



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electrical Power and Machines Engineering

PQ for the Grid Supported with Wind Turbines

A Thesis submitted in partial fulfilment of the requirements of the degree of

Master of Science in Electrical Engineering

(Electrical Power and Machines Engineering)

by

KARIM MOHAMED GAMAL AL DEEN ISHAK

Bachelor of Science in Electrical Engineering

(Electrical Power and Machines Engineering)

Faculty of Engineering, Ain Shams University, 2010

Supervised By

PROF. DR. ELSAYED ABDEL ALEEM

DR. KHALED ABDEL-ATY MOHAMED

DR. MOHAMED AHMED EBRAHIM

Cairo – July 2017

Statement

This thesis is submitted as a partial fulfillment of Master of Science in Electrical Engineering, Faculty of Engineering, Ain Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

Karim Mohamed Gamal Al Deen

Signature

.....

Date:23 November 2017

Acknowledgment

First of all, I would like to thank Allah “God” for providing me with health and patience to finish this dissertation.

I would like to thank a lot of people for their support toward the completion of this degree. Specifically Prof. Dr. Elsayed **Abdel Aleem**.

I wish to express my sincere gratitude to **Dr. Mohamed Ibrahim & Dr. Khaled Abdel Aty**.

Though away from them during the completion of this degree, I would like to send my deepest appreciations and thanks to my parents and sister for their support and to whom this dissertation is dedicated.

Karim Mohamed Gamal AL Deen

ABSTRACT

Wind energy is considered as one of the clean and renewable energy sources that can be used in the extraction of electric energy. This draws attention to increase the usage of such energy for electricity generation. The operation of Wind Energy Conversion System (WECS) introduces power quality challenges. These challenges motivate many researchers to overcome these power quality issues especially total harmonic distortion. In this work, the impact of connecting wind farms with different conversion systems on the quality of the produced power was studied. In the first part of the thesis, the power quality criteria will be presented focusing on the harmonics emissions, then the international standard IEEE519-2014, IEC 61400-21 and the national Egyptian wind farm grid connection code are presented. The Second part discusses wind energy conversion systems in details. The various types of wind turbines are studied. The different technologies of the commonly used generators in converting rotational energy of the wind to electrical power energy are also discussed showing the merits and demerits of each. Then, some optimization techniques were introduced, selecting the Particle Swarm Optimization technique (PSO) as one of the most important and frequent used technique. This technique is used in our work for optimizing the controllers' gains.

After that, the static compensation devices are clarified as one of the modern power conditional devices. These devices are able to perform voltage and reactive power regulation in order to enhance the performance of wind farms and compensate reactive power consumption from the grid. In this work, two of them are evaluated and compared, namely Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC).

WECS has been modeled in MATLAB/Simulink, with the use of Doubly Fed Induction Generator (DFIG) and Synchronous Generator (SG) as two alternative scenarios recently used and with the modeling of the whole power grid as groups of step-up transformers, feeding lines and bus bars. Their response is studied together with the case when static compensation devices are implemented as compensation techniques.

The major contributions of this thesis are: (i) providing comprehensive comparative study for different types of generators in WECS, (ii) application of PSO technique in controllers' gains tuning and (iii) The compensation devices are optimally used to study their effect on the total harmonic distortion index measured at the point of grid connection.

Key words:-

Power quality, Total harmonic distortion(THD), static compensators, point of common coupling(PCC) & Fast Fourier Transform tool(FFT).

TABLE OF CONTENTS

		<i>page</i>
	<i>ACKNOWLEDGEMENT</i>	I
	<i>ABSTRACT</i>	II
	<i>TABLE OF CONTENTS</i>	IV
	<i>LIST OF FIGURES</i>	VI
	<i>LIST OF TABLES</i>	IX
	<i>LIST OF SYMBOLS & ABBREVIATIONS</i>	X
<i>CHAPTER 1</i>	<i>INTRODUCTION</i>	
1.1	Research Motivation	1
1.2	Literature Review	2
1.3	Objectives	3
1.4	Thesis Outline	3
<i>CHAPTER 2</i>	<i>POWER QUALITY</i>	
2.1	Power Quality Definition	5
2.2	Need for Power Quality Studies	6
2.3	Harmonics	7
2.4	Practical method for total harmonic distortion measurement	10
2.4.1	Measurement window width	10
2.4.2	Very short time harmonic measurements	11
2.4.3	Short time harmonic measurements	11
2.4.4	Statistical evaluation	12
2.5	Grid Code for Wind Farms	14
2.6	Disconnection from the Grid	15
2.6.1	Voltage ranges	15
2.6.2	Frequency ranges	16
<i>CHAPTER 3</i>	<i>WIND TURBINES</i>	
3.1	Introduction	17
3.1.1	Types of Turbines	21
3.1.1.1	Fixed-Speed Wind Turbine	22
3.1.1.2	Variable Speed Wind Turbine with Variable Rotor Resistance	23
3.1.1.3	Variable Speed Wind Turbine with Doubly Fed Induction Generator	24
3.1.1.4	Variable Speed Wind Turbine with Multi-pole or Permanent Magnet Synchronous Generator	24

3.1.1.5	Variable Speed Wind Turbine with Wound Rotor Synchronous Generator	25
3.2	Modeling of the wind electrical conversion systems	26
3.2.1	Synchronous Generator Model	26
3.2.2	Modeling of DFIG	29
CHAPTER 4	PARTICLE SWARM OPTIMIZATION	
4.1	Introduction	31
4.2	Particle Swarm Optimization: Basic Concepts	33
4.3	Developed Heuristic Technique: PSO Algorithm	33
4.4	Fitness Function	35
4.5	Termination Criteria	35
CHAPTER 5	STATIC COMPENSATORS	
5.1	Introduction	37
5.2	Static Synchronous Compensator(STATCOM)	39
5.2.1	Principle of STATCOM	39
5.2.2	Operation Modes	41
5.2.3	Characteristics of STATCOM	41
5.3	Static Var Compensator(SVC)	44
5.3.1	Principle of SVC	44
CHAPTER 6	SIMULATIONS RESULTS	
6.1	System description	48
6.2	Optimization results	49
6.3	System response at normal operating conditions	54
6.4	Simulation Model with DFIG generator at 120kV Bus (PCC)	63
6.4.1	Case (I): THD analysis of the model without static compensators	63
6.4.2	Case (II): THD analysis of the model with STATCOM	70
6.4.3	Case (III): THD analysis of the model with SVC	77
6.5	Simulation Model with DFIG generator at B25 (POE)	84
6.6	Simulation Model with SG generator at B120 (PCC)	85
6.7	Simulation Model with SG generator at B25 (POE)	86
6.8	Comparison results	87
CHAPTER 7	CONCLUSIONS	
7.1	Conclusions	98
7.2	Future work	99
	LIST OF REFERENCES	100
	APPENDIX (A)	103
	ARABIC SUMMARY	

LIST OF FIGURES

Fig. 2.1 Power quality problems criteria chart.....	6
Fig. 3.1 Ratio between C_p and lambda according to the type of turbine	18
Fig. 3.2 Representative C_p - Lambda curve for a fixed pitch wind turbine	18
Fig. 3.3 Comparison between power curves (P-v)	19
Fig. 3.4 Wind electric scheme	20
Fig. 3.5 Modes of operation of wind turbines	21
Fig. 3.6 Fixed-speed turbine scheme	22
Fig. 3.7 Variable speed turbine with rotor resistance scheme	23
Fig. 3.8 Variable speed turbine with DFIG scheme	24
Fig. 3.9 Scheme of the power electronics with a PMSG	25
Fig. 3.10 Full-scale power electronics WECS with multi-pole synchronous generator	26
Fig. 3.11 Wind turbine with synchronous generator matlab model.....	28
Fig. 3.12 Wind turbine with DFIG matlab model	30
Fig. 4.1 Modern heuristic techniques	31
Fig. 4.2 PSO advantages chart	32
Fig. 4.3 fundamental concepts of PSO	33
Fig. 4.4 Flowchart diagram of the implemented PSO algorithm	34
Fig. 5.1 Advantages of FACTS	38
Fig. 5.2 Functional model of STATCOM	40
Fig. 5.3 Operating modes of STATCOM.....	41

Fig. 5.4 V-I Characteristics of STATCOM	42
Fig. 5.5 STATCOM control scheme	43
Fig. 5.6 Schematic diagram of SVC.....	45
Fig. 5.7 SVC control scheme	46
Fig. 6.1 Schematic diagram of wind farm connected to grid	48
Fig. 6.2 Matlab Simulink model for DFIG without compensators	49
Fig. 6.3 Output power with time before optimizing controller gains.....	50
Fig. 6.4 Output power with time after optimizing controller gains.....	51
Fig. 6.5 The turbine Cp curves.....	52
Fig. 6.6 Normal operation conditions for the wind farm to grid system.....	62
Fig. 6.7 Voltage waveforms with time interval 0.1s at PCC.....	64
Fig. 6.8 THD for Voltage waveforms with intervals of 0.2s at PCC	65
Fig. 6.9 Current waveforms with time intervals of 0.1s measured through PCC.....	67
Fig. 6.10 TDD for Current waveforms with time interval of 0.2s coming from WF at PCC	68
Fig. 6.11 Model of wind farm with DFIG with STATCOM.....	70
Fig. 6.12 Voltage waveforms with time interval 0.1s at PCC.....	71
Fig. 6.13 THD for Voltage waveforms with time intervals of 0.2s at PCC with STATCOM...	72
Fig. 6.14 Current waveforms with time intervals of 0.1s measured through PCC with h STATCOM at B575.....	73
Fig. 6.15 TDD for Current waveforms with time interval of 0.2s coming from WF at PCC STATCOM	74
Fig. 6.16 Model of wind farm with DFIG with SVC.....	77
Fig. 6.17 Voltage waveforms at PCC with SVC connected at B575 with time interval 0.1s.....	78
Fig. 6.18 THD for Voltage waveforms with time intervals of 0.2s at PCC with SVC.....	79
Fig. 6.19 Current waveforms with time intervals of 0.1s measured through PCC with SVC at B575..	80

Fig. 6.20 TDD for Current waveforms with time interval of 0.2s coming from WF at PCC with SVC	81
Fig. 6.21 Waveforms for both DFIG and SG at PCC and POE without and with compensators.....	95
Fig. 6.22 THD & TDD at B120,B25 with DFIG	96
Fig. 6.23 THD & TDD at B120,B25 with SG	97

LIST OF TABLES

Table 2.1 Voltage Harmonics Limit	8
Table 2.2 Maximum level of integer harmonic current distortion in the frequency range up to 2 kHz.....	9
Table 2.3 Maximum level of harmonic current distortion in the frequency range above 2 kHz.....	9
Table 2.4 Maximum level of inter-harmonic current distortion up to 2 kHz.....	10
Table 2.5 Voltage distortion limits	13
Table 2.6 Current distortion limits for systems rated above 69 kV through 161 kV	14
Table 2.7 Minimum time periods	16
Table 2.8 Bench mark for voltage and current evaluation	16
Table 6.1 THD of the system voltage at PCC	66
Table 6.2 TDD of the system current through PCC(coming from wind farm)	69
Table 6.3 THD of the system voltage at PCC with STATCOM at B575.....	75
Table 6.4 TDD of the system voltage at PCC with STATCOM at B575.....	76
Table 6.5 THD of the system at PCC with SVC connected at B575.....	82
Table 6.6 TDD of the system through PCC with SVC connected at B575.....	83
Table 6.7 THD and TDD of the system measured at B25 with DFIG	84
Table 6.8 THD and TDD of the system measured at B120 with SG.....	85
Table 6.9 THD and TDD of the system measured at B25 with SG.....	86
Table 6.10 THD & TDD at both B120 and B25 for both DFIG and SG.....	96

List of Symbols and abbreviations

A	Area swept by wind turbines
C_p	Power coefficient.
DFIG	Doubly Fed Induction Generator.
FACTS	Flexible AC Transmission System.
FFT	Fast Fourier Transform.
IEC	International Electro-technical Commission.
IEEE	Institute of Electrical and Electronics Engineers
K_I	Integral control gain.
K_P	Proportional control gain.
m	Mass of air.
PI	Proportional- integral controller.
PQ	Power quality.
PCC	Point of Common Coupling
POE	Point Of Evolution
THD	Total Harmonic Distortion
TDD	Total Demand Distortion
R	Turbine radius.
STATCOM	Static Synchronous Compensator.
SVC	Static Var Compensator.
SG	Synchronous Generator.
S_n	Rated apparent power of wind turbine.
S_k^*	Short circuit apparent power of the grid.
U	Kinetic energy.
WECS	Wind Energy Conversion System.
ρ	Air density.
λ	Tip speed ratio.
β	Pitch angle.
Ω	Rotational speed of the turbine.

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

The interest for renewable energy sources has increased greatly in the last years due to both environmental concerns and conventional fossil fuel increasing cost. Wind energy, as one of the most important and attractive renewable energy sources, has gained a lot of heavy investments from all over the world. It is estimated that about 16% of the world's electricity will be obtained from wind energy by 2020[1]. The wind power sector is suggested to meet a great growth in terms of total installed capacity. After an observable slowdown in 2013, the wind industry set a new positive record for annual installations in 2014. Globally, according to the global wind market statistics, 51473MW of new wind generating capacity was added in 2014[2]. The record points out that about 44% increase in the annual market and is a positive sign of the recovery of the industry after a rough patch in the past few years. Wind Energy Conversion Systems (WECSs) have become a focal point in the research of renewable energy sources. There are various technologies of generators used in WECSs [3]. Due to the uncertain nature of wind speed and power electronics converters used in the WECS of different generators, this affects the quality of power produced from the wind farm.

This thesis presents models of WECS of different generators and a comparative study of the total harmonic distortion index produced from the wind farm at the

grid point of interconnection was performed. Also, the total harmonic distortion index is measured when FACTS are connected and the controllers' gains are optimized using Particle Swarm Optimization (PSO).

1.2 Literature Review

There are two operation modes of WECS, the fixed speed operating mode and the variable speed operating mode [1].

Fixed speed wind turbine, mainly include the Squirrel Cage Induction Generators (SCIG), led the market until 2003 when the DFIG began to spread and proved its performance as an excellent performance variable speed wind turbine [4].

Variable speed wind turbine includes different types of technologies of generators for which are synchronous generators and permanent magnet synchronous generators. Although their need to a full-scale converter, a great attention is drawn to it enhancing its market share in the past recent years [1].

The interconnection of the variable speed wind turbines equipped with power electronic devices introduces significant harmonics into the grid. Several international and national standards specify certain limits for the introduced harmonic contents [5][6][7][8].

Power quality problems consist of various terms as harmonic distortions, impulses, swells, and sags. Voltage sags are very serious and can cause a large amount of damage [9].

FACTS devices are a very good choice for regulating the voltage and compensating reactive power of the systems. In this thesis, STATCOM and SVC are chosen and are connected at B575 and their effect on THD was evaluated [10].

1.3 Objectives

Based on the review of the discussed points mentioned before, the following points of interest will be researched in this thesis, concentrating mostly on the use and optimize of PI-based controller for the STATCOM and SVC:

1. Model the WECS consisting of wind, wind turbine, gear box, power electronic converters, and generators.
2. Choosing two different alternative types of generators used in the WECS.
3. Simulate the proposed WECS using MATLAB Simulink environment.
4. Use elected FACTS device and show its effect on THD.
5. Introduce an optimization technique and use it to optimize the gains of the PI-controller of the FACTS device.

1.4 Thesis Outline

The thesis is structured as follows: Chapter 2 presents the power quality characteristics of wind turbines. It also describes the power quality terms, it's regulating standards, national and international codes recommendations.

Chapter 3 discusses and categorizes the types of WECS. It also presents the model of WECS with DFIG and SG.