	0		$\hat{f}_{sensor}(t)$	

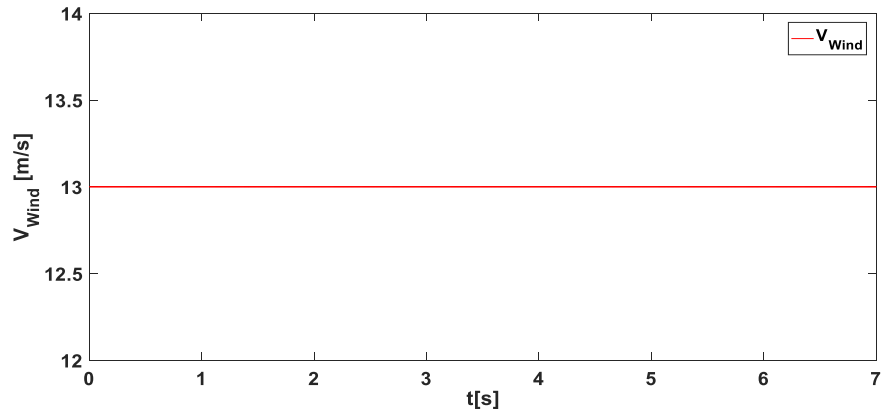


FIGURE 4.9 Fixed wind speed

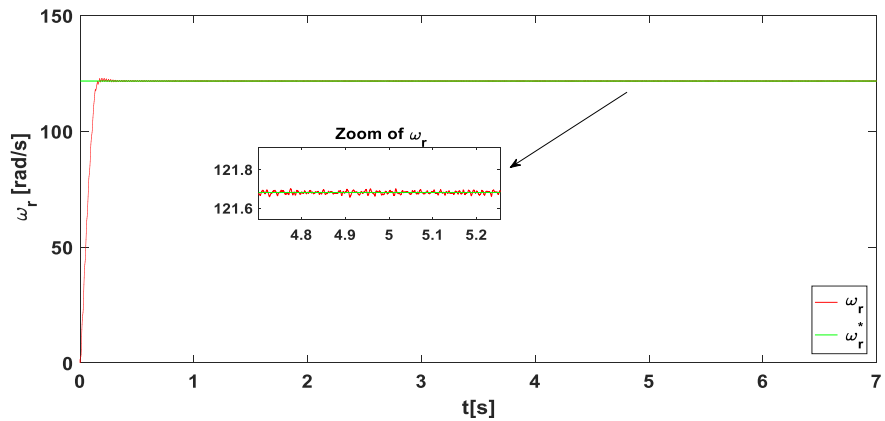


FIGURE 4.10 Variation of rotor speed

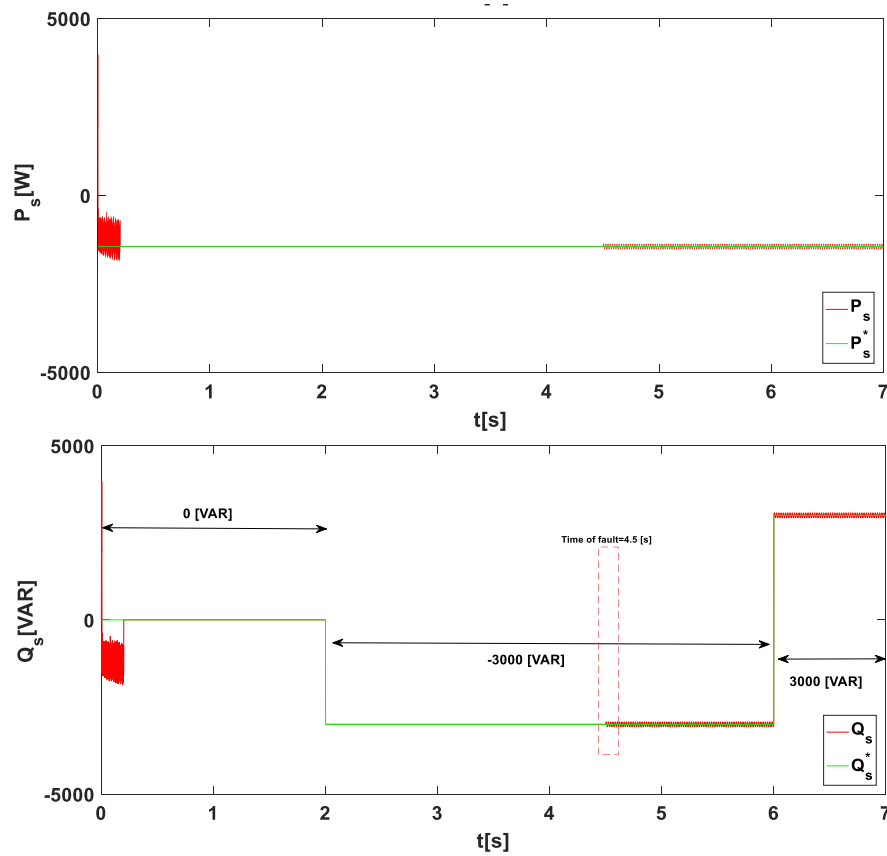


FIGURE 4.11 Variation of stator active and reactive powers

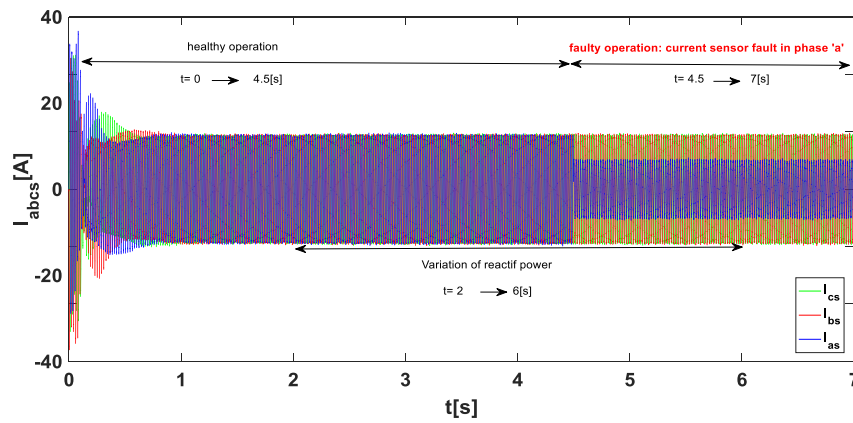


FIGURE 4.12 Three-phase stator currents with variation of reference reactive stator powers

Figure 4.10 present the variation of measured and estimated values of rotor speed of the DFIG , for a variation of the reference of reactive power and constant wind speed for healthy and faulty operation.

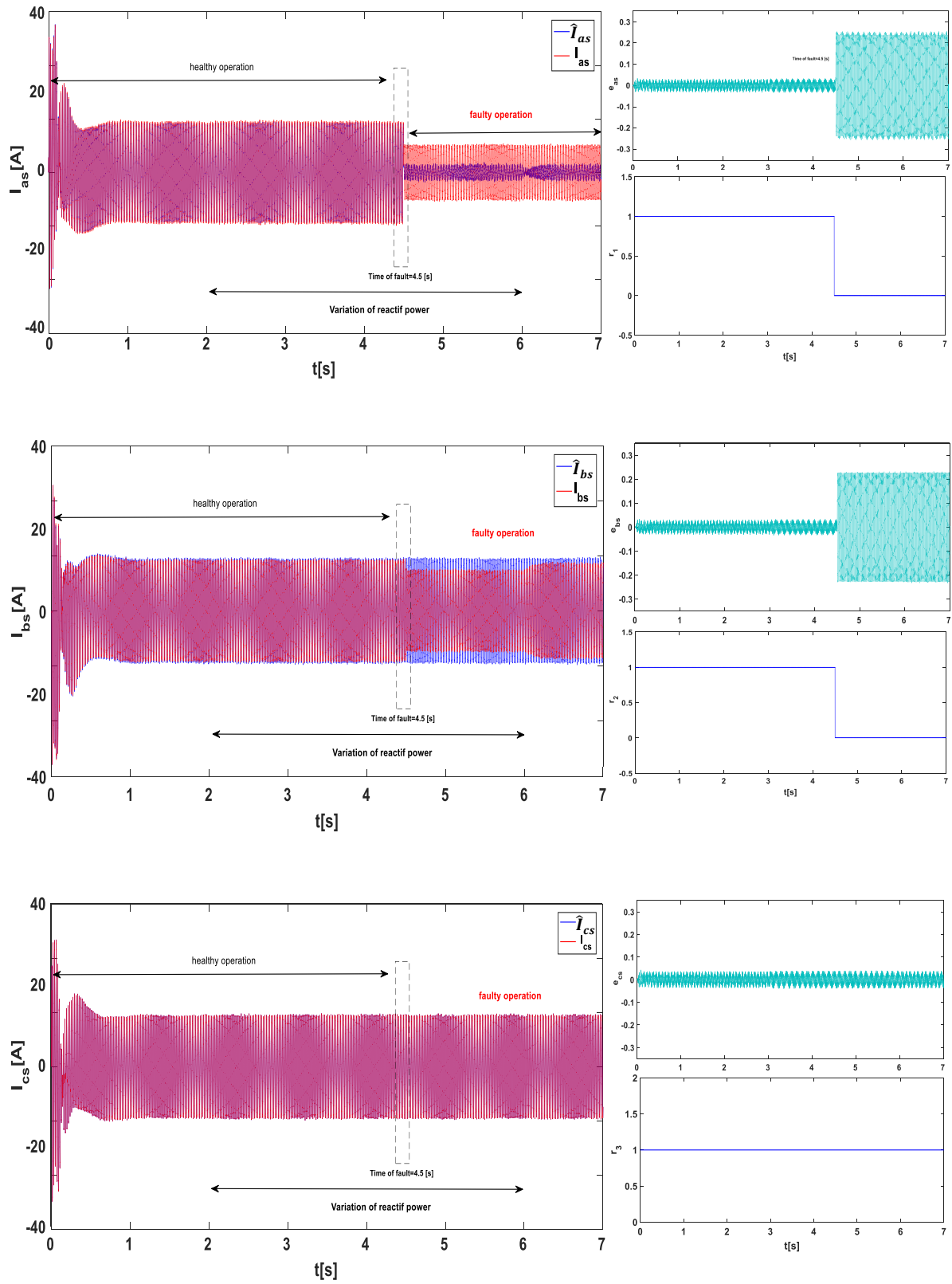


FIGURE 4.13 Three-phase stator currents and their residual signatures

After a transient state, the rotor speed follow its reference value. In Figure 4.10, we notice that measured and estimated values of the rotor speed follow exactly their reference independently of the variation of the reactive power.

As for active and reactive powers Figure 4.11, we can see the same remarks about the increase in the oscillations after the application of the fault, compared to the healthy operation. According to the results obtained, the variation in reactive power does not affect the appearance of active power.

Figure 4.12 presents the evolution of the measure of three-phase stator currents I_{abs} for healthy operation between the times $t = 0$ [s] and 3 [s], as well as in the faulty operation of a current sensor in phase ‘a’ at $t = [4.5; 7s]$. In healthy operation, it can be clearly observed that the behavior of three-phase stator currents is normal and stable and gives high performance.

Figure 4.13 presents the evolution of the measure of three-phase stator currents of the DFIG and their estimated values based on the use of SMO ; they are dynamic errors and the residual signatures generated by proposed SMO. At the time of the fault at $t=4.5$ [s], this fault influences in the equilibrium of the three-stator phases and therefore the equilibrium of stator currents which effects of the power developed. affects the power that is generated. We also notice, in the evolution of the stator currents, a distortion after the application of the fault sensor.

The variation of the reactive power has no remarkable effect on the stator currents. Consequently, the simulation results show the efficiency and feasibility of the proposed current sensor fault detection strategy.

4.5.3 Fault in Two Current Sensors

In the case of two or three faulty current sensors, one will not be able to correct them because in vector control there is a need for at least two-phase currents and a speed sensor to ensure control of the DFIG. To ensure continuity of operation, scalar control can be used. The principle of scalar control is to keep $V/f = constant$ which means to keep the flow constant. The torque control is done by the action on the slip.

4.6 Summary

In this chapter, we have treated the problem of sensor fault detection and isolation of stator currents in a DFIG- based WECS. In faulty conditions, the DFIG was unbalanced and there was a significant decrease of the stator’s current. For the proposed control scheme, the

estimated value of the speed remained equal to their real value and the overshoot currents cannot be avoided. When the current was not exceeding the acceptable level, the DFIG continued to operate with degraded performances until its repair or exchange.

Hence, it was always necessary to execute early fault detection for less damage. A multiple Dedicated Observers Scheme (DOS) and statistical change detection algorithms had been used as a residual generator and decision systems, respectively. So, the global control and sliding mode observer schemes introduced high performances of robustness, stability, and precision. Through simulations, it had been demonstrated that the detection and isolation of current sensor fault for stator currents had been correctly achieved, and the diagnosis result was not affected by disturbances and reference changes.

GENERAL CONCLUSION

The growing evolution of induction machines, especially at DFIG-based WECS, forces some users to protect themselves against the appearance of a fault, most often causing the machine's untimely stop. The work presented in this thesis was devoted to the study of the FDD and FTC schemes of the DFIG based-WECS with two fault scenarios that are specifically discussed : ITSC and current sensor faults. The short-circuit faults between turns can appear following the degradation of the insulators caused by an overcurrent or overvoltage during the switching of the converter thus inducing a circulation of a very high current in the short-circuited coils. This type of fault can lead to short circuits between phases or between a phase and the earth which can be avoided by permanent monitoring of the state of the generator.

For this reason, we have proposed new and adapted FDD approaches for a DFIG-based WECS with a stator ITSC and current sensor faults which is based on SMO. The proposed observer is able to generate specific residuals. These residuals are the difference between measured three-phase stator currents and reconstructed ones. Residuals are allowing to detect and isolate the a or b or c faulty phase. However, in order to avoid false alarms, the threshold value must be established after the analysis of the residual level in healthy operating case of the DFIG. Based on the proposed fault diagnosis scheme, a fault compensator is developed and integrated with a traditional control algorithm (i.e., stator flux-oriented control), which is able to provide online compensation of any possible faults, regardless of their level and location.

The simulation studies confirm that the proposed fault FDD approach offers rapid and precise detection and isolation of faults. The robustness and effectiveness of the proposed approaches from the obtained results, the superiority of the proposed approaches is clearly revealed and demonstrated.

PERSPECTIVES

1. In this thesis, we only examined two types of faults. DFIG winding short circuit and current sensor faults. Other fault scenarios of wind turbine systems, such as grid fault and pitch control failure, require further investigation.
2. To improve our study of the diagnosis of induction machine faults, the study could be extended by considering other types of faults and other advanced diagnostic and detection

tools or by parametric estimation.

3. The most significant future work, of course, is to put the created problem diagnosis and FTC methods to the test on an actual wind turbine system. All of the work provided in this thesis is based on MATLAB simulation, which raises the question of how well it will perform in real-world situations. As a result, some additional experimental research will be required in the future.

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