Yarmouk University
Hijjawi Faculty for Engineering Technology

Improving System Voltage Stability with a Large Scale of SCIG Wind Generation Using STATCOM

A Thesis Submitted to
The Department of Electrical Power Engineering

In partial fulfillment of the requirements for the degree of
Master of Electrical Power Engineering

By
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Supervisor
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List of Principle Symbols:

δ	Power angle
$\emptyset$	Phase angle
P_L	Power demand
Q_L	Reactive power demand
E	Generator internal voltage
V	Terminal voltage
X	Reactance
S_g	System gain
S_r	Shunt reactor
S_c	Shunt capacitor
R_s	Resistive load
G	Generator
D	Demand
M	MVARs
V_S	Voltage from voltage source converter
$i^*_{Sd,q}$	Reference source current in d-q reference frame
Q_S^*	Reference reactive power supplied by the source
$\overline{Q}_L$	Average reactive power
V_t	Voltage at point of common coupling
G(s)	Transfer function
$i_{ld,q}$	Load current in d-q reference frame
i_{cq}	Output of AC controller
i_{cd}	Output of DC controller

List of Abbreviations:

SCIG	Squirrel Cage Induction Generator
PMG	Permanent Magnetic Generator
DFIG	Doubly Fed Induction Generator
LVRT	Low Voltage Ride Through
WPP	Wind Power Plant
PCC	Point of Common Coupling
FACTS	Flexible AC Transmission System
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
WRIG	Wound Rotor Induction Generator
VSWT	Variable Speed Wind Turbine
PSPC	Partial Scale Power Converter
FSPC	Full Scale Power Converter
TSOs	Transmission System Operator
PLL	Phase Locked Loop
HVDC	High Voltage DC
SSSC	Static Synchronous Series Compensator
VSC	Voltage Source Converter
UPFC	Unified Power Flow Controller

Declaration

I am, Bilal Al-Majali, recognize what plagiarism is and I hereby declare that this thesis proposal, which is submitted to the department of Electrical Power Engineering at Hijjawi Faculty for Engineering Technology, for the partial fulfillment of the requirements for the degree of Master of Science, is my own work. I have not plagiarized from any sources. All references and acknowledgments of sources are given and cited in my proposal. I have used the conventional citation and referencing. Each significant contribution to and quotation in this report from work of other people has been attributed and referenced.

Bilal Al-Majali

Acknowledgments

Firstly, I would like to express my sincere gratitude to my advisor Dr. Abedalgany A. Athamneh for the continuous support of my master study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my master study.

Besides my advisor, I would like to thank my family: my parents and to my brothers and sister for supporting me spiritually throughout writing this thesis.

Abstract

Increase of the penetration of wind energy in electrical power generation makes it an important portion in the electrical power system, and a stable operation for wind turbines considered an essential part of power system stability. This thesis aims to analyze the behavior of Squirrel Cage Induction Generator (SCIG) based wind farm for various load conditions and faults situations. Also, voltage profile and reactive power balance in a distribution system are noticed in this study for different cases

Usage of a static synchronous compensator (STATCOM) as a main compensating device in this study to ensure an optimal operation for wind turbines by compensating reactive power and improving voltage profile. STATCOM was installed in different places with different voltage levels to explore the most suitable location for STATCOM.

Modeling and simulation results will be carried out using MATLAB / SIMULINK software.

Key words: Wind energy, Voltage stability, STATCOM, SCIG wind turbine

الاسم: بلال حسين ذياب المجالي

عنوان الرسالة: تحسين استقرارية الجهد في الشبكة الكهربائية مع وجود نسبة كبيرة من توليد الرياح باستخدام المعوضات التزامنية الثابتة STATCOM.

الدرجة: الماجستير في العلوم الهندسية

الجامعة: اليرموك

التاريخ: 2015/8/13

الملخص:

أزدياد مساهمة الطاقة الكهربائية الناتجة عن طاقة الرياح في النظام الكهربائي جعلها جزء مهم في نظام توليد الطاقة الكهربائية, ونتيجة لذلك فأن ظروف عمل مستقرة لعنفات الرياح تعتبر جزءً مهماً في استقرار النظام الكهربائي بشكل عام.

في هذه الاطروحة سوف يتم تحليل اداء عنفات الرياح في ظروف حمل مختلفة ومتغيرة بالإضافة الى حالاتالأعطال الكهربائية في الشبكة, وسوف يتم تحليل تاثير هذه الحالات على استقرارية الجهد في الشبكة.

المعوض التزامني الثابت سيستخدم في هذه الاطروحة كجهاز تعويض اساسي لضمان استمرارية عمل عنفات الرياح في ظروف مناسبة, حيث ان المعوض التزامني الثانب سيتم تركيبه في مكانيين مختلفين بمستويات جهد مختلفة وسيتم تحليل الاداء في كل حالة للوصول الى المكان الاكثر ملاءمة لتركيب الجهاز المعوض التزامني الثابت فيه.

Chapter 1

Introduction

Introduction

1.1 Overview

The increase in electric power demand, depleting natural resources and rapid change in fuel cost in recent years has led to the increase need for renewable energy sources such as wind energy to generate electrical power [1]. Wind energy can contribute to reduce the environmental pollution where the electricity generated by wind turbines does not pollute the air or the water, in other words wind energy is less smog, and fewer greenhouse gas emissions. For instance, a single 1 megawatt from wind turbine can supersede 1,800 tons of carbon dioxide (CO2) in 12 months, whereas achieving 20% of total electrical energy from wind energy by 2030 may provide huge environmental benefits, such as averting approximately 825 million metric tons of CO2 emissions in the air [2].

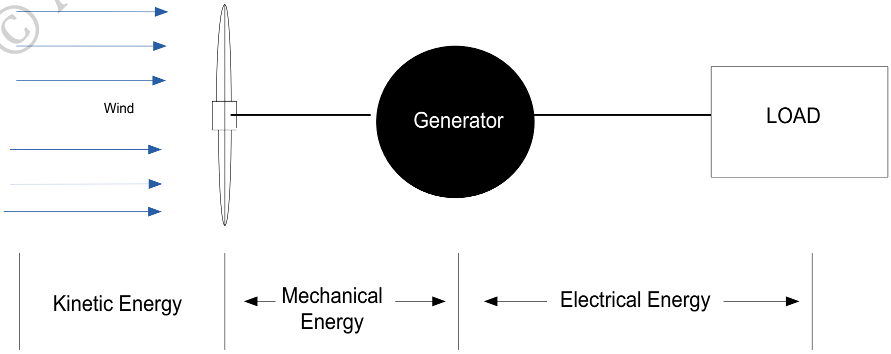

Figure 1.1 General wind power system

In Jordan - a country that suffers from the shortage of energy resources such as oil and gas – exploitation of wind energy to generate electrical power seems as a very effective economic solution to invest [3]. Jordan has large areas with an average annual wind speeds in higher than 6-6.5 m/s, two wind farm plants have been built in Jordan one of them at Alibrahimiyah which consists of 4 wind turbines each one is 80 KW with a rated wind park power of 320 kW established in 1988 with annual energy production 750 MWh, the second station at "Hofa" which consists of 5 wind turbines each one is 225 KW with a rated wind park power of 1,125 kW, Hofa station was constructed in 1996 with annual energy production of 2.5 GWh. [4].

The wind power penetration has increased dramatically in the past few years, hence it has become necessary to address problems associated with maintaining a stable electric power system that contains different sources of energy including hydro, thermal, coal, nuclear, wind, and solar. Along with the increasing demand for wind power different types of wind turbines and different technologies of generation are improving.

Fixed-speed wind turbine with squirrel cage induction generator (SCIG) is the main and the oldest type of wind turbines that is used to generate electrical power. In recent years another types of wind turbines have been evolved such as permanent magnet generator (PMG) and doubly-fed induction generator (DFIG), but the (SCIG) still remains as an important portion of the globally installed wind farm because it is has some advantages like simplicity, robust structural, reliability and resistance against disturbance and vibration [5].

Voltage stability and an efficient fault ride through capability are the basic requirements for higher penetration of wind generation. Wind turbines have to operate under transient voltage conditions without interruptions to be in accordance with the grid codes [6]. Grid codes are certain standards set by regulating agencies and wind power systems should meet these requirements for interconnection to the grid.

Voltage stability is one of the major issues related to the wind farm when connected it with power grid [7]. Voltage instability problems occur when the power system is not able to meet the reactive power demand during faults and heavy loading conditions. Squirrel cage induction generator (SCIG) wind turbine consume reactive power from the grid to create the magnetic field in the stator windings of the turbine, this consumption of reactive power from wind turbines become very high at the moment of connecting wind turbine to the grid due to the high inrush current draws from turbines at start of operation which case a voltage dip and reactive power shortage in the power system.

To ensure the stability of the system, grid codes issued that wind farms must withstand voltage dips to a certain percentage of the nominal voltage and for specific duration. These requirements are known as Low Voltage Ride through (LVRT). The LVRT required also fast active and reactive power restoration to the normal values after disturbances when system voltage returns to its stable levels [8]. For these reasons grid codes demand that the Wind Power Plant (WPP) must be able to produce reactive power at the point of the common coupling (PCC). When dealing with WPP, adding the reactive power capability of each individual wind turbine (WT) may not be sufficient to comply with the grid codes because of the losses in connection cables and line losses between WPP and PCC.

One solution is to use external reactive power compensation like adding large compensating capacitor banks which help to improve voltage profile of the system at steady state conditions but at contingency situations and disturbances when the voltage drop dramatically this solution does not provide the best dynamic response where the reactive power generated by a shunt capacitor is proportional to the square of the voltage [9]. In other words, during system conditions of low voltage the var support from capacitors drops sharply and as a result wind generators trip from the grid.

The transient behavior of wind turbines can be improved by injecting large amount of reactive power during contingency situations and disturbances. So, to achieve system requirements Flexible AC Transmission Systems devices (FACTS) such as Unified Power Flow Controller (UPFC) and the Static Synchronous Compensator (STATCOM) are being used extensively in power system because of their ability to provide flexible power flow control [10].

FACTS devices can be classified by the way that they are connected with the network into:shunt-connected devices like STATCOM and Static Var Compensator (SVC), and series-connected devices (SSSC).

Shunt-connected FACTS devices have very important tasks in order to enhance the stability of the network like controlling power flow and transmission line voltage, reducing reactive losses, and damping of power system oscillations [11]. STATCOM has the advantage of better transient response than SVC. Also in the weak grids, STATCOM has lower overshoots and faster response compared with that of the SVC [12].

This thesis explores the optimal ways to install STATCOM in the system where results and recommendations will base on system voltage response when STATCOM is installed at low voltage level regions and medium voltage level regions. Thereafter, compares the impacts on the power system parameters for different disturbances situations and load conditions.

1.2 Literature Review

[13] Shows the effect of large amount of wind turbines on transmission stability rendering in the power system, and exploring some of possible control procedures that can help stabilize the system after the fault occur.

[14] Explain the changing in nature of power system due to increase permeation of generators that have choppy characteristic, and submit some analysis of this changing nature of power system to correspond future cases that either rectify or describe the limits of the permissible level.

The matters that relate of interconnection large wind farms to the electrical power system are debated in [15], conceivable solutions to prevent predicted problems by employing AC and DC transmission technologies and FACTS devices are showed in this paper.

The repercussions of induction motor loads and load changing transformers on system stability have been illustrated in [16]

The confines for voltage stability at various wind power integrations levels have been explained in [17] for cases with and without additional stabilizing control devices in the system and for different attributes for the wind turbine generator. While [18] submit technique to detection the steady state voltage stability zone for each bus of power system, considering the existence of wind power in the network.

[19] Presents a procedure to examination the relation between voltage and active power at the load bus to find the voltage stability confines, while [20] shows the effects on the voltage stability and network losses at the time of integrating two large wind parks into sub transmission system and discuss these effects when the system loading is augmented.

In [21] the impacts of STATCOM and SVC in static voltage stability had been studied, and present a comparison between SVC and STATCOM and their performances on the network.

Author in [22] discussed the some of the power quality problem (voltage variations, harmonics and flicker) that is caused by connecting the wind turbines to the electrical grid, and try to solve it by using FACTS devices.

Power quality issues such as harmonic distortion and voltage flicker that happened due to continuously varying wind speed and synchronization problem related to connection of wind generator to grid has been discussed in [23], while harmonic distortion occur because of power electronic converter that is used in wind generators to regulate the speed of the turbine, STATCOM was introduced by author in this paper as a shunt active filter to mitigate harmonics and at the same time to generate or absorb reactive power in order to keep the voltages at its rated values in bus bars.

K. Sree Latha explained in [24] the effects of variation of wind speed and fluctuation of load on system voltage and shows their impact on the consumed reactive power and supplied active power (by/from) the wind farm, also he show how these influences can be controlled and limit it by using SVC.

[25] Presents a method by using Unified Power Flow Controller (UPFC) to achieve reactive compensation and voltage control in distribution system with a large scale of wind power generation.

Authors in [9] discussed the differences in structure and performance between three sorts of FACTS devices SVC, STATCOM and SSSC (static synchronous series compensator) and showed their impacts on power system with wind generation; outcomes proved that SVC and STATCOM provide additional reactive power while SSSC improves the voltage stability.

[26] Presents a methodology based on Genetics Algorithms for optimal location of FACTS devices in order to achieve voltage stability on power system and to increase the voltage load-ability limits under normal and abnormal conditions, also show how this method can make the system more reliable and stable.

Work in [27] explained PQ controller technique with voltage regulation as method to control the STATCOM for purpose of enhance transient voltage margins and help to maintain the continuity of the operation of wind turbines during the faults and contingencies disturbances in the network, moreover it can minimize both voltage and current harmonics occurring in the system.

Robert Neumann and Jia Wei Hong discussed in [28] the importance of wind farms monitoring to measure power characteristics of turbines and explain how it can improve the turbine reliability and system stability, also this monitoring has very important benefits especially in field of predictive maintenance in wind turbines, in addition to that, authors introduced in their study an economic method to achieve good synchronization between wind speed and output power.

1.3 Project Outline

This Project shows the best way to install STATCOM for optimal voltage profile in the system and the presented report is structured in five chapters

- The first chapter may be seen as an introduction to wind energy and power quality problem associated with it.

- The second chapter presents an overview of different wind turbine types and explains its effect on the system parameters. The focus is made on reactive power shortage and voltage stability issues. Furthermore it mentions most frequent disturbances and contingency situations that may be experienced by the grid.
- The third chapter concentrates on the Flexible AC Transmission System (FACTS) devices that are used in electrical power system. It mentions the different types of (FACTS) devices and explains the advantage of (STATCOM) in wind energy application. Furthermore this chapter shows the principle of operation of (STATCOM) and explains how it works.
- Chapter 4 presents a model system that has the same characteristics of general distribution network with a 9 MW wind farm using MATLAB software. This chapter shows the system response under contingency situations and different load conditions.
- In the last chapter conclusion and future work are presented.

Chapter 2

Wind Energy and Power System Requirements

Wind Energy and Power System Requirements

Modern wind farms use generators for the production of electricity. Wind farms include wind turbines connected to the prime mover through a gear box, while the gear box connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm (the rotational speed required by most generators to produce electricity). The prime mover is connected to the shaft of the generator's rotor, while the stator is connected to the electrical grid. This layout converts energy from mechanical energy to electrical energy at the grid.

2.1 Types of Wind Turbines

There are mainly two types of wind turbines generators. The first one is induction generator and under this category, the Squirrel Cage, Wound Rotor and Doubly Fed type of generators are investigated. The second type is synchronous generator like permanent magnet generator.

Wind turbines can be also classified based on the rotational speed to:

1- Fixed speed wind turbines like Squirrel Cage Induction Generator (SCIG), in this type the generator is directly connected to the grid through a transformer as shown in figure 2.1. Therefore the speed of this wind turbine is fixed by grid frequency so the SCIG operates only in a narrow range around the synchronous speed. In this type of wind turbine, the generator consume reactive power from the grid to create the magnetic field in the stator windings and for this reason SCIG equipped with capacitor bank to improve power factor close to unity [29].

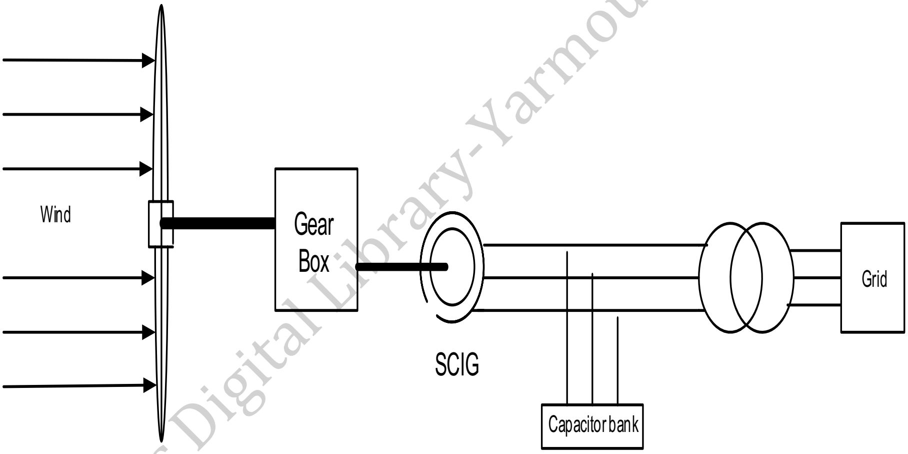

Figure 2.1 Squirrel Cage Induction Generator

2- Limited variable speed wind turbine like Wound Rotor Induction Generator (WRIG), Figure 2.2. The Generator for this turbine topology is a (WRIG) with variable rotor resistance where the stator is directly connected to the grid and the rotor winding is connected in series with a controlled resistor. Variable speed operation can be achieved by controlling the energy extracted from the WRIG rotor; and this power must be dissipated in the external resistor [29].

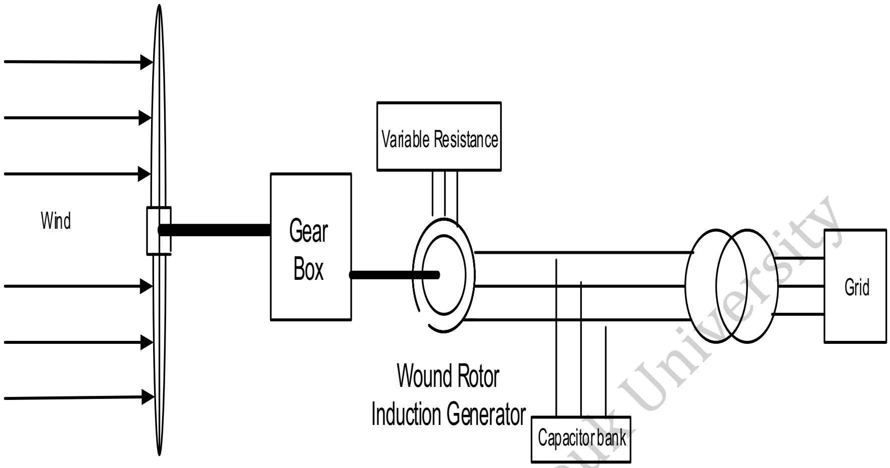

Figure 2.2 Limited variable speed wind turbine

3- Variable Speed Wind Turbine (VSWT) with Partial Scale Power Converter (PSPC) like Doubly Fed Induction Generator (DFIG), Figure 2.3. In this generator the stator is connected to the grid and the rotor is connected through a power electronic converter to control the rotor frequency and thus the rotor speed. This type of turbines is also available with Full Scale Power Converter (FSPC) where the controllability is much improved [29].

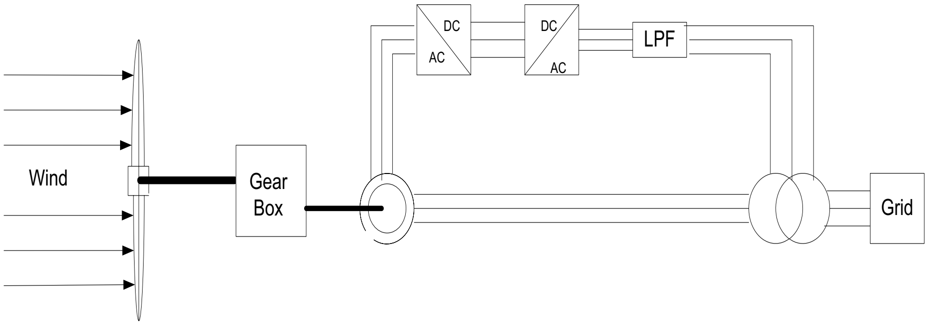

Figure 2.3 Doubly Fed Induction Generator

2.2 Squirrel Cage Induction Generator (SCIG)

A squirrel cage induction generator is the common choice for constant speed configuration because of its mechanical simplicity and low maintenance requirements.

SCIG has an opposite operation principle of induction motor. When the wind rotates the blades of turbine, the rotor will be accelerated to a speed more than the synchronous speed and the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cuts the stator magnetic field. This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in the opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator [30].

This thesis will focus on SCIG wind turbine as a main component of wind farm in the case study because of several considerations and advantages like:

1- It is simple and robust.
2- Easy and cheap for mass production.
3- It doesn't have current harmonics since it has no frequency conversion.

4- Because of that SCIG is the oldest types of wind generators, most of the existing wind energy systems equipped with SCIG turbines.

With these advantages SCIG wind turbines have some disadvantages and most of them concentrated in power quality issues because of SCIG wind turbines always consume reactive power to create magnetic field in the stator windings, reactive power absorption can lead to instability and voltage fluctuation. Over the past years, many researches talked about these problems and offered different methods to improve generation quality [5].

Later in this chapter, power quality problems that are related to the wind power system will be discussed. Also, this chapter will explain the effect of disturbances on the wind generating and other parameters like voltage profile and reactive power balance in the grid.

2.3 Wind Energy Specifications

Wind is an uncontrollable resource and this characteristic makes it a difficult mission to combine large wind parks into a grid. Power quality and stability are the main issues. Wind turbines are looked at as distributed generators (DGs) which are connected to the distribution portion of a power grid. Rather than conventional electric energy resources such as nuclear and hydropower plants that are centralized as the main sources of electric power generators, DGs are based in remote rural sites and located in weaker parts of the power grid which make it prone to faults, unbalances, and voltage sags. As a result, this unstable voltage profile can cause many problems such as reactive power shortage and unbalanced currents. With small capacity wind farm connected to the power system, choppy power flow of wind farm does not create a great menace to the stability of power system. As wind turbines become larger and level of penetration becomes higher, voltage stability and power quality of the system must be taken into account. One of the issues that can endanger uninterrupted operation of wind turbines is grid disturbance [31].

In the past, the wind power systems were permitted to disconnect on system events like three phase faults and interruptions because their impacts on the grid were not considerable. Only recently, after the increase in wind power penetration, the disconnection of huge saucepan of wind power generators will have earnest negative impact on the power system. To keep up with the significant increase in wind power generation, energy agencies and Transmission System Operators (TSOs) issued special rules and instructions known as (grid codes)

2.4 Grid Codes

In order to maintain reliable grid performance with increasing wind penetration, transmission system operators (TSOs) update their grid connection codes with specific requirements about the operation of wind generators. In general, wind farms are foreseeable to support the grid and to provide useful services like conventional power plants (e.g., active power control, frequency regulation, dynamic voltage control and low voltage ride through (LVRT)).

The requirements differ between countries, and their acuteness usually depends on the wind power penetration level as well as on the validity of the national power network. Grid codes require that wind farms must be qualified to operating ceaselessly within the voltage and frequency alteration limits encountered in typical operating conditions. In addition to that, wind turbines must remain in operation in case of frequency deviations outside the typical operating limits for a specified time and in some cases with a specific active power output [32].

To enable wind turbine collaboration in frequency control there are two main controls:

1- Turbine based control: In this control system, each turbine has to have some particular control abilities such as reactive power or power factor control
2- Substation based control: In this control reactive power compensation is provided either by switched capacitors or FACTS devices.

Besides frequency control, grid codes required also active power control which means that the wind power plants have the ability to regulate their active power output to a defined level and at a defined ramp rate. These requirements have a great importance to keep transmission lines from overloading and to prevent wind turbine from over speeding in case of faults and disturbances.

2.5 Wind Energy and Voltage Stability Issues

Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system at normal operating and after being subjected to a disturbance. In other word, the voltage levels in a power system must be maintained constant (within a very narrow range) because equipment of the utility and consumers are designed to operate at particular voltage levels.

Voltage stability issues become more sensitive and important when related with wind energy system because most of them were installed at remote rural location which gives some of weak grid characteristics.

Generally a grid is considered weak when the distribution system is not able to supply appropriate reactive power to the electrical load in the system. So, in weak grid the danger of instability voltage becomes more significant and for this reason wind turbine should be disconnected from the grid during faults and disturbances.

Voltage stability is an essential part of the power system stability. In general, voltage stability problems exist more repeatedly in a tremendously loaded system. The change in voltage is directly proportional to change in load and hence voltage stability is, in some cases, described as load stability. Main reasons for voltage stability problems in power system are:

1- High reactive power consumption at heavy loads
2- Generating stations are too far from load centers
3- Large disturbance between generation and load

The voltage stability is classified into four categories:

1- Large disturbance voltage stability: defines as the ability of the system to maintain steady voltage following large disturbances such as, system faults or loss of generation.
2- Small disturbance voltage stability: It refers to the system’s ability to maintain acceptable level of steady voltages, when subjected to small disturbances such as incremental changes in system load.
3- Short term voltage satiability: It includes dynamics of fast acting load components like HVDC converters and induction motors (several seconds)
4- Long term voltage satiability: It includes dynamics of slower acting equipment like on load tap changing transformers (tens of seconds to tens of minutes)

Voltage stability achieved by proper voltage control, which is important for power system to prevent equipment from damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the system to withstand and prevent voltage collapse.

In general, increasing reactive power caused voltage to rise while decreasing it caused voltage to fall. A voltage collapse occurs when the system try to supply much more load than the voltage can support. When reactive power supply lower voltage, current must increase with same rate of voltage drops to preserve power supplied at its rated value, current increasing caused system to consume more reactive power and the voltage drops more and more [33].

If the voltage drops extremely, some generators will disconnect automatically to preserve themselves from overheating and damage, continue if this situation will cause additional elements to trip leading further loss of the load. On AC power system, voltage is controlled by managing absorption and production of reactive power, while absorption of reactive power at overvoltage situations and production at under voltage situations.

Neglecting the resistance of generator, transformer and transmission line, the equivalent circuit of the system and its phasor diagram are shown in Fig 2.4 and 2.5 respectively

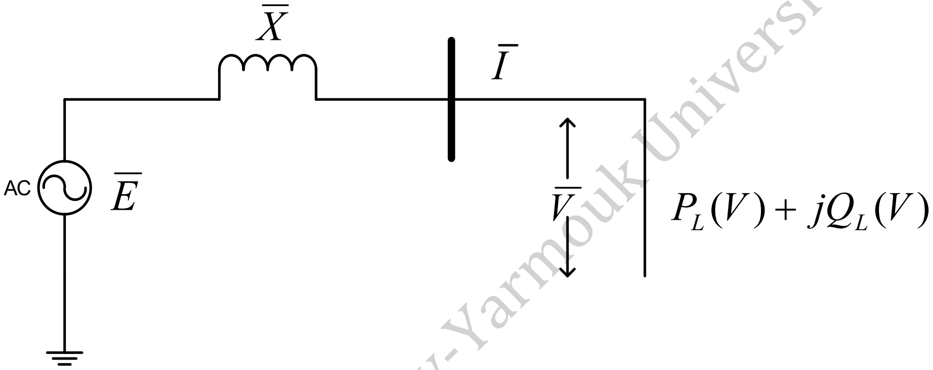

Figure 2.4 Equivalent circuit of the electrical system

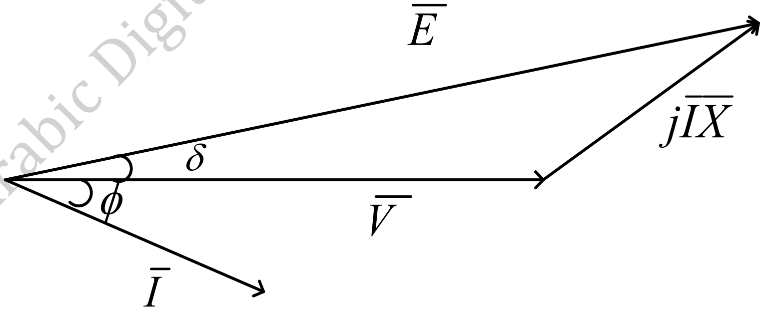

Figure 2.5 Phasor diagram

From the phasor diagram:

$$I\,X\cos\emptyset = E\sin\delta \qquad 2.1$$

$$I\,X\cos\emptyset = E\sin\delta \qquad 2.2$$

Active power and reactive power at load given by

$$P_L = V\ I \cos \emptyset \qquad 2.3$$

$$Q_L = V\ I \sin \emptyset \qquad 2.4$$

From equations 2.1, 2.2, 2.3, and 2.4

$$P_L = \frac{E\ V}{X} \sin \delta \qquad 2.5$$

$$Q_L = \frac{E\ V}{X} \cos \delta - \frac{V^2}{X} \qquad 2.6$$

Where (δ) is the power angle which is kept very low due to stability reasons and (X) is the reactance of the transmission line Q_L become

$$Q_L = \frac{E\ V}{X} - \frac{V^2}{X} \qquad 2.7$$

Now equation is formed as,

$$V^2 = E\ V + X\ Q_L = 0 \qquad 2.8$$

$$V = \frac{E - \sqrt{E^2 - 4\ X\ Q_L}}{2} \qquad 2.9$$

As shown in above equations, active power is controlled mainly by power angle (δ) which is related to grid frequency while reactive power is controlled by voltage (V), and this explain the importance of balancing of reactive power in the voltage stability of the system.

Because the power systems may experience both overvoltage and under voltage violations during daily operation, the system operator will perform switching actions to maintain a secure and economical voltage profile while maintaining a reactive power balance equation:

$$G - M + S_g + S_c = [\, M - D + R_s + S_r] \qquad 2.10$$

Where G = Generator, M = MVARs, S_g = System gain (reactive power generated by the capacitive nature of the transmission network itself), S_c=Shunt Capacitor, D=Demand, Rs=Reactive losses, S_r=Shunt reactors.

The basic voltage control provided by the generating units, because the automatic voltage regulators control field excitation to maintain suitable voltage level at the terminals of the generators, but throughout the system it is necessary to use additional devices to compensate reactive power and voltage control [34].

Reactive compensation can be divided into series and shunt compensation, and mostly consideration will be focused on:

1- Shunt capacitors
2- Series capacitors
3- Shunt reactors

4- Synchronous condensers
5- SVC
6- STATCOM

This thesis will focus on STATCOM as a compensating device due to some of considerations mentioned in next chapter.

2.6 Low Voltage Ride Through (LVRT)

Low Voltage Ride Through known as the capability of electrical devices, especially wind generators, to operate through periods of lower grid voltage.

Low voltage ride through is the most important requirement relating to wind farm operation that has been recently introduced in the grid codes. Faults on grid may cause huge voltage dips and some generation units can be lost as a result from this voltage situation.

In case of a large amount of wind generation in the network, disconnection of wind generating units can cause larger voltage reduction and eventually collapse of voltage in the affected region. As a result of this situation, system suffers from loss of power generation and thus drops in the system frequency [35].

Grid codes require wind farms to remain connected and support the grid during and after a fault. They must withstand voltage dips of a certain percentage of the nominal voltage for the specified time durations.

Chapter 3

Static Synchronous Compensator (STATCOM)

STATCOM

Most of the wind turbines installed in the past were induction generators which absorb reactive power from the system even during normal operating conditions and this absorbing become more during contingency situations.

Mechanically switched capacitors are used in wind parks which consist of induction generators to supply reactive power during system disturbances. However, this finite support from these capacitors is important to meet grid codes requirements like low voltage ride through requirement. Despite that, supplemental compensating equipment is necessary for the system in order to restore quickly after the fault has been cleared, thus to maintain system stability and to avoid generator tripping.

Grid codes requirements led to the investigation of power electronic devices into power systems to get fast dynamic control over reactive and active power. Thus Flexible AC Transmission system (FACTS) devices were introduced as a solution for improving the power system performance.

3.1 FACTS Devices

The concept of FACTS (Flexible Alternating Current Transmission System) refers to a family of power electronics-based devices that used to enhance AC system controllability and stability and to increase power transfer capability. They can also damp power system oscillation and provide transient voltage support to prevent system collapse. FACTS devices can be used in wind power systems to improve the transient and dynamic stability of the overall power system.

FACTS controlle is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability"[36].

The design of the different configurations of FACTS devices is based on the combination of conventional power system components (such as transformers, reactors, switches, and capacitors) with power electronics elements (such as various types of transistors and thyristors).

3.2 Types of FACTS controllers

The FACTS controllers can be classified as

1- Shunt connected controllers
2- Series connected controllers
3- Combined series-series controllers
4- Combined shunt-series controllers

Depending on the power electronic devices used in the control, the FACTS controllers can be classified as:

- Variable impedance type
- Voltage Source Converter (VSC) based.

The variable impedance type controllers include:

- Static Var Compensator (SVC), (shunt connected)
- Thyrister Controlled Series Capacitor or compensator (TCSC), (series connected)
- Thyristor Controlled Phase Shifting Transformer (TCPST) of Static PST (combined shunt and series)

The VSC based FACTS controllers are:

- Static synchronous Compensator (STATCOM) (shunt connected)
- Static Synchronous Series Compensator (SSSC) (series connected)
- Interline Power Flow Controller (IPFC) (combined series-series)
- Unified Power Flow Controller (UPFC) (combined shunt-series)

In addition to these, there is Some of FACTS controllers for special purpose. In general the FACTS controllers based on VSC like STATCOM have several advantages over the variable impedance type.

3.3 STATCOM

STATCOM is a power electronic-based synchronous var compensator that generates a three-phase reactive power in synchronism with the transmission line voltage and is connected to it by a coupling transformer. STATCOM acts as a source of reactive power (capacitor) or a sink of reactive power (inductor).

STATCOM has some of technical advantages over SVC like:

1- Faster response
2- STATCOM require less space comparison with SVC because it's not use passive components like reactors which have large size
3- Easily moved from one place to another
4- A STATCOM has excellent performance during low voltage situations.

The output current of STATCOM is adjusted to control either the nodal voltage magnitude or reactive power injected at the bus by varying the amplitude of the converter voltage with respect to the system bus voltage. The power exchange between STATCOM and rest of the system is purely reactive with a small amount of active power supplied by the grid to compensate for converter losses [37].

3.3.1 STATCOM Design

STATCOM is composed of the following components:

1- Voltage-Source Converter (VSC)

The voltage-source converter transforms the DC input voltage to an AC output voltage, most common (VSC) types is:

A- PWM Inverters using Insulated Gate Bipolar Transistors (IGBT)

It uses Pulse-Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. It uses Pulse-Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. IGBT based VSC use a fixed DC voltage and control output AC voltage by changing the modulation index of the PWM modulator.

B- Square-wave Inverters using Gate Turn-Off Thyristors

VSC controls reactive power flow by changing the DC capacitor input voltage where the fundamental component of the converter output voltage is proportional to the DC voltage.

2- DC Capacitor to provide the DC voltage for the inverter.

3- Inductive Reactance (X) which represent the leakage inductance of a coupling transformer between inverter and power system.

4- Harmonic Filters to mitigate harmonics due to the inverters.

3.3.2 STATCOM Operation

Basic principle operation of STATCOM depends on two important facts:

- Active or Real Power flows from the leading source to the lagging source.
- Reactive Power flows from the higher to the lower voltage magnitude source.

The active power flow depends on the phase angle difference between the sources, while the reactive power flow depend he voltage magnitude difference between the sources. According to this principle STATCOM can be used to regulate the reactive power flow by changing the output voltage of the voltage-source converter with respect to the system voltage

STATCOM has two mode of operation:

1- Voltage Regulation

In this mode, voltage regulation achieved by controlling the amount of reactive power that absorbed from or injected into the power system through a voltage-source converter.

To ensure that active power flow is zero, the voltage V_S generated by the VSC through the DC capacitor should be in phase with the system voltage V_t $(\delta = 0)$. Reactive power flow is given by equation 3.1

$$Q = \frac{[\,V_t(V_t - V_s)]}{X} \qquad 3.1$$

2- Var Control

In this mode, the STATCOM kept reactive power output constant independently from other system parameters.

3.3.3 STATCOM Model

Equivalent system with the unbalanced load and the shunt compensator (STATCOM) shown in figure 3.1, from the figure the compensating current from STATCOM I_C is given by equation 3.2

$$I_C = I_L - I_S \qquad 3.2$$

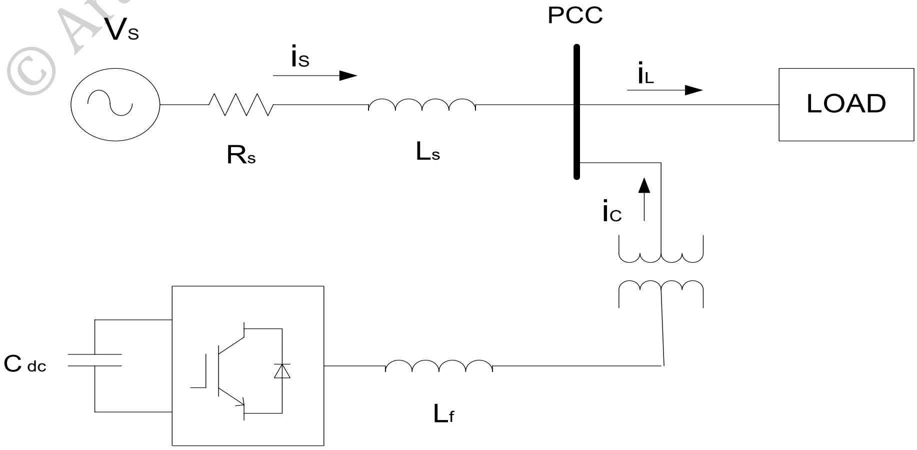

Figure 3.1 General System Diagram

The compensator current should have negative, zero sequence fundamental frequency component in addition to harmonic of all sequences.

Equation 3.1 explained that the difference between the load and the source (reference) currents gives the desired compensation current. Figure 3.2 show the block diagram of the control scheme to generate the reference source current [38].

The d-q components of reference current obtained as shown in equations 3.3 and 3.4

$$i_{Sd}^{*} = \bar{i}_{Ld} + i_{Cd} \qquad 3.3$$

$$i_{Sq}^{*} = K_q \bar{i}_{Lq} + ui_{Cq} \qquad 3.4$$

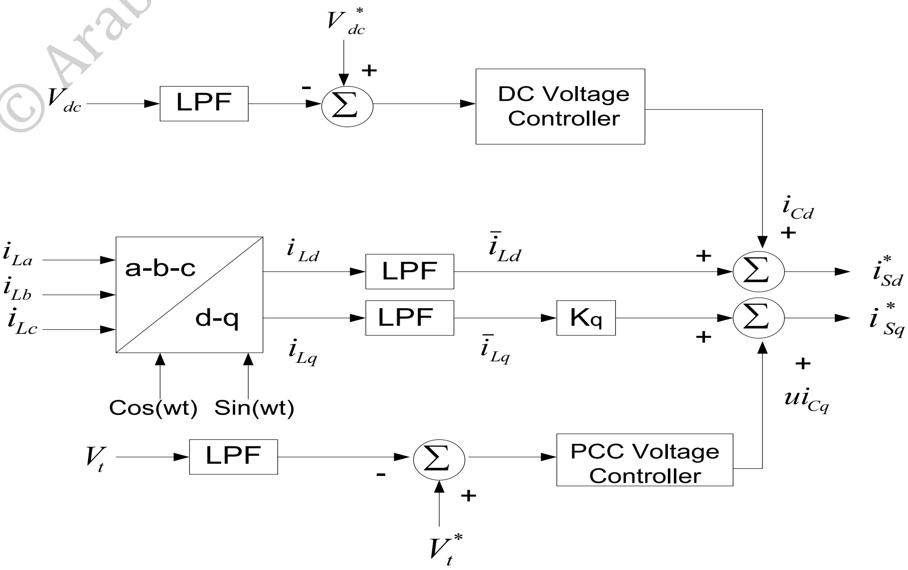

Figure 3.2 Computation of Reference Source Currents (d and q components)

$\bar{i}_{Ld}$ and $\bar{i}_{Lq}$ are the average values of the d- and q- axis components of the load current. i_{Cq} is the output of the AC voltage controller and i_{Cd} is the output of the DC voltage controller.

(u) is a logical variable equal to:

- Zero (Var control mode)
- One (Voltage regulation mode)

K_q = 1 in voltage regulation mode where in Var control mode defined by:

$$K_q = \frac{Q_S^*}{\overline{Q}_L} \quad 3.5$$

Where (Q_S^*) is the reference reactive power supplied by the source and ($\overline{Q}_L$) the average reactive power which defined by:

$$\overline{Q}_L = |V_t|\bar{i}_{Lq} \quad 3.6$$

For unity power factor Q_S^* = 0 and K_q = 0

The average value of $\bar{i}_{Ld}$ and $\bar{i}_{Lq}$ defined as the outputs of two identical low pass filters (G(s) is transfer function)

$$\begin{bmatrix} \bar{i}_{Ld} \\ \bar{i}_{Lq} \end{bmatrix} = G(s)\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \qquad 3.7$$

The d-q components are obtained as:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix}\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \qquad 3.8$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad 3.9$$

The reference vector of source currents are computed from the equations 3.10 and 3.11 and explained in figure 3.3

$$\begin{bmatrix} i_{Sa}^{*} \\ i_{Sb}^{*} \\ i_{Sc} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{S\alpha}^{*} \\ i_{S\beta}^{*} \end{bmatrix} \qquad 3.10$$

$$\begin{bmatrix} i_{S\alpha}^{*} \\ i_{S\beta}^{*} \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix}\begin{bmatrix} i_{Sd}^{*} \\ i_{Sq}^{*} \end{bmatrix} \qquad 3.11$$

The unit vectors $\cos \omega t$ and $\sin \omega t$ are obtained from Phase-Locked Loop (PLL) where ω is the supply frequency expressed in radians/sec.

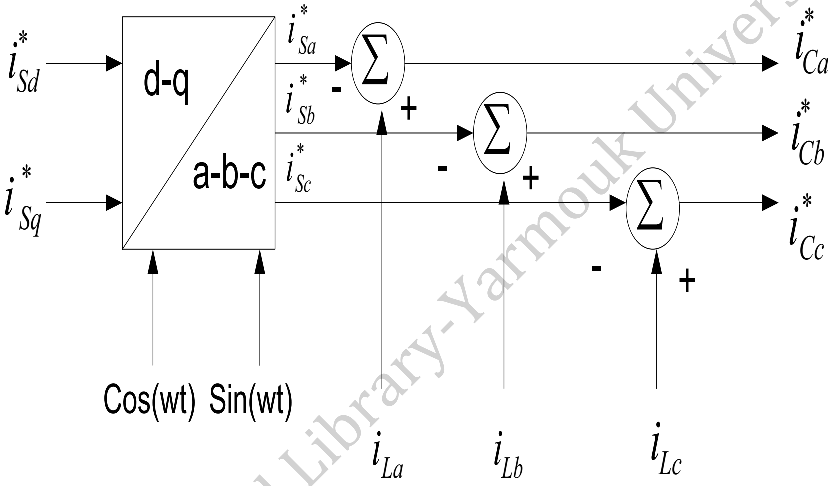

Figure 3.3 Generation of Reference Compensator Currents

Chapter 4

Experimental Procedure and Results

Experimental Procedure and Results

4.1 Experimental Procedure

A distribution system supplying a wind farm is taken up for study in this thesis. Figure 4.1 show a grid (132 KV) supplying the distribution system (33KV) which connected with wind farm and other loads. This distribution system wills expert different contingency situations (5 cases) which are:

1- At the instant of connecting wind turbines with the grid (Normal conditions)
2- Sudden load changes
3- Sudden interruption of some of the electrical loads for specific time
4- Connecting fluctuating loads such as arc furnaces
5- Single line to ground fault at medium voltage level

During the above situations, system parameters will noticed for each case, which are:

- Wind turbines generation
- Active power flow and losses
- Reactive power flow
- Voltage profile at low voltage level (44 V)
- Voltage profile at medium voltage busbar (33 KV)

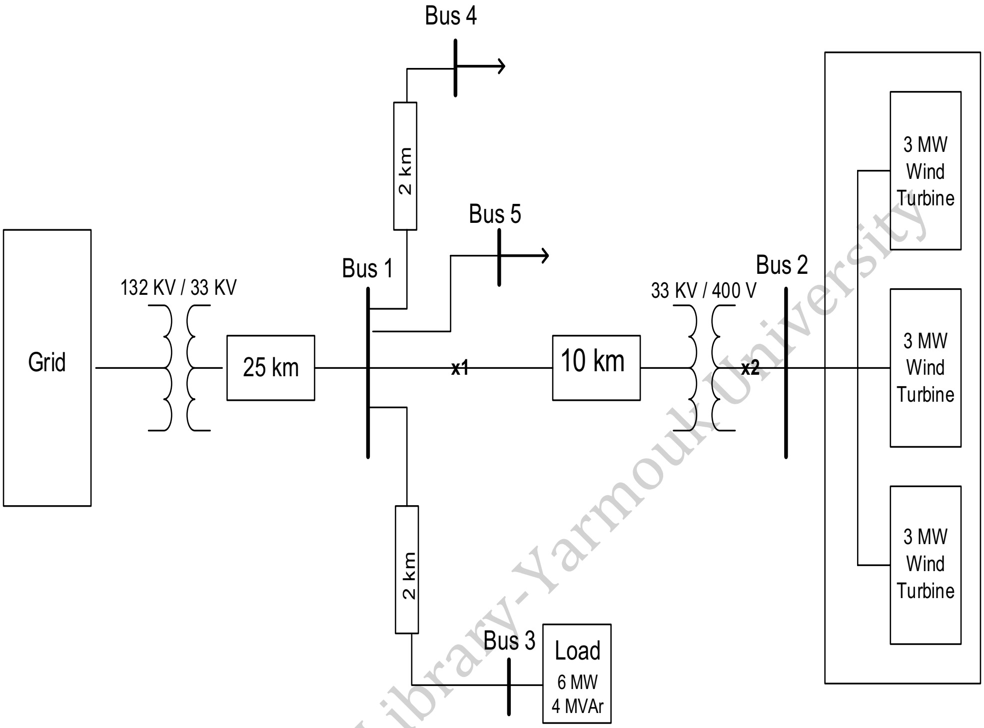

Figure 4.1 Circuit diagram of the case study

This procedure will be done in case of:

1- System without compensating devices
2- System with STATCOM installed at low voltage level close to wind turbine.
3- System with STATCOM installed at medium voltage level (33 KV busbar).

4.2 Experimental Results

4.2.1 Case (1)

In this case, the system operates at normal conditions, System parameters (voltage, current, active power flow, reactive power balance) and wind turbine generation will be explained with and without STATCOM (STATCOM at low and medium voltage level).

Figure 4.2 show voltage at 33 KV busbar (bus 1), voltage value at the main busbar (bus 1) is acceptable (0.96 pu), this value improved to (0.97 pu) when the STATCOM installed at x2 (low voltage level) and this improving reach to (0.99 pu) for the voltage value when the STATCOM installed at x1 (medium voltage level).

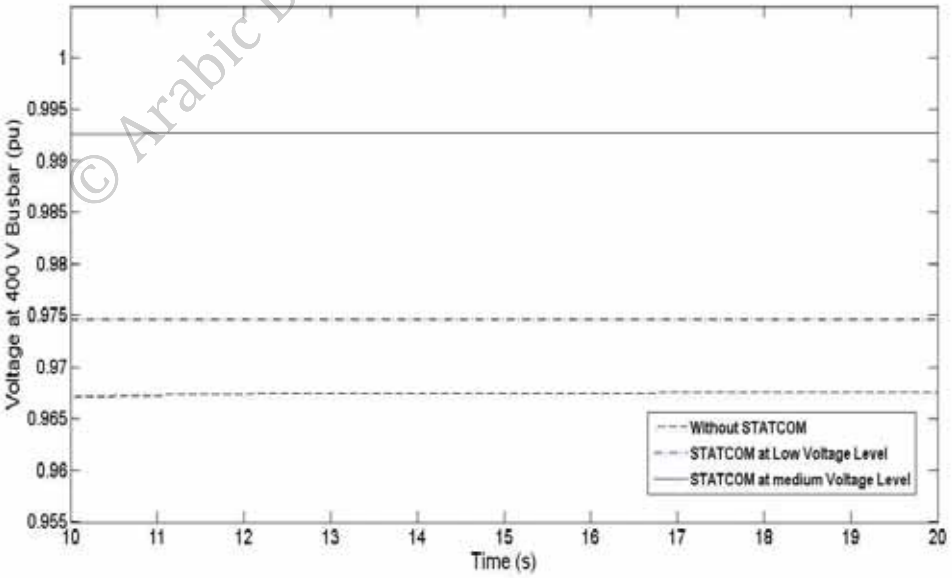

Figure 4.2 Voltage at bus1 (pu) – case (1)

At wind turbine busbar (400 V – bus2), figure 4.3 shows that the voltage value is (0.985 pu) and reach to (0.998 pu) when STATCOM installed at x2, while installing the STATCOM at x1 will cause to the over voltage situation (1.015 pu).

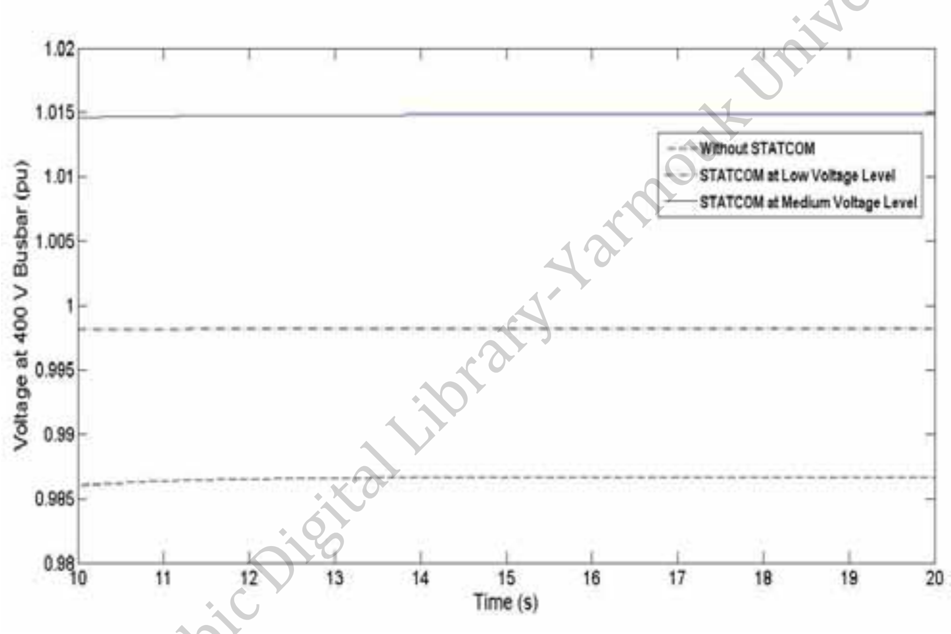

Figure 4.3 Voltage (pu) at Wind Turbine Busbar (bus2) – case (1)

Voltage improved at bus 1 and bus 2 due to the reactive power support from STATCOM. Reactive power support from STATCOM at x1 is more than reactive power supports from STATCOM at x2, this differentiation of reactive power support explained from equation 3.1 which show that reactive power support become larger for the higher voltages.

The survival of the voltage within normal limits let the wind turbine to generate the rated output power (3 MW) as shown in figure 4.4.

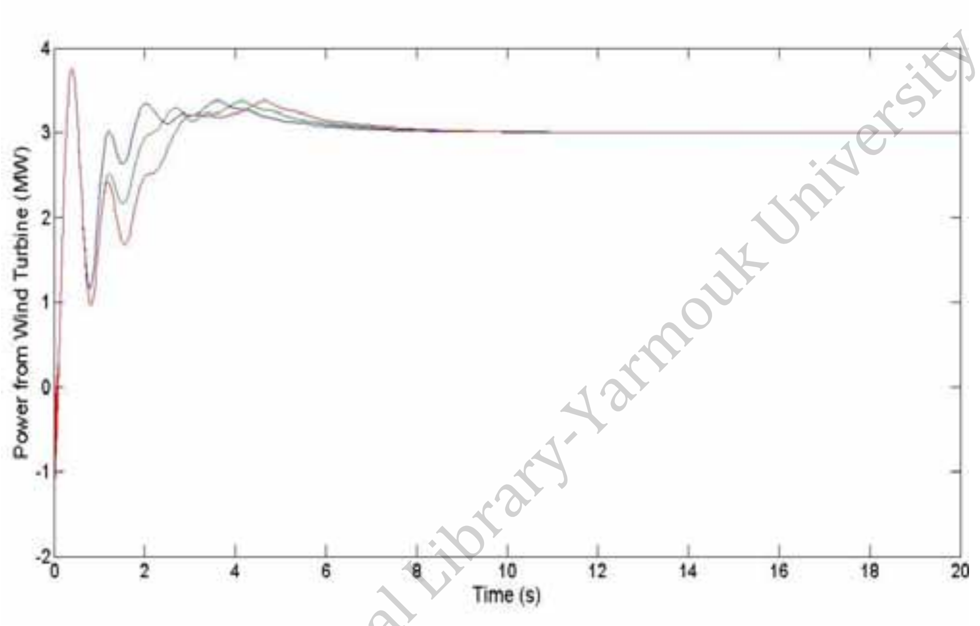

Figure 4.4 Power Generated from Wind Turbine (MW) – case (1)

Wind turbine consumes 1.4 MVAr from the grid to create the magnetic field in the stator windings as shown in figure 4.5, for this reason wind turbine equipped with large capacitor banks to compensate the shortage of reactive power in the grid.

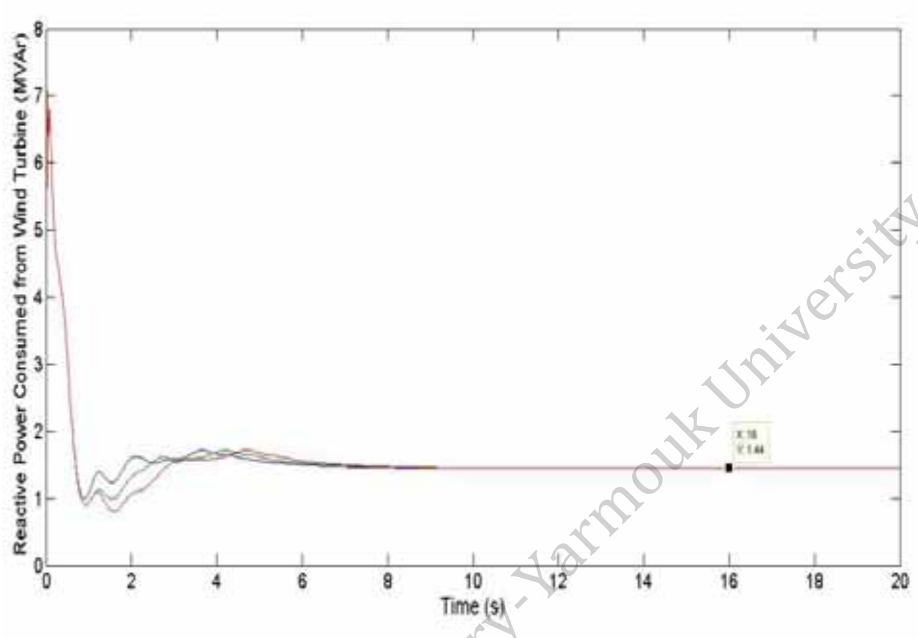

Figure 4.5 Reactive Power Consumed from Wind Turbine (MVAr) – case (1)

Active power flow from distribution system to the grid is shown in figure 4.6. Installing STATCOM in the distribution system has caused to increase the contribution of wind farm for supplied the demand in the distribution system, this has caused to reduce the active power flow from distribution system to grid from 4.11 MW to 4.05 MW when STATCOM installed at x2 and reduced further to become 3.91 MW when STATCOM installed at x1.

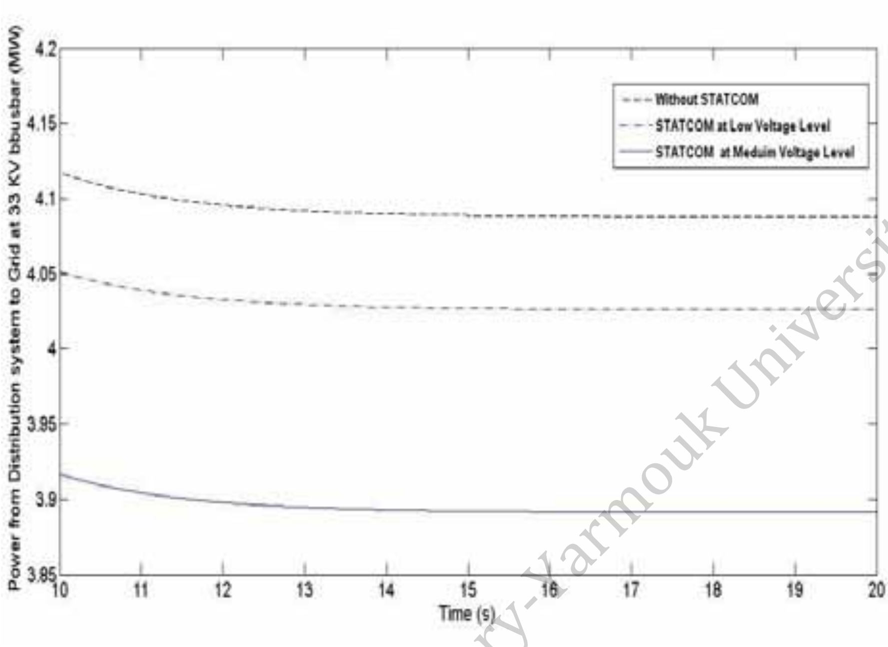

Figure 4.6 Power from Distribution system to Grid at bus1 (MW) – case (1)

Figure 4.7 shows the reactive power flow from grid to distribution system. Reactive Power flow from grid to distribution has been reduced from 3.25 MVAr to 2.7 MVAr when the STATCOM installed at x2, and reduced further to 2.25 MVAr when STATCOM installed at x1.

Reactive power support from STATCOM either at x1 or x2 in the distribution system has caused to reduce the need of reactive power from grid.

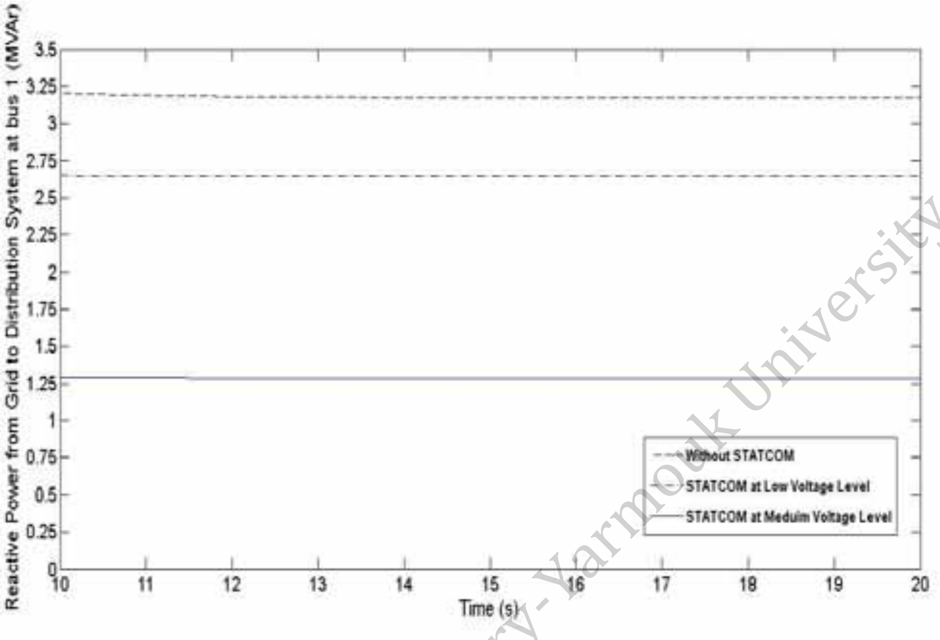

Figure 4.7 Reactive Power (MVAr) from Grid to Distribution System at bus1 – case (1)

Figure 4.8 shows the current at bus 1, improving voltage due to install STATCOM has caused to reduce the current from 0.54 pu to 0.49 pu when STATCOM installed at x2, while installing STATCOM at x1 reduce the current to become 0.41 pu.

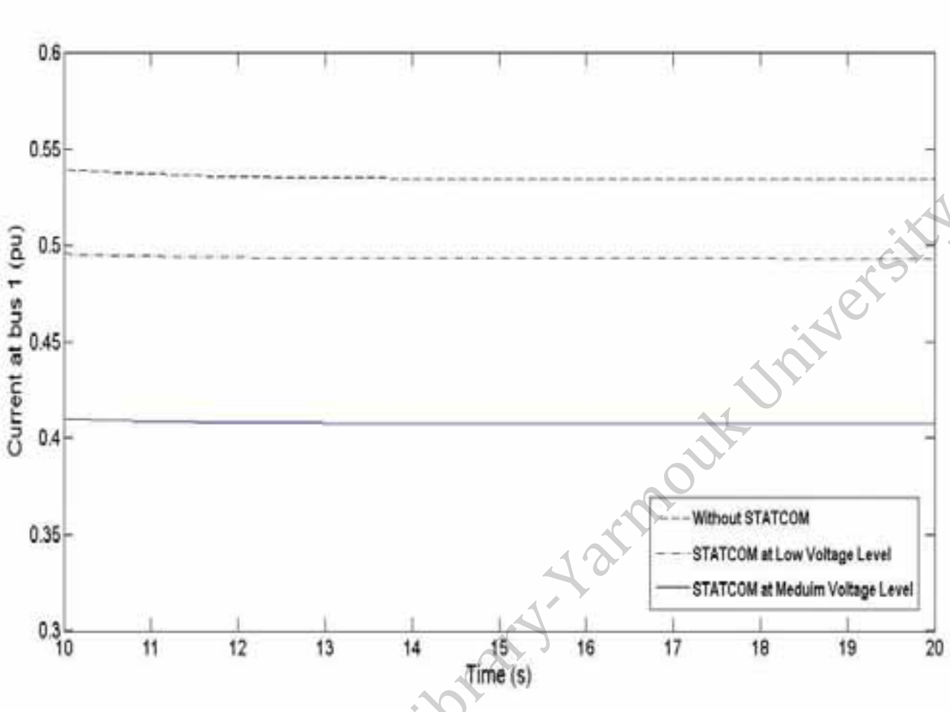

Figure 4.8 Current at bus1 (pu) – case (1)

4.2.2 Case (2)

In this case, the system will expert a sudden increase in reactive power demand in the load at bus 4 for 1 second, System parameters (voltage, current, active power flow, reactive power balance) and wind turbine generation will be explained with and without STATCOM (STATCOM at low and medium voltage level).

The high reactive power demand at bus 4 (from 15s to 16s) cause a voltage drop to (0.92 pu) at bus 1 as shown in figure 4.9, this drop was limited to (0.95 pu) when STATCOM installed at x2, but when the STATCOM installed at x1 the voltage at bus 1 dropped to (0.98 pu) for the same time period.

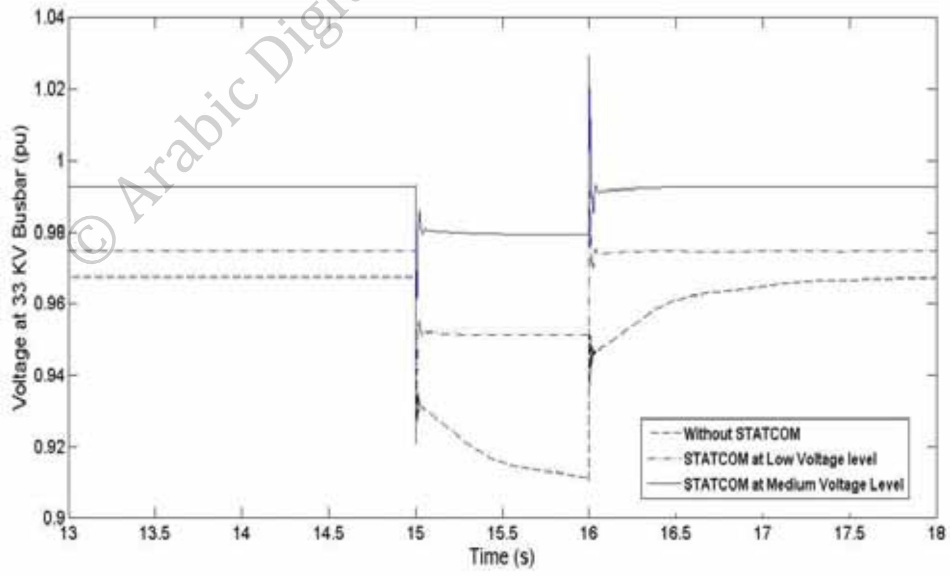

Figure 4.9 Voltage (pu) at bus1 – case (2)

As in the previous case, voltage drop at bus 1 will reflect on voltage profile at wind turbine bus (bus 2) as shown in figure 4.10, voltage drop to 0.92 pu, installing STATCOM improves voltage to 0.992 pu when STATCOM installed at x2 and (1.01 pu) for the STATCOM at x1.

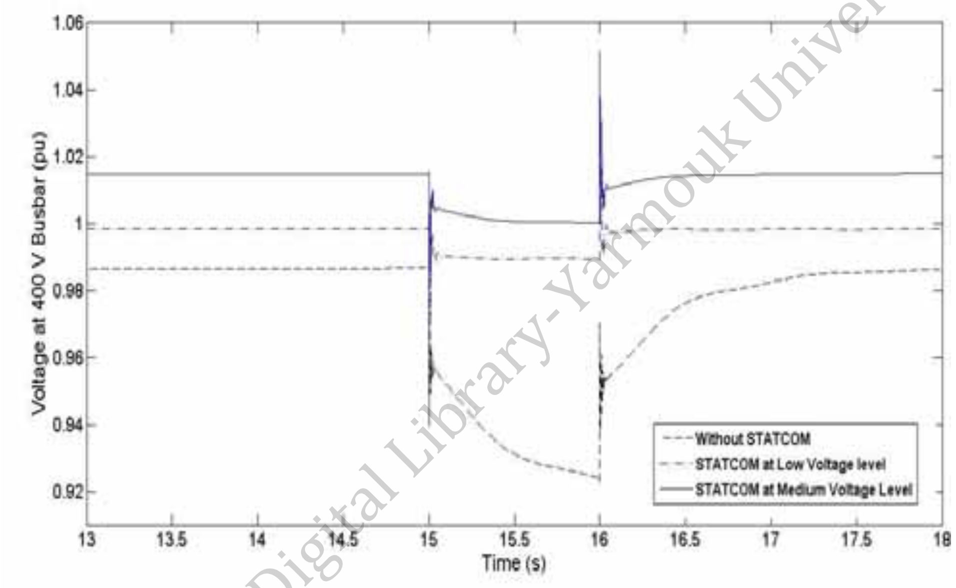

Figure 4.10 Voltage (pu) at wind turbine Busbar (bus2) – case (2)

Voltage improved at bus 1 and bus 2 due to the reactive power support from STATCOM. Reactive power support from STATCOM at x1 is more than reactive power supports from STATCOM at x2, this differentiation of reactive power support explained from equation 3.1 which show that reactive power support become larger for the higher voltages.

Wind Turbine output power varied from 2.85 MW to 3.15 MW as shown in figure 4.11, this variation occurs due to the voltage variation on wind turbine busbar. Installing STATCOM cause to narrow the gap of output power variation to become from 2.93 MW to 3.04 MW.

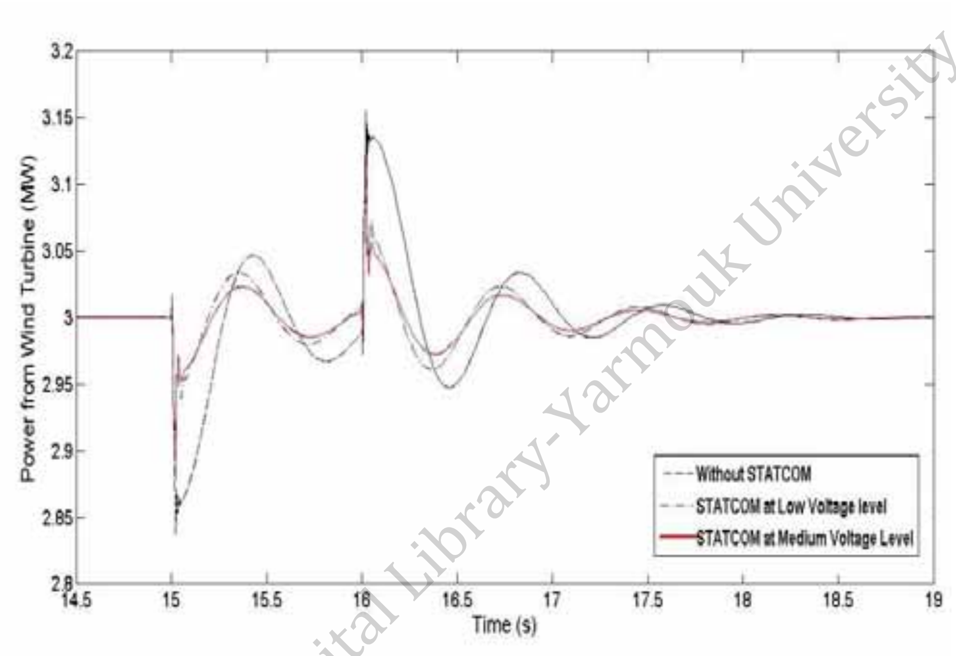

Figure 4.11 Active Power generated from Wind turbine (MW) – case (2)

Voltage variation on wind turbine busbar affect also the reactive power that consumed from wind turbine to be varied from 1.1 MVAr to 1.9 MVAr, using STATCOM keep the consumed reactive power around 1.4 MVAr as shown in figure 4.12.

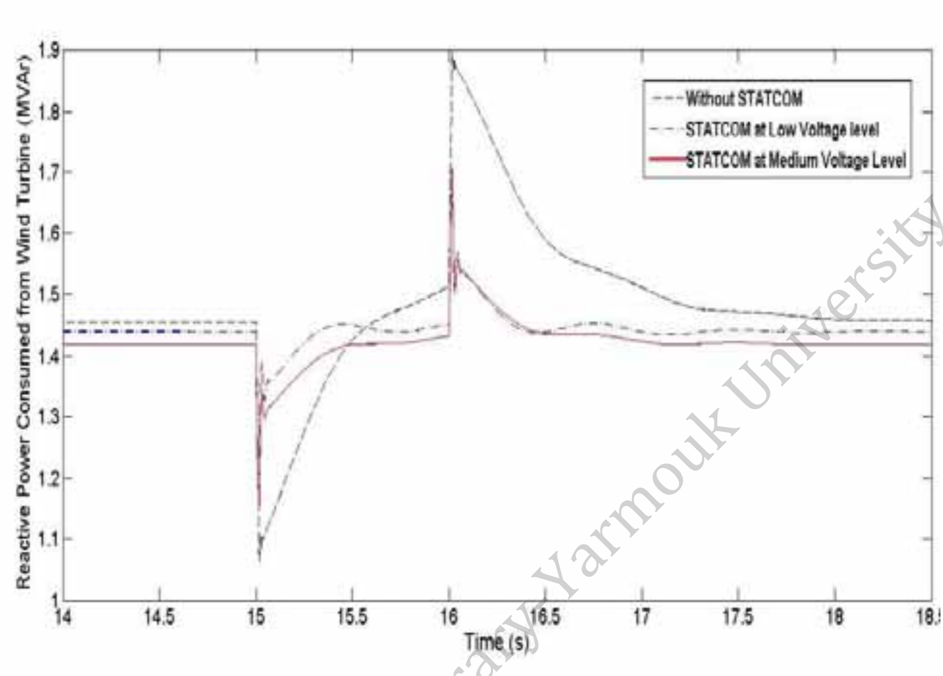

Figure 4.12 Reactive Power (MVAr) Consumed from Wind Turbine – case (2)

Installing STATCOM improves the voltage on wind turbine busbar which make the operation of turbine more stable and keep the active power flow in distribution system without huge variations.

Active power flow toward the grid increased by 600 KW during the period of reactive load increase at bus 4 as shown in figure 4.13, using STATCOM at x2 cause to reduce the increasing to become 300 KW, while installing STATCOM at x1 make the increasing about 100 KW.

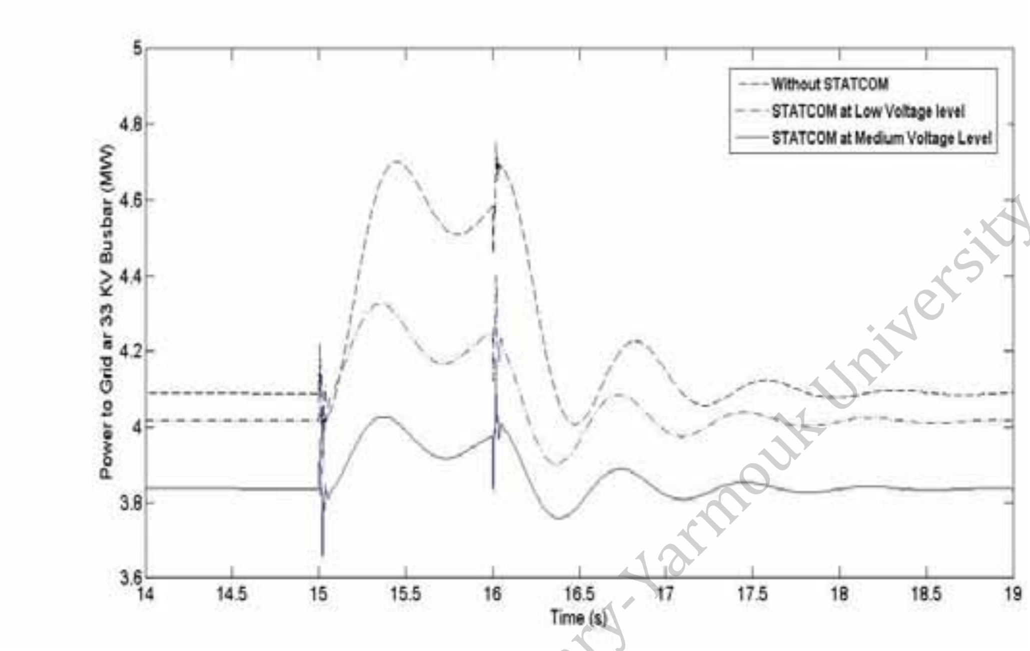

Figure 4.13 Active Power from Distribution System to Grid at bus1 (MW) – case (2)

Increase the reactive demand in distribution system cause an increase of consumed reactive power at bus 1 as showm in figure 4.14, consumed reactive power reach to 7 MVAr, this consuming reduced to 4.1 when STATCOM installed at x2 and reduced more to become 2 MVAr when STATCOM at x1.

Reactive power support from STATCOM either at x1 or x2 in the distribution system has caused to reduce the need of reactive power from grid and limit the variation of reactive power in the distribution system.

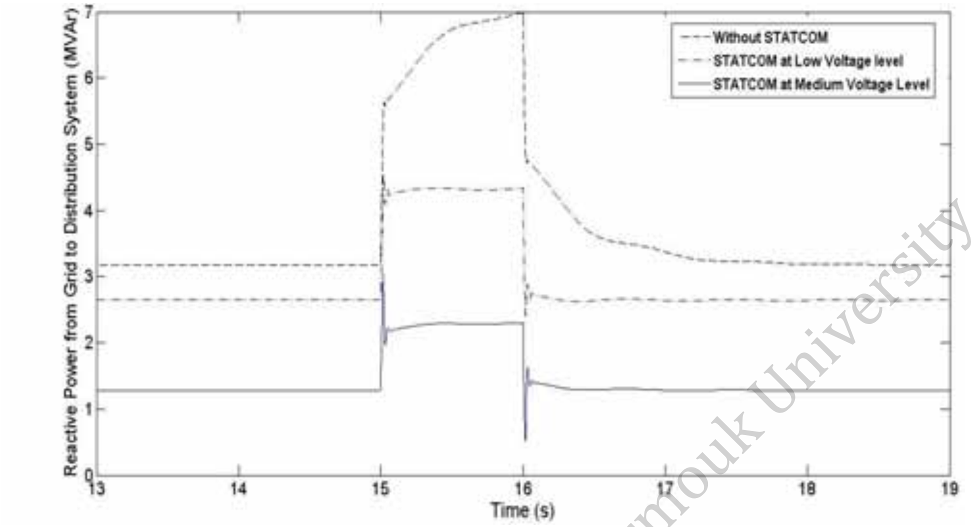

Figure 4.14 Reactive Power (MVAr) from Grid to Distribution system at bus1 – case (2)

Voltage variation effect the current as shown in figure 4.15, without STATCOM the variation is 0.45 pu, while installing STATCOM at x1 limit the variations to become 0.1 pu.

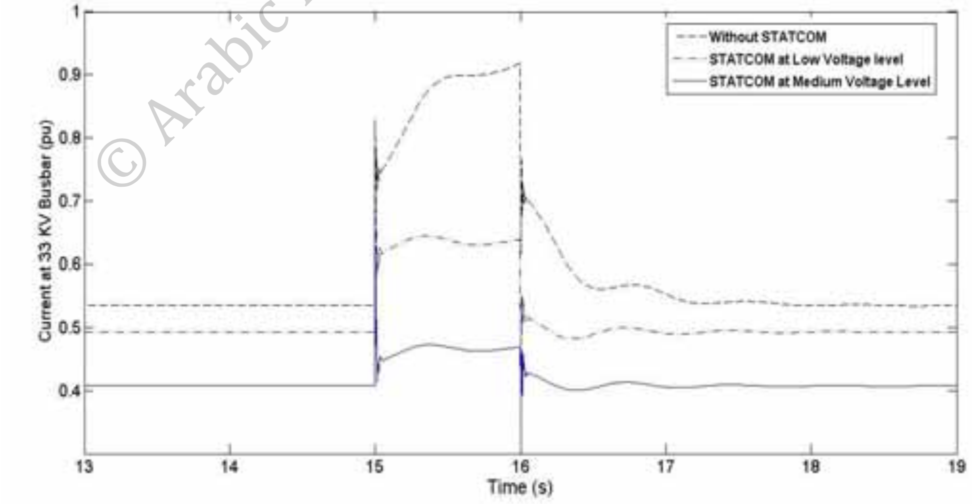

Figure 4.15 Current (pu) at bus1 – case (2)

Figure 4.16 shows the reactive power support from STATCOM, reactive power support from STATCOM at x1 is more than reactive power supports from STATCOM at x2, this differentiation of reactive power support explained from equation 3.1 which show that reactive power support become larger for the higher voltages.

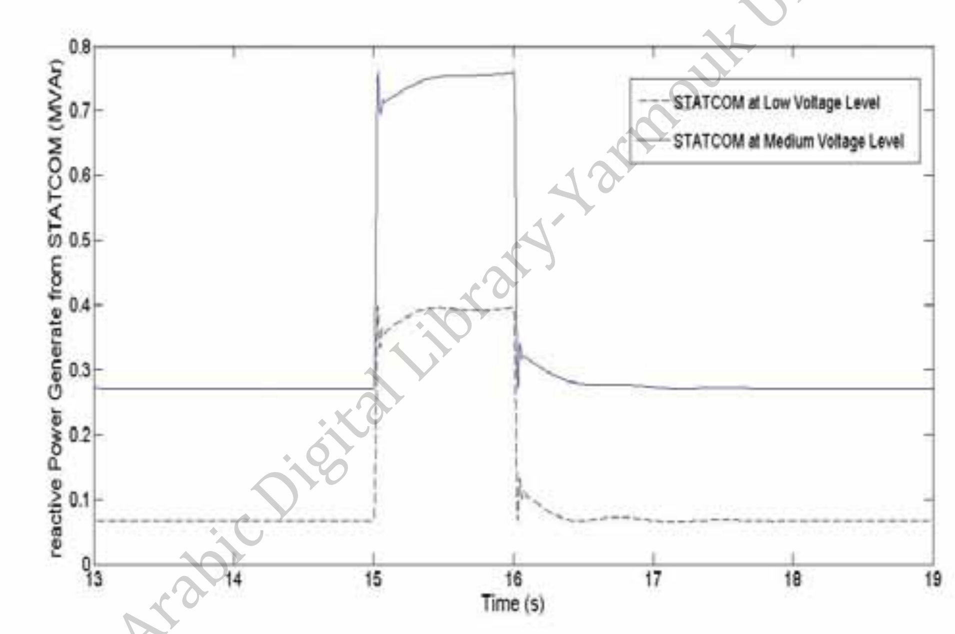

Figure 4.16 Reactive Power Generated from STATCOM (MVAr) – case (2)

4.2.3 Case (3)

In this case, the system will expert load interruption in the load at bus3 for short period 1 second, System parameters (voltage, current, active power flow, reactive power balance) and wind turbine generation will be explained with and without STATCOM (STATCOM at low and medium voltage level).

Load interruption causes a huge voltage increase at main busbar (bus 1) to become 1.09 pu as shown in figure 4.17, and reach to 1.15 pu at wind turbine busbar (bus 2) as shown in figure 4.18.

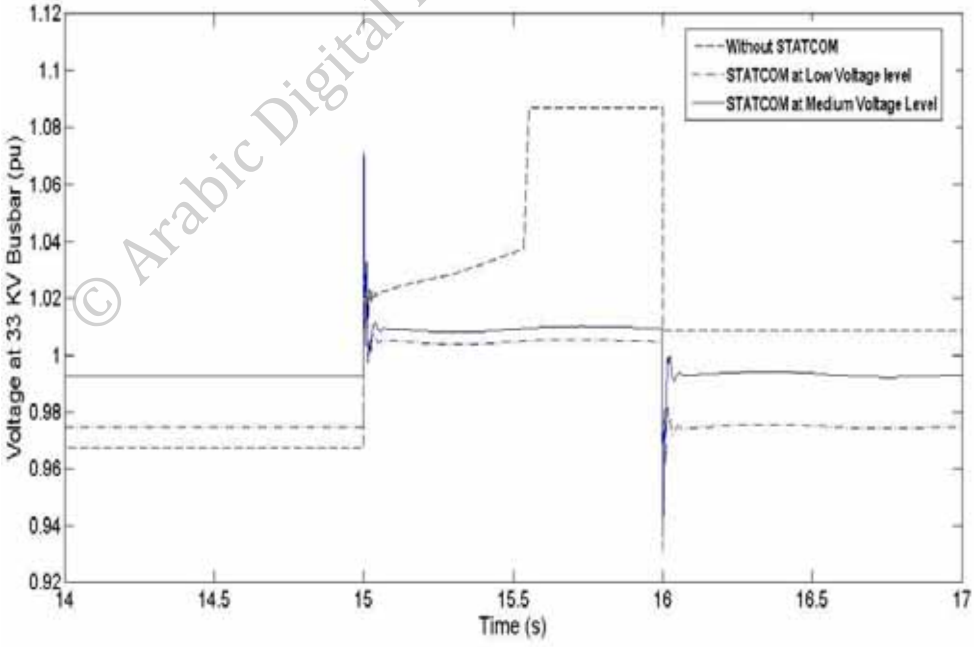

Figure 4.17 Voltage (pu) at bus1 – case (3)

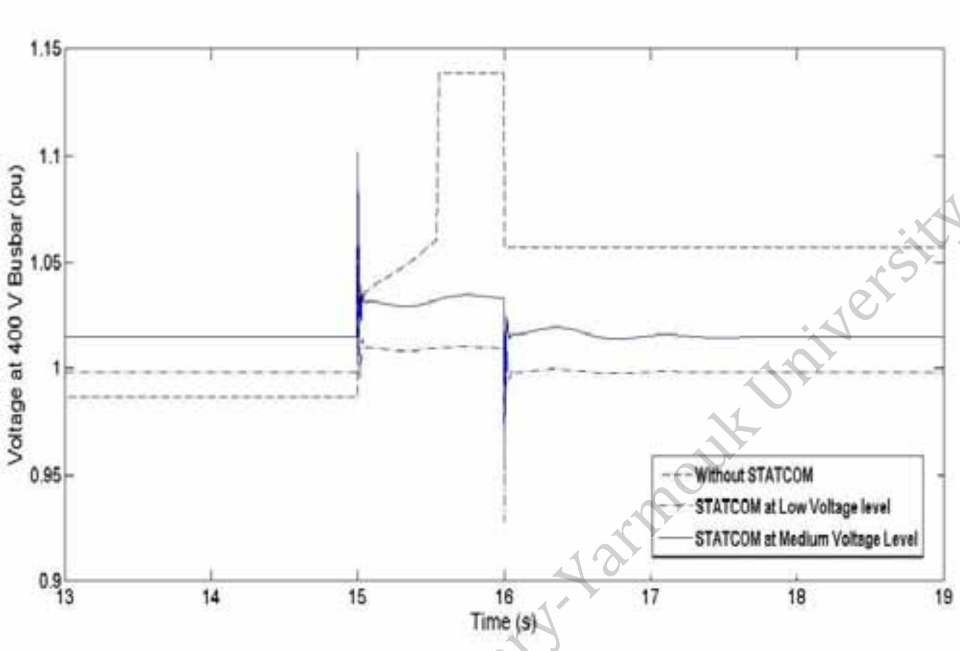

Figure 4.18 Voltage (pu) at Wind Turbine Bus (bus2) – case (2)

Installing STATCOM at x1 has contributed to limiting the increase of voltage to be 1.01 pu at bus 1 and 1.03 pu at bus 2, while reach 1.01 pu when STATCOM was installed at x2. STATCOM absorbs the excess reactive power in the distribution system.

Voltage increasing at bus 2 caused to trip wind turbine from the grid due to the wind turbine's overvoltage protection system as shown in figure 4.19, over voltage occurs because of the significant contribution in reactive power generation from wind farm's capacitor banks which no longer supplied the wind turbines after separated it from the network.

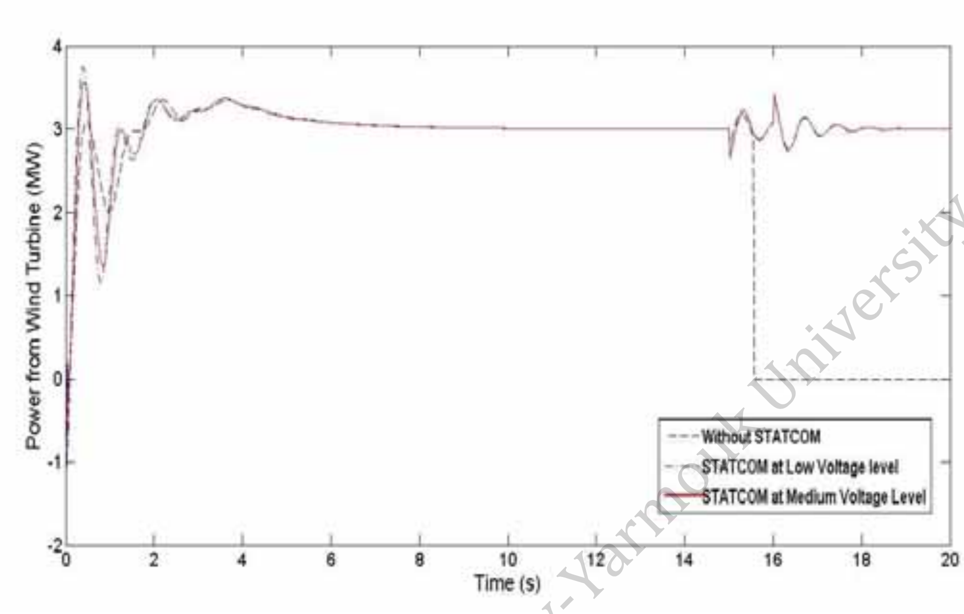

Figure 4.19 Active Power generation from Wind turbine (MW) – case (3)

Installing STATCON either at x1 or x2 make the voltage values acceptable at bus 2, and let the normal operation of wind turbine to generate the rated output power (3 MW) from it as shown in figure 4.19.

Figure 4.20 shows the reactive power that consumed from wind turbine for this case. When wind turbine separated from grid there is no need to consume reactive power to the induction generator in the turbine.

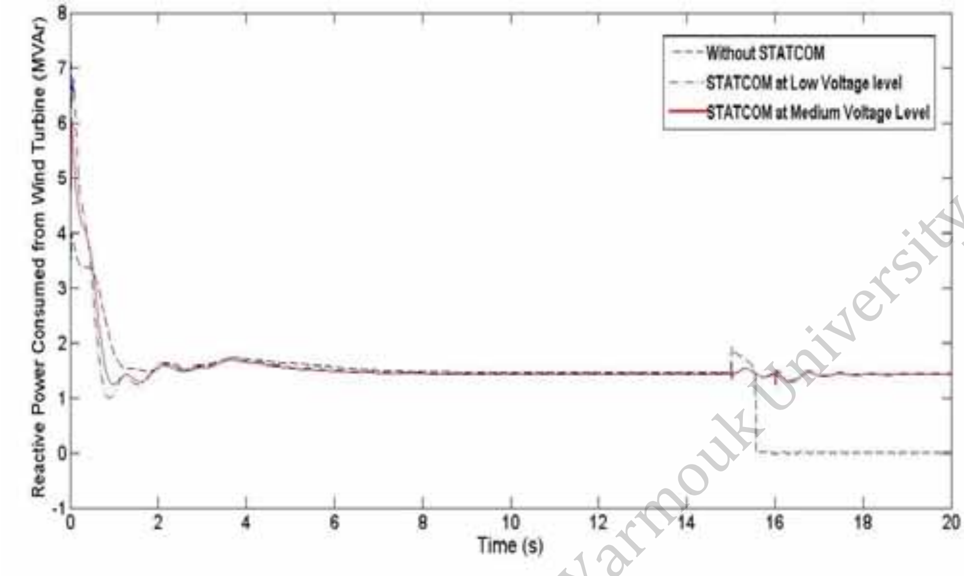

Figure 4.20 Reactive Power Consumed from Wind Turbine (MVAr) – case (3)

Tripping of wind turbine force the distribution system to consumed 6 MW from grid to supply the demand at bus 3 as shown in figure 4.21.

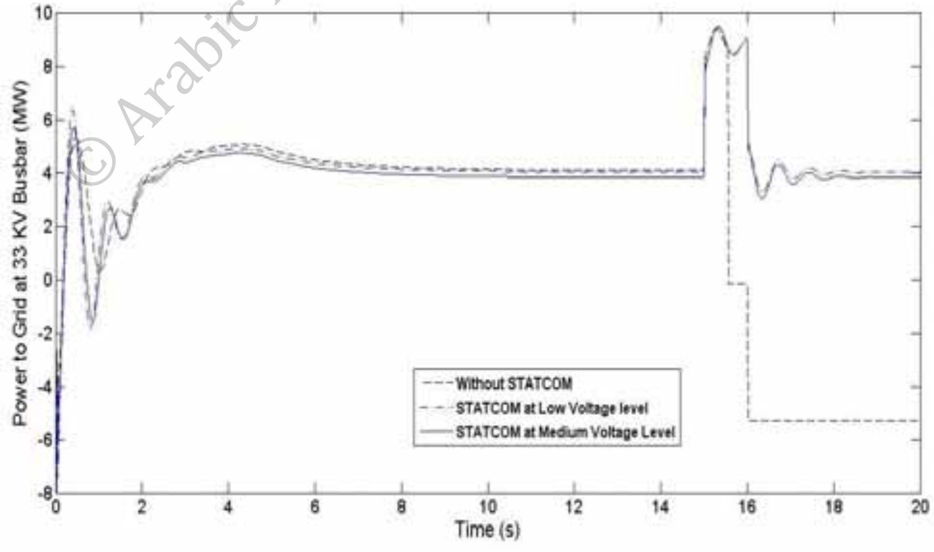

Figure 4.21 Power to Grid from Distribution system at bus1 (MW) – case (3)

Tripping of wind turbine causes a reflection of reactive power flow to become from distribution system to the grid because of the significant contribution in reactive power generation from wind farm's capacitor banks which no longer supplied the wind turbines after separated it from the network as shown in figure 4.22.

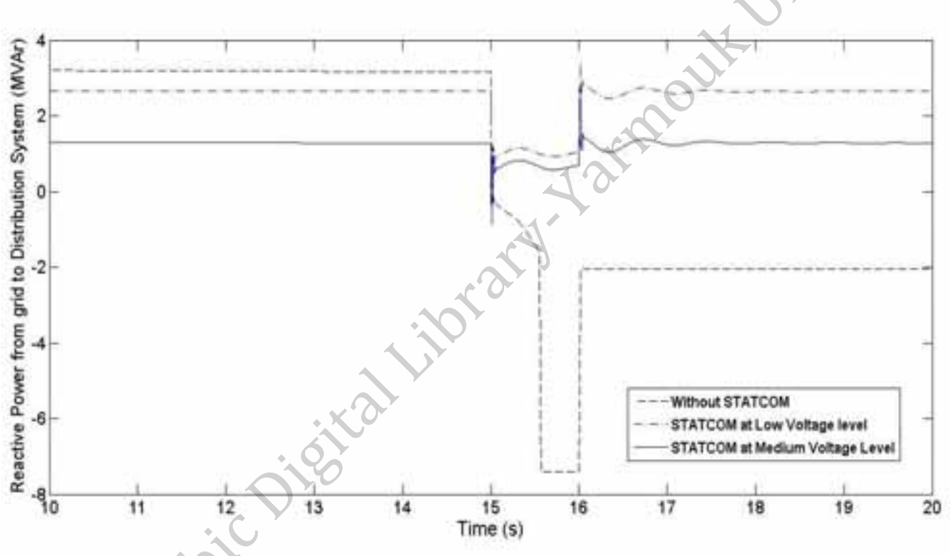

Fig 4.22 Reactive Power from Grid to Distribution system at bus1 (MVAr) – case (3)

STATCOM in this case absorbs same amount of reactive power wherever it was installed at x1 or at x2 as shown in figure 4.23, reactive power absorption is not affected by the value of the STATCOM location voltage.

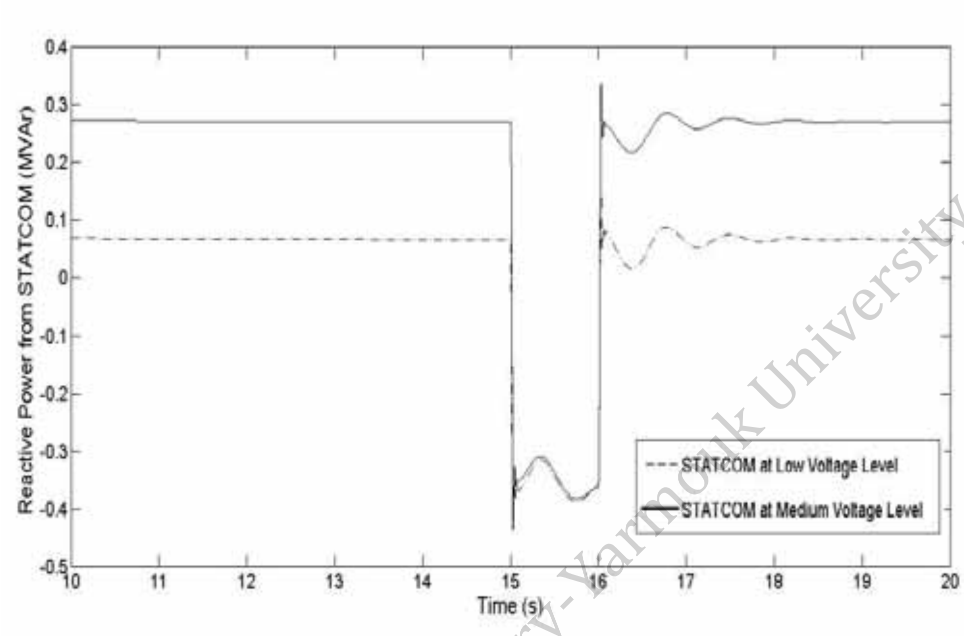

Figure 4.23 Reactive Power from STATCOM (MVAr) – case (3)

4.2.4 Case (4)

In this case, the system will expert variable inductive load at bus 5 for 10 second, System parameters (voltage, current, active power flow, reactive power balance) and wind turbine generation will be explained with and without STATCOM (STATCOM at low and medium voltage levels).

Connecting a variable inductive load at bus 5 causes a continuous variations on voltage values at bus 1 and bus 2 as shown in figures 4.24 and 4.25 respectively.

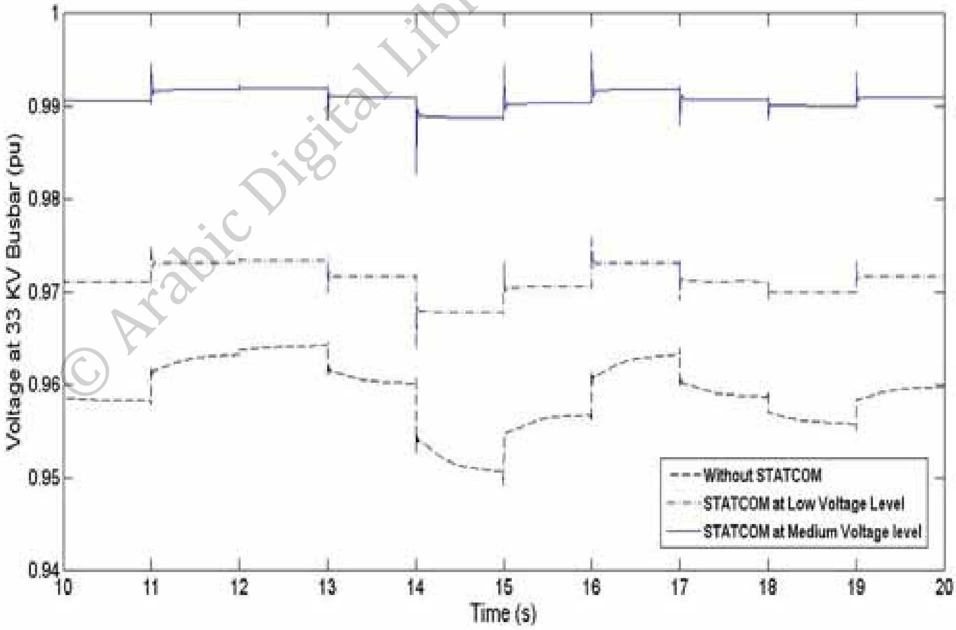

Figure 4.24 Voltage (pu) at bus1 – case (4)

Reactive power support from STATCOM has contributed to reduce the voltage variations; STATCOM improved the voltage characteristics of the system during and after the load change.

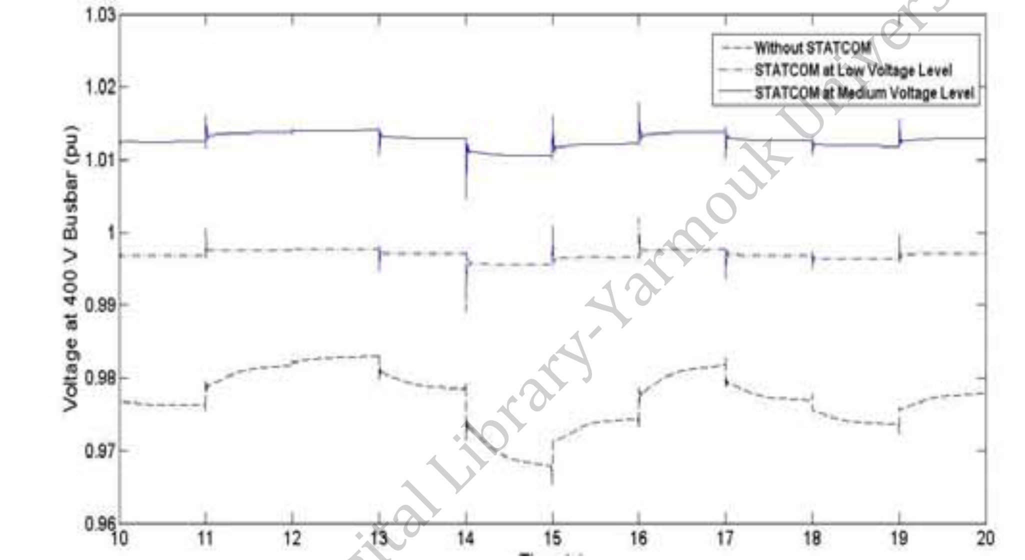

Figure 4.25 Voltage (pu) at Wind Turbine Bus (bus2) – case (4)

Voltage variations affect the operation of wind turbine as shown in figure 4.26, output MW from wind turbine varied due to the voltage variations, installing STATCOM make the voltage stable which let a stable operation of STATCOM

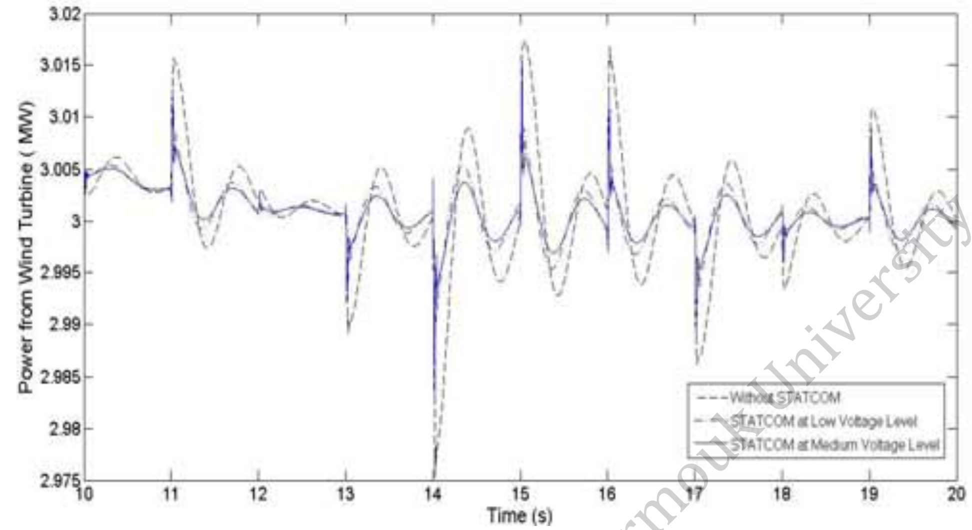

Figure 4.26 Active Power Generated from Wind Turbine (MW) – case (4)

Reactive power support from STATCOM causes to limit variations of reactive power consumed from induction generator in the wind turbine as shown in figure 4.27.

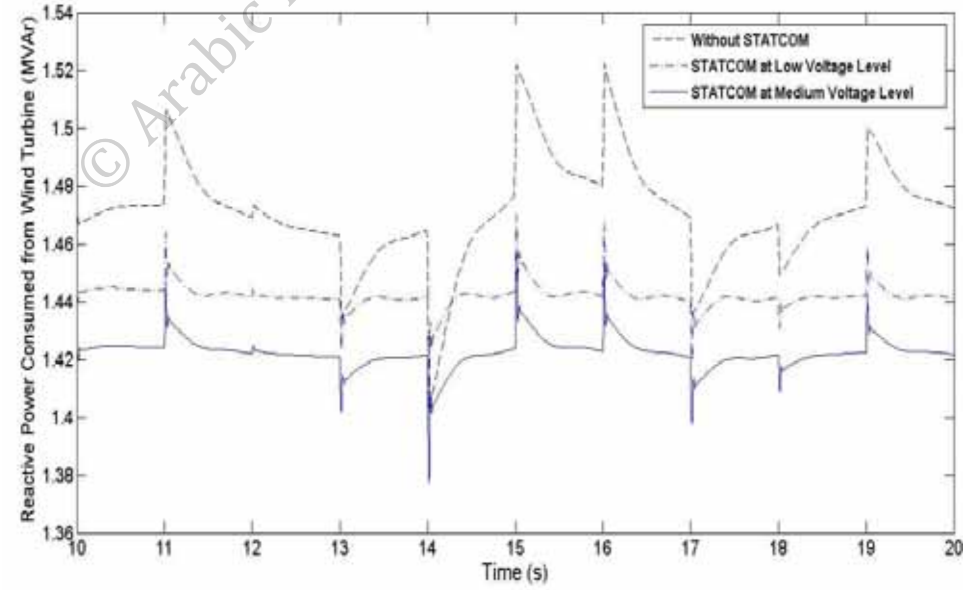

Figure 4.27 Reactive Power Consumed from Wind Turbine (MVAr) – case (4)

Figures 4.28 and 4.29 show the effect of voltage variations on power flow and reactive power balance in the distribution system respectively.

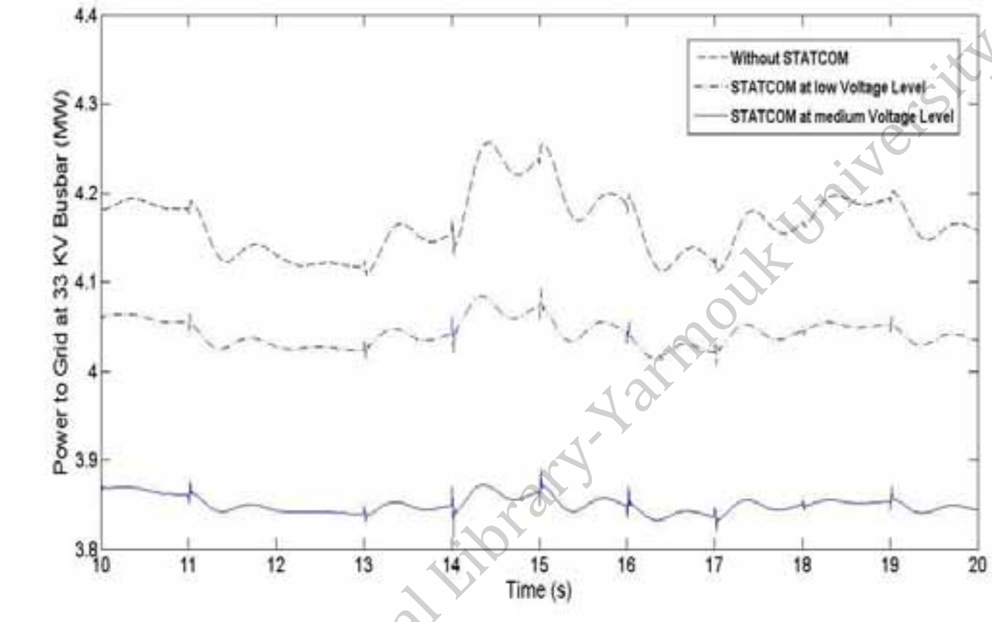

Figure 4.28 Power to Grid from Distribution system at bus1 (MW) – case (4)

Unstable operation of wind turbines makes a variation on active power and reactive power flow in the distribution system due to the variable inductive load at bus 5. Installing STATCOM cause to absorb the excess reactive power and limit the variations.

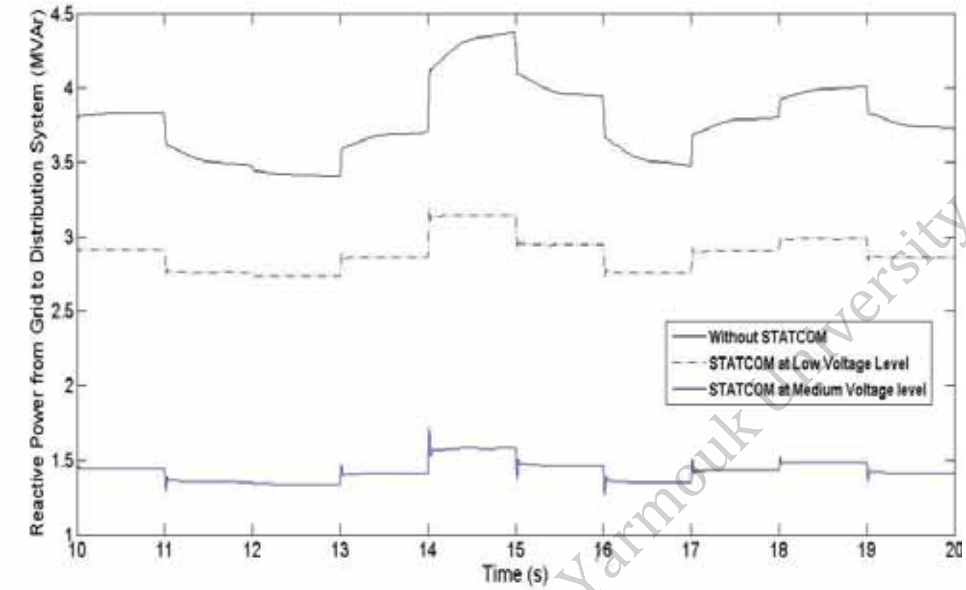

Figure 4.29 Reactive Power to Distribution system from Grid at bus1(MVAr) – case (4)

STATCOM output MVAr when the variable load connected at bus 5 is shown in figure 4.30 for different locations of STATCOM.

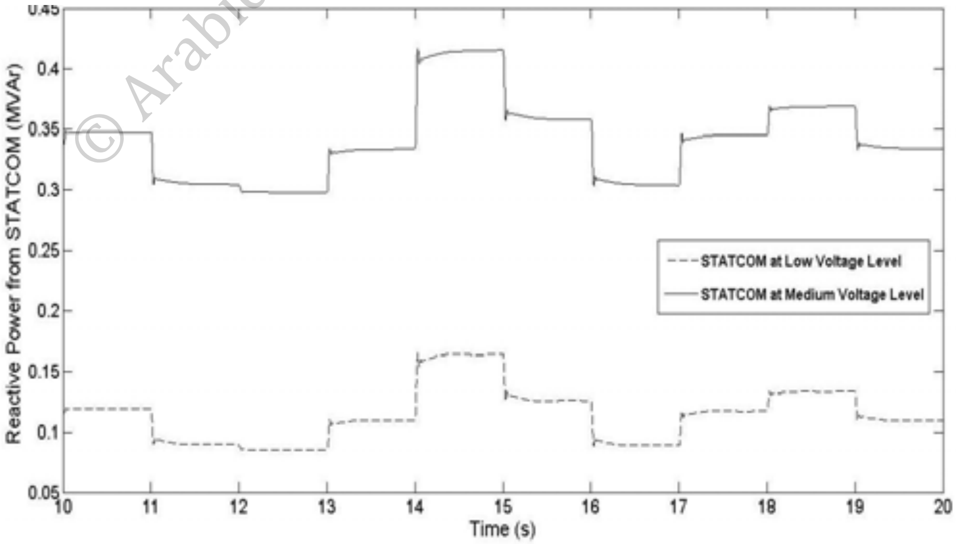

Figure 4.30 Reactive Power Generated from STATCOM – case (4)

4.2.5 Case (5)

In this case, the system will expert single line to ground fault for a period (from 14s to 14.4s) at x3, System parameters (voltage, current, active power flow, reactive power balance) and wind turbine generation will be explained with and without STATCOM (STATCOM at low and medium voltage level).

Single line to ground fault at x3 causes a large voltage drop due to the high current flow through wind turbine bus bar. At bus 1 voltage become 0.77 pu as shown in figure 4.31, while voltage at bus 2 drop to 0.82pu (figure 4.32).

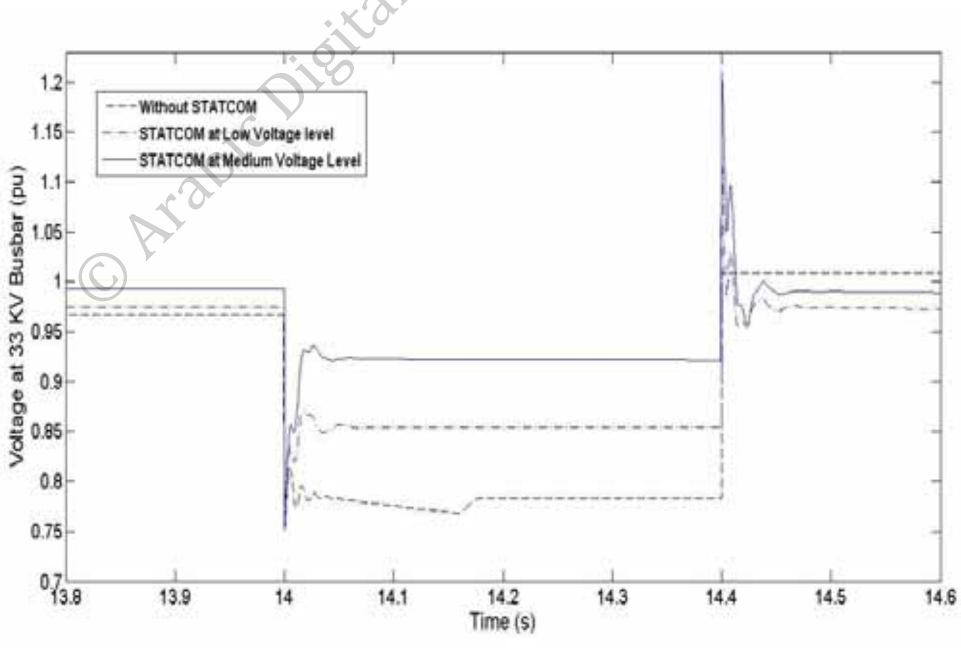

Figure 4.31 Voltage (pu) at bus1 – case (5)

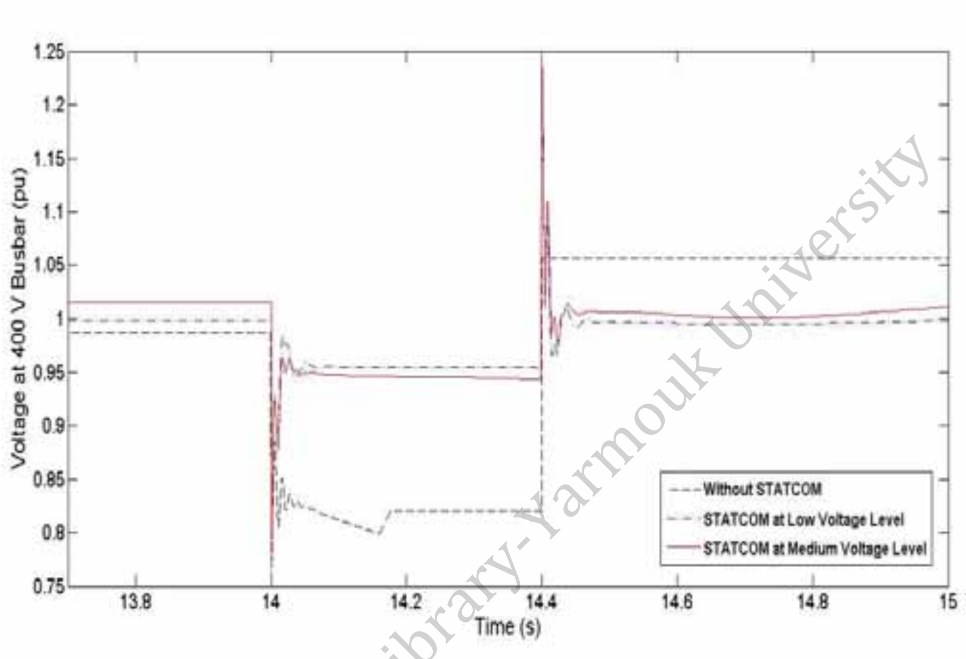

Figure 4.32 Voltage (pu) at Wind Turbine Bus (bus2) - case (5)

Installing STATCOM at x2 limited the decreasing of voltage at bus 1 and bus 2 to become (0.85) and (0.96) respectively, while installing STATCOM at x1 make the voltage at bus 1 (0.92 pu) and (0.95) at bus 2.

Voltage improved at bus 1 and bus 2 due to the reactive power support from STATCOM. Reactive power support from STATCOM at x1 is more than reactive power supports from STATCOM at x2, this differentiation of reactive power support explained from equation 3.1 which show that reactive power support become larger for the higher voltages.

Without STATCOM, voltage drop cause to trip wind turbine from the grid due to the wind turbine's under voltage protection system as shown in figures 4.33 and 4.34, but when STATCOM was installed at x1 or x2 the voltage values become acceptable which let the normal operation of wind turbine and generate the rated output power (3 MW) from it.

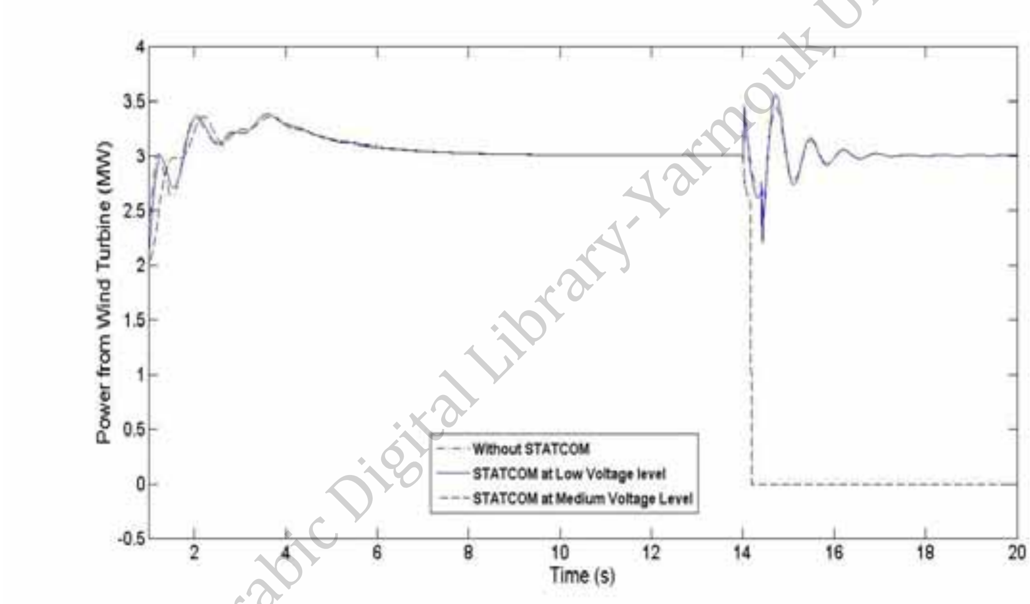

Figure 4.33 Power Generated from Wind turbine (MW) - case (5)

Figure 4.34 shows the reactive power that consumed from wind turbine for this case. When wind turbine separated from grid there is no need to consume reactive power to the induction generator in the turbine.

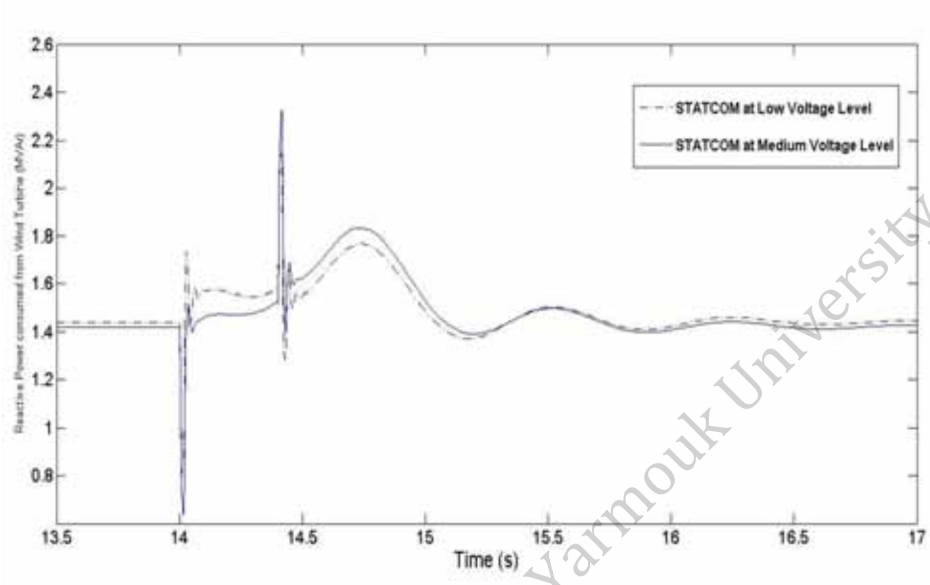

Figure 4.34 Reactive Power Consumed from Wind Turbine (MVAr) – case (5)

Tripping of wind turbine force the distribution system to consumed 6 MW from grid to supply the demand at bus 3 as shown in figure 4.35.

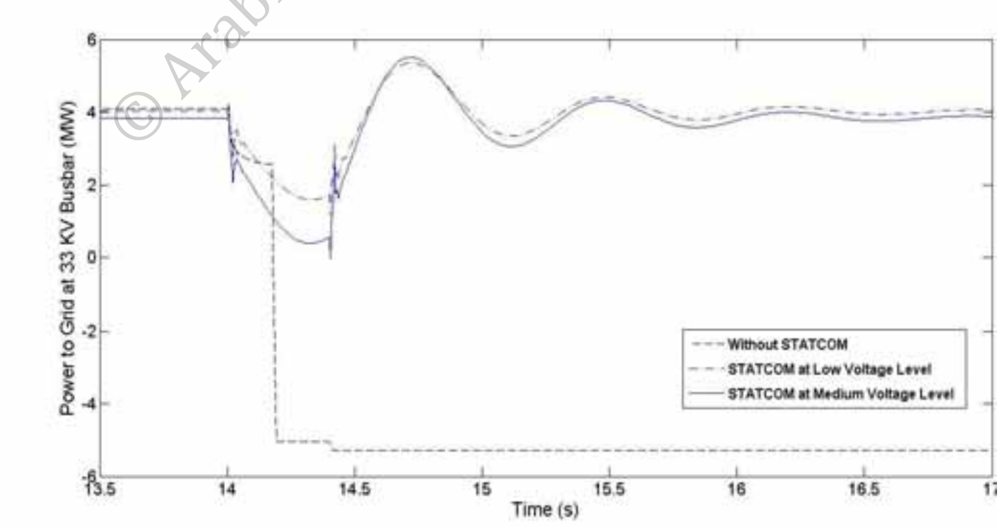

Figure 4.35 Power to Grid from Distribution system at bus1 (MW) – case (5)

Tripping of wind turbine causes a reflection of reactive power flow to become from distribution system to the grid because of the significant contribution in reactive power generation from wind farm's capacitor banks which no longer supplied the wind turbines after separated it from the network as shown in figure 4.36.

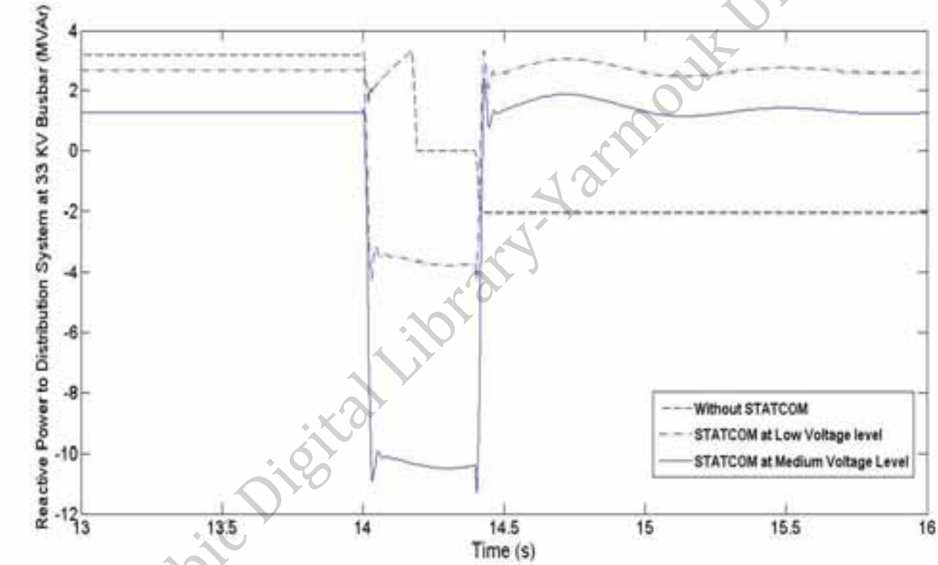

Figure 4.36 Reactive Power to Distribution system from Grid at bus1 (MVAr) – case (5)

Single line to ground fault at x3 cause an increase in current to reach 1.8 pu as shown in figure 4.37, installing STATCOM limit this increasing to become 0.7 pu.

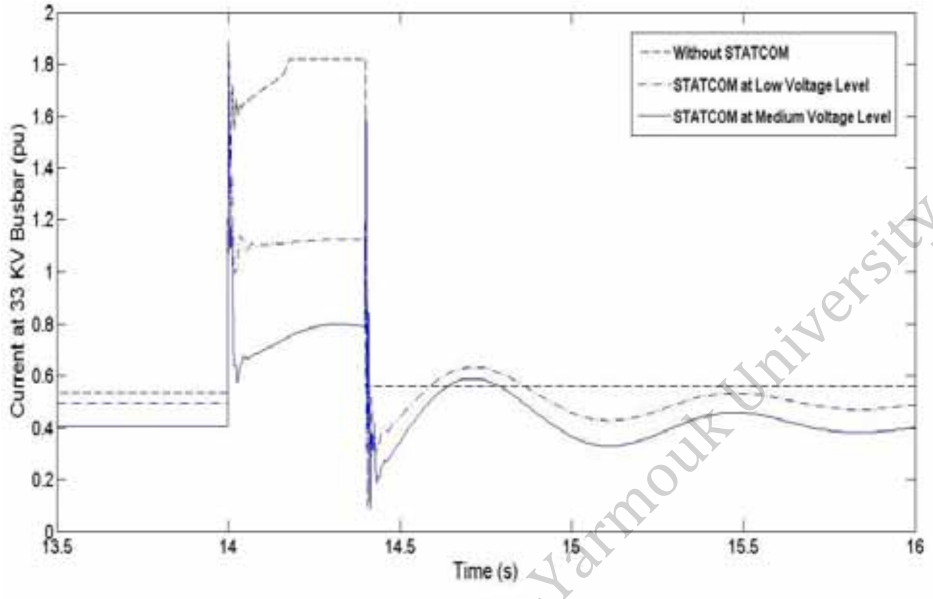

Figure 4.37 Current at bus1 (pu) – case (5)

Figure 4.38 shows the reactive power support from STATCOM at x1, which is more than reactive power supports from STATCOM at x2, this differentiation of reactive power support explained from equation 3.1 which show that reactive power support become larger for the higher voltages.

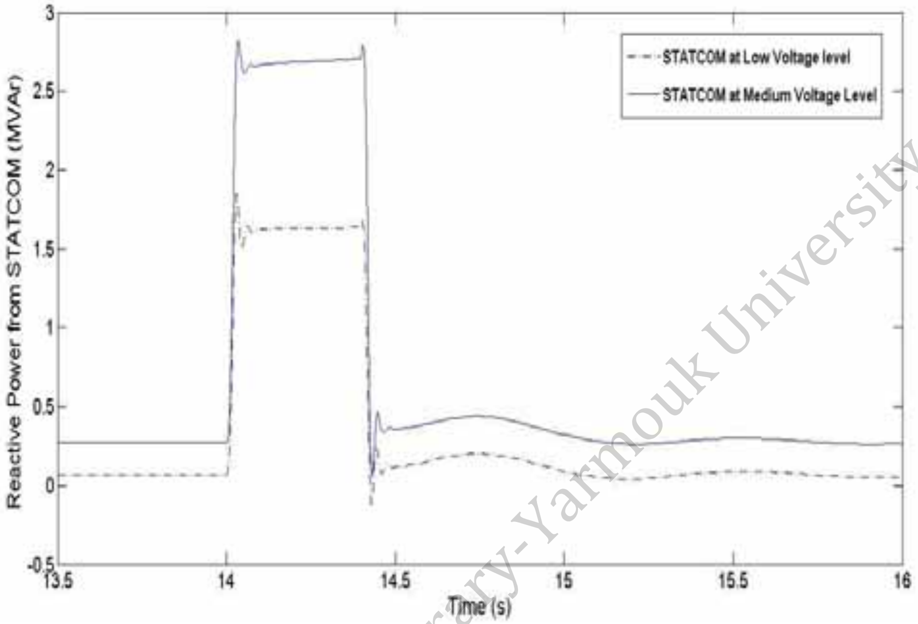

Figure 4.38 Reactive Power Generated from STATCOM (MVAr) – case (5)

4.2.6 Case (6)

In this case the STATCOM rating will reduce from 18 MVA to 8 MVA for the same contingency situation in case 5.

Reduce STATCOM rating in previous case from 18 MVA to 8 MVA had an impact on voltage values on bus 1 and bus 2 as shown in figures 4.40 and 4.41 respectively. Voltage value on bus 2 acceptable when STATCOM installed at x2, this acceptable value let the normal operation of wind turbine.

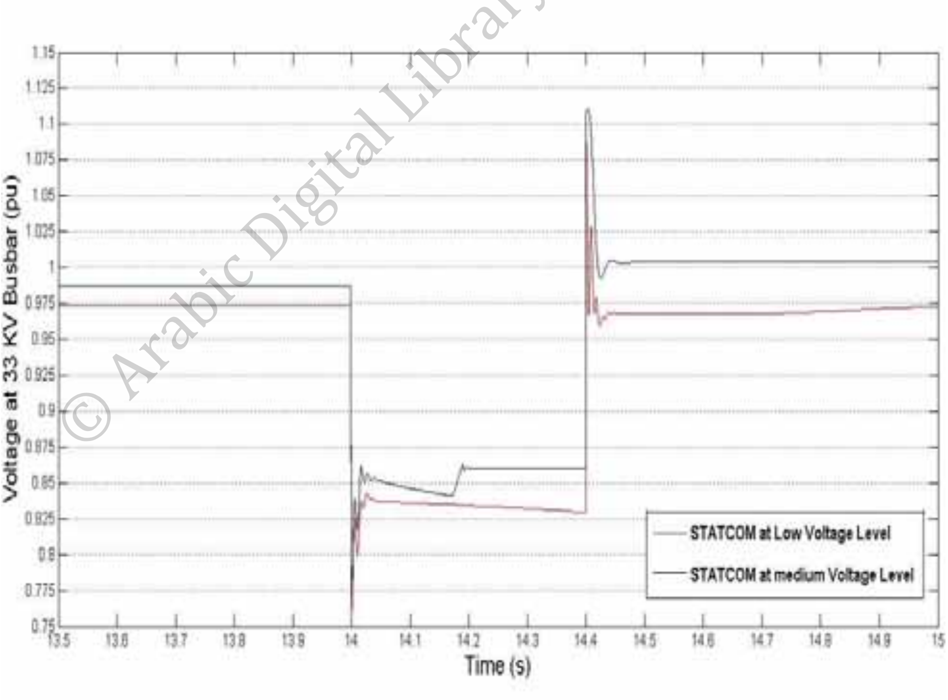

Figure 4.39 Voltage (pu) at bus1 – case (6)

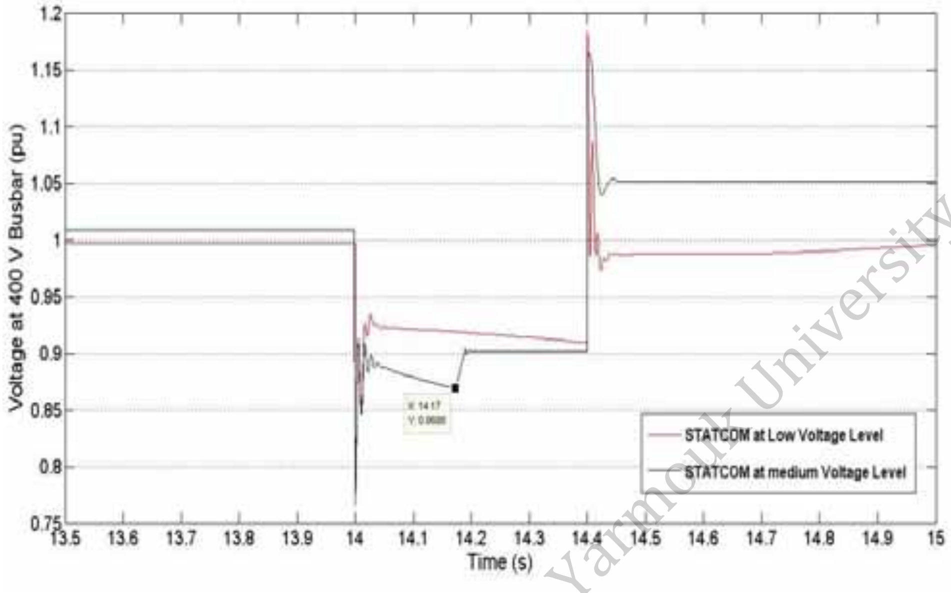

Figure 4.40 Voltage at Wind Turbine bus (bus2) – case (6)

Installing STATCOM at x1 does not help to support the voltage at bus 2 to prevent the tripping of wind turbine as shown in figure 4.42

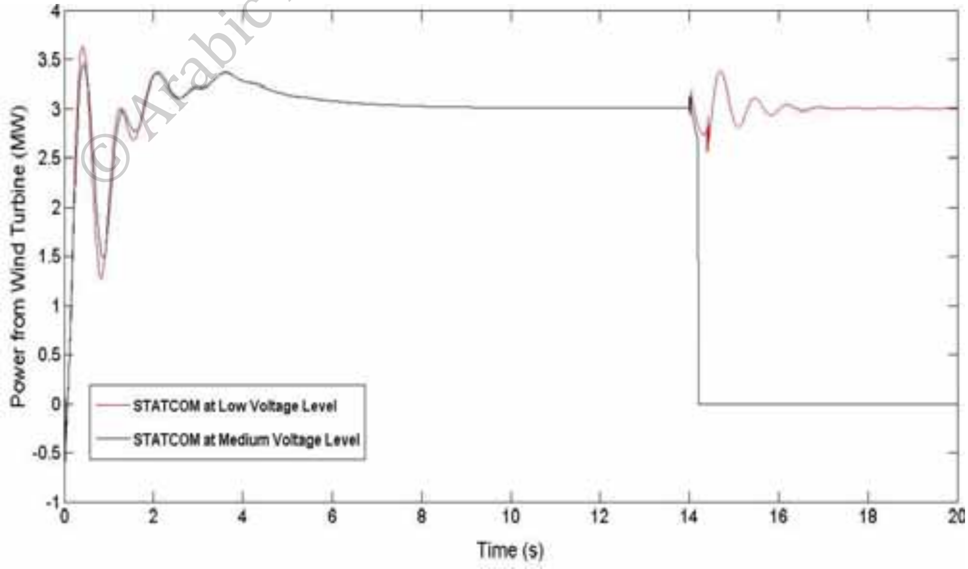

Figure 4.41 Power Generated from Wind Turbine (MW) – case (6)

4.3 Discussion of Results

In the first case, at normal condition, voltage value at the main busbar (bus 1) is acceptable (0.96 pu), this value improved to (0.97 pu) when the STATCOM installed at x2 (low voltage level) and this improving reach to (0.99 pu) for the voltage value when the STATCOM installed at x1 (medium voltage level). This acceptable situation reflect positively on wind turbine busbar (bus 2) where the voltage value is (0.985 pu) and reach to (0.998 pu) when STATCOM installed at x2, while installing the STATCOM at x1 will cause to the over voltage situation (1.015 pu).

The survival of the voltage within normal limits let the wind turbine to generate the rated output power (3 MW) and consuming 1.4 MVAr. Reactive Power flow from grid to distribution has been reduced from 3.25 MVAr to 2.7 MVAr when the STATCOM installed at x2, and reduced further to 2.25 MVAr when STATCOM installed at x1. This situation occures due to the STATCOM at medium voltage level generate reactive power more than STATCOM at low voltage level.

In the second case, the high reactive power demand at bus 4 (from 15s to 16s) cause a voltage drop to (0.92 pu) at bus 1, this drop was limited to (0.95 pu) when STATCOM installed at x2, but when the STATCOM installed at x1 the voltage at bus 1 just drop to (0.98 pu) for the same time period. As in the previous case, this voltage drop reflected on voltage profile at wind turbine bus (bus 2) which drop to (0.92 pu) and to (0.992) when STATCOM at x2 and (1.01 pu) for the STATCOM at x1.

Voltage variation on wind turbine busbar affect the output power which varied from 2.85 MW to 3.15 MW, installing STATCOM cause to narrow the gap for output power to be from 2.93 MW to 3.04 MW. This variation include also the reactive power that consumed from wind turbine which varied from 1.1 MVAr to 1.9 MVAr, but using STATCOM keep the consumed reactive power around 1.4 MVAr.

it's noticed that how the active power flow toward the grid increased by 600 KW during the period of reactive load increase at bus 4, but using STATCOM at x2 cause to reduce the increasing to become 300 KW, while installing STATCOM at x1 make the increasing 100 KW. increase the reactive demand in distribution system cause an increase of consumed reactive power at bus 1 which reach to 7 MVAr, this consuming reduced to 4.1 when STATCOM installed at x2 and reduced more to become 2 MVAr when STATCOM at x1.

In third case, the load at bus 3 interrupted for one second which cause a huge voltage increase at main bus 1 to become (1.09 pu) and reach (1.15 pu) at wind turbine busbar (bus 2). Voltage increasing cause to trip wind turbine from the grid due to the wind turbine's overvoltage protection system, tripping of wind turbine force the distribution system to consumed 6 MW from grid to supply the demand at bus 3, and it is noticeable also reflection of reactive power flow to become from distribution system to the grid because of the significant contribution in reactive power generation from wind farm's capacitor banks which no longer supplied the wind turbines after separated it from the network.

Installing STATCOM at x1 has contributed to limiting the increase of voltage to be (1.01 pu) at bus 1 and (1.03 pu) at bus 2, while reach (1.01 pu) when STATCOM was installed at x2. The acceptable voltage values at bus 2 let the normal operation of wind turbine and generate the rated output power (3 MW) from it.

In the fourth case, connecting a variable inductive load at bus 5 caused a continuous variation on voltage values at bus 1 and bus 2 which effect the operation of wind turbine and reactive power balance in the distribution system. Installing STATCOM contributed to the reduction of these changes significantly.

In the fifth case, a single line to ground fault at x3 for a period from 14s to 14.4s caused a large voltage drop at bus 1 to become (0.77 pu) while at bus 2 (0.82 pu).voltage drop cause to trip wind turbine from the grid due to the wind turbine's under voltage protection system, tripping of wind turbine forced the distribution system to consumed 6 MW from grid to supply the demand at bus 3, and also reflection of reactive power flow to become from distribution system to the grid because of the significant contribution in reactive power generation from wind farm's capacitor banks. Installing STATCOM at x2 limited the decreasing of voltage at bus 1 and bus 2 to become (0.85) and (0.96) respectively, while installing STATCOM at x1 make the voltage at bus 1 (0.92 pu) and (0.95) at bus 2. The acceptable voltage values at bus 2 let the normal operation of wind turbine and generate the rated output power (3 MW) from it.

Reduce STATCOM rating in previous case from 18 MVA to 8 MVA had an impact on voltage values on bus 1 and bus 2. The voltage profile at bus 2 when STATCOM was installed at x2 is better than in the case of installed STATCOM at x1; despite that the voltage profile at bus 1 was more appropriate when installed STATCOM at x1.

Chapter 5

Conclusion and Future Work

Conclusion and Future Work

5.1 Conclusion

Increasing demand for electric power, depleting natural resources and rapid change in fuel cost in recent years has cause to increase needed for renewable energy sources such as wind energy to generate electrical power which makes it an important research topic. Due to increased penetration of wind turbines in power system, it is necessary to provide efficient power control during normal operating conditions and enhanced support during and after faults to ensure continuous operation for wind turbine, for this purpose grid codes are placed.

Consuming reactive power from the grid to create the magnetic field in the stator windings of the "Squirrel Cage Induction Generator (SCIG) wind turbine" caused a voltage dip and shortage of reactive power in the power system. Installing compensating devices are important to achieve reactive power balance in the network. Large compensating capacitor banks could help to improve voltage profile of the system at steady state conditions but at contingency situations and low voltage conditions the var support from capacitors drops sharply and as a result wind generators trip from the grid.

This thesis explores the possibility of connecting a STATCOM to the wind power system in order to provide efficient control by injecting or absorbing reactive power. In this thesis, a power distribution system with connected SCIG wind farm is studied based on Matlab Simulink model and the behavior of the system for different cases which include sudden load changes and faults.

Simulation studies have shown that the voltage in the system without STATCOM was badly affected and led the wind turbine to trip from the network in some cases. Installing STATCOM helps to provide better voltage characteristics during unstable load conditions and faults, stable voltage characteristics cause to improve dynamic performance of wind farms.

The results of simulation show that the STATCOM performance and its effect on voltage profile in the distribution network depend on STATCOM location. Installed STATCOM at medium voltage level had better impact on voltage stability for all sections in the distribution system, while installed STATCOM at low voltage level near to the wind farm is more suitable for voltage profile on wind turbine busbar even with lower STATCOM ratings.

5.2 Future Work

In this thesis, simulation studies show that the performance of wind turbine is improved with the use of a STATCOM. Future work can involve using multilevel STATCOM to reduce the harmonics of the system. Single line to ground fault has been studied in this thesis that can be extended to observe the response of the wind turbines to other types of faults. The performance of SCIG wind turbine has been studied in this thesis that can be extended to various types of wind turbines. Different types of FACTS device could be used as a compensating device instead of STATCOM.

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Appendix A

- Distribution System (MATLAB/SIMULINK)

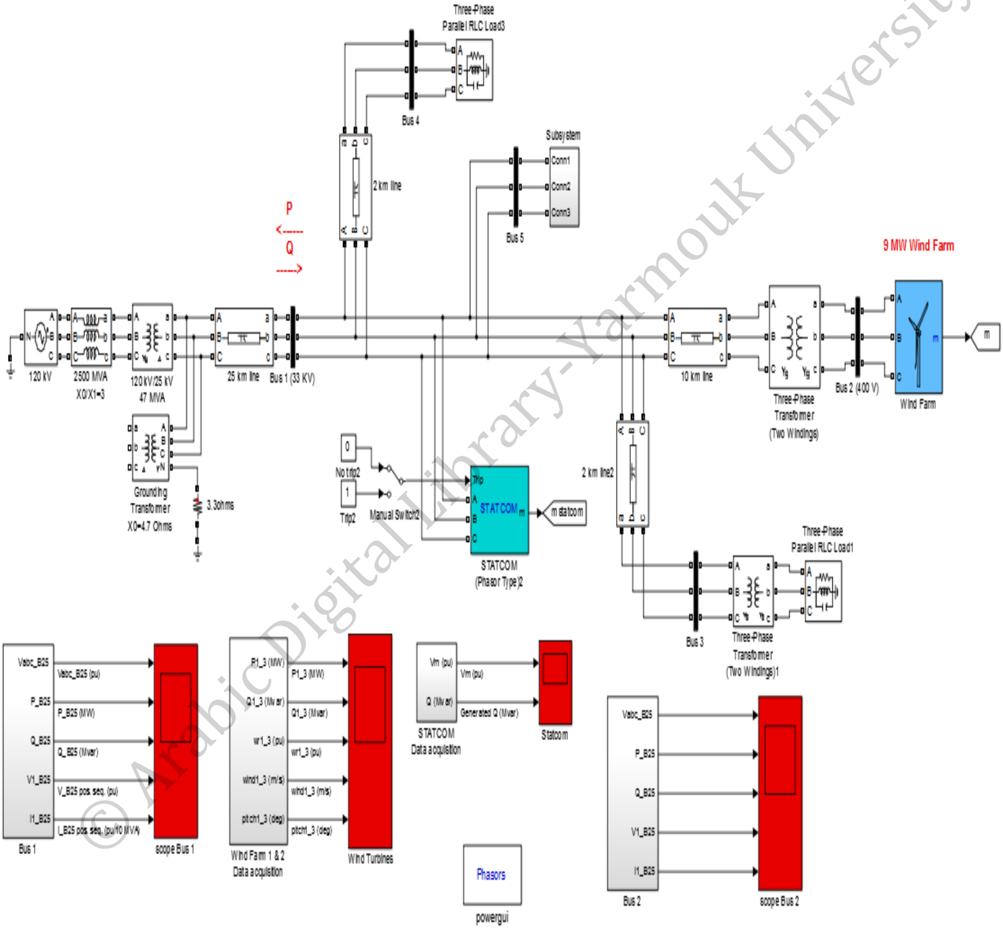

Fig A.1 Distribution System

Appendix B

- Wind Farm (MATLAB/SIMULINK)

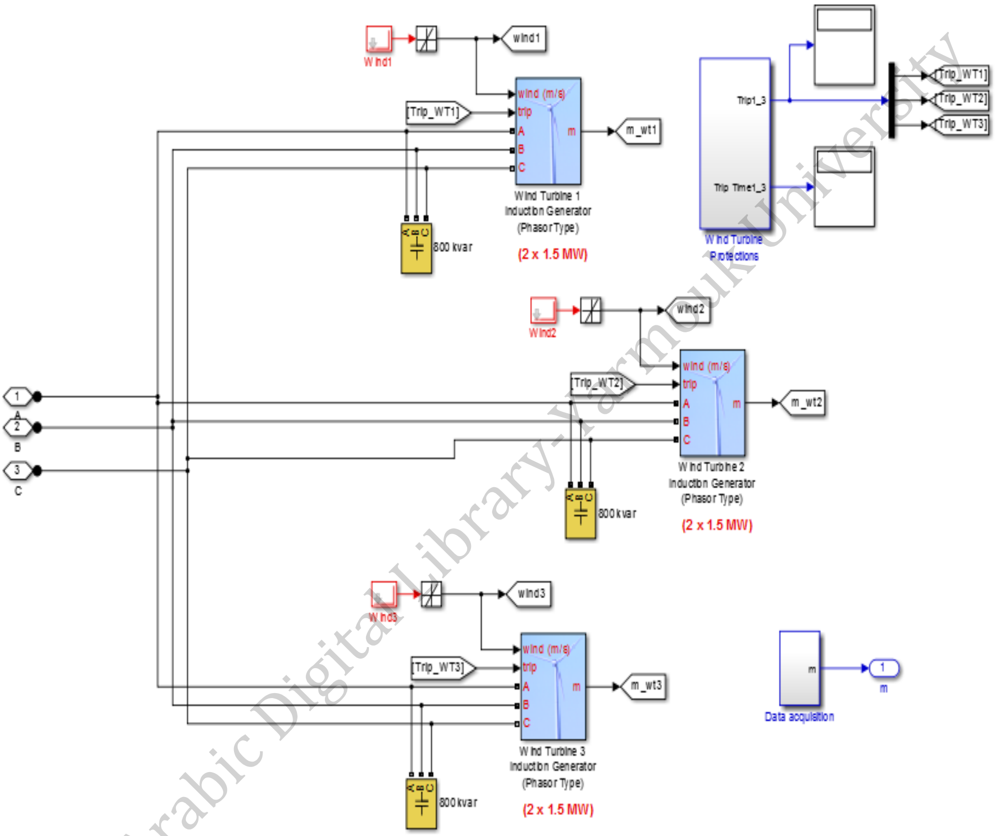

Fig B.1 Wind Farm

Appendix C

Table C.1 show the STATCOM characteristic which chosen in the case study

No.	Characteristics		
1	Operation Mode		Voltage Regulation Mode
2	Reference Voltage (pu)		1 pu
3	AC Voltage Regulator gain	kp	5
		ki	1000
4	DC Voltage Regulator gain	kp	$0.1\ e^{-3}$
		ki	$20\ e^{-3}$
5	Current Regulator gain	kp	0.3
		ki	10
6	STATCOM Converter Rating		18 MVA
7	Converter impedance	R (pu)	0.007
		L (pu)	0.22
8	DC link total equivalent capacitor		375 µF

Table C.1 STATCOM characteristics

Table C.2 show wind turbine characteristics as presented in the case study

No.	**Characteristics**		
1	Nominal output power		3 MW
2	Generator pairs of pole		3
3	Pitch angle controller gain	kp	5
		ki	25
4	Base wind speed		9 m/s
5	Generator stator impedance	Rs (pu)	0.004843
		Ls (pu)	0.1248
6	Generator rotor impedance	R'r (pu)	0.004377
		L'r (pu)	0.1791
7	Magnetizing inductance Lm (pu)		6.77

Table C.2 Wind Turbine characteristics

Table C.3 show the transmission line parameters

Parameter	**Positive Sequence**	**Zero Sequence**
Resistance	0.1153 ohms/km	0.413 ohms/km
Inductance	1.05 mH/km	3.32 mH/km
Capacitor	11.33 nF/km	5.01 nF/km

Table C.3 Transmission line parameters