INTEGRATION OF WIND FARMS INTO WEAK AC GRIDS

A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy

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CONTENT

ABSTRACT

Large wind farms are usually located in remote and offshore areas. High voltage transmission systems that have long transmission distances are used to deliver the wind power to main grids. Weak AC grids have high impedance, low short circuit ratio (SCR) and/or low inertia compared to strong AC grids. The voltage stability of weak AC grids is a challenging issue that needs to be considered.

This thesis compares weak and strong AC grids based on the voltage stability analysis. The steady-state characteristics of the weak AC grids are investigated. The power transfer characteristics of the wind farms that are connected to weak AC grids are studied under different voltage control technologies. The mitigation of the voltage recovery problems for weak AC grids is proposed by supplementary voltage control.

The main characteristics of a weak AC grid are determined using P-V and V-Q curves. Different short circuit levels of the AC grid are presented with an increase in grid load and active power generation. Weak AC grid has a poor voltage stability limit and a low reactive power margin, which make the grid close to voltage instability.

A static model is developed to study a test system including wind farm, AC grid, and reactive power compensators. Variable-speed wind turbines are examined under different control modes (power factor control, AC voltage control and reactive power control) using full power converters to increase the limit of transferred wind power to weak AC grids. Reactive power compensators of STATCOM, SVC, and fixed capacitor are compared to the full power converters. The capability of transferring power using STATCOM and SVC is greater than the full power converters.

A dynamic model for the wind farm connected to the AC grid is developed and a STATCOM. The AC grid is modelled using two methods: as an ideal voltage source behind a Thevenin impedance and as a synchronous generator. A reactive power versus AC voltage droop is designed in STATCOM. The effectiveness of the STATCOM control is tested to increase the power transferred to the weak AC grids.

The new supplementary voltage control is proposed using the full power converters with DC chopper considering three-phase to ground fault. Although the DC chopper is inadequate to keep the transient stability, a fast voltage control of the STATCOM is utilized to support the DC chopper in weak AC grids. The voltage recovery is improved using this controller after fault clearing.

DECLARATION AND STATEMENTS

DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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DEDICATION

I would like to dedicate doctoral thesis to the spirit of my dear father who missed him a lot during my studies

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I am deeply thankful to God for His amazing grace, which has kept me from the beginning of my life until now.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CSCs	Current source converters
CUPS	Custom Power System devices.
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DVR	Dynamic Voltage Restorer
ESCR	Effective Short Circuit Ratio
ESS	Energy Storage Systems
FACTS	Flexible Alternating Current Transmission System
FRT	Fault Ride Through
FSIG	Fixed Speed Induction Generator
GR	Gearbox ratio
GSC	Grid Side Converter
HV	High Voltage
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistors
LCC	Line-Commutated Converter
MPPT	Maximum Power Point Tracking
MSC	Mechanical Switched Capacitor
MV	Medium Voltage
PF	Power Factor
PI	Proportional Integral
PLL	Phase Locked Loop
PMSG	Permanent Magnet Synchronous Generators
PSL	Power Synchronisation Loop
R.M.S	Root Mean Square
RSC	Rotor Side Converter
SCIG	Squirrel cage induction generators
SCR	Short Circuit Ratio
STATCOM	Static Synchronous Compensation
SVC	Static VAR Compensator
TC	Tap Changer
UPQC	Unified Power Quality Compensator
VSC	Voltage Source Converter
WSC	Wind Turbine Side Converter
WTG	Wind Turbine Generator

LIST OF SYMBOLS

B	The friction coefficient
β	The blade angle
C	The capacitor of DC link
C_P	Power coefficient
d	The duty ratio
i_{sq}	The instantaneous stator current in the q-axis
i_{sd}	The instantaneous stator current in the d-axis
i_{q-max}	Maximum converter current in the q-axis
i_q^*	The converter current reference in the q-axis
i_{max}	Maximum converter current
i_{gq}	The instantaneous grid current in the q-axis
i_{gd}	The instantaneous grid current in the d-axis
i_{d-max}	Maximum converter current in the d-axis
i_d^*	The converter current reference in the d-axis
i_{ST-q}	The instantaneous STATCOM current in the q-axis
i_{ST-d}	The instantaneous STATCOM current in the d-axis
J	Total moment of inertia
K_{vQ}	The droop gain in STATCOM
L	Inductance of converter reactor
L_q	The stator winding inductance in quadrature axis
L_d	The stator winding inductance in direct axis
p	Pole pair number
ρ	Air density
P	The output power of the wind farm
P_s	The generator power
P_g	The grid power
P_{ST}	The STATCOM's active power
$P_{Chopper}$	The power dissipated in DC chopper
Q	The reactive power of the wind farm
Q_{ST}	The STATCOM's reactive power
Q^*	Set reference reactive power for reactive power control in GSC
r	The radius of the wind turbine rotor
r_s	The stator winding resistance
R	Resistance of converter reactor
R_g	The grid resistance
R_{braking}	The braking resistor in DC chopper
S_{sc}	Short circuit level of the AC grid
S_{WF}	Nominal MVA rating of the wind farm
T_m	The mechanical torque of the turbine
T_e	The generator electromagnetic torque
v_{sq}	The instantaneous stator voltage in the q-axis
v_{sd}	The instantaneous stator voltage in the d-axis
v_q	The instantaneous STATCOM converter voltage in the q-axis

v_{iq}	The instantaneous GSC voltages in the q-axis
v_{id}	The instantaneous GSC voltage in the d-axis
v_{gq}	The instantaneous grid voltage in the q-axis
v_{gd}	The instantaneous grid voltage in the d-axis
v_{d}	The instantaneous STATCOM converter voltage in the d-axis
v_{cq}	The instantaneous converter voltages in the q-axis
v_{cd}	The instantaneous converter voltages in the d-axis
v_{ST-q}	The instantaneous STATCOM voltage in the q-axis
v_{ST-d}	The instantaneous STATCOM voltage in the d-axis
V_{strat}	The threshold to start threshold controller in DC chopper
V_{max}	The allowed maximum DC voltage
V_{g-ac}	The measured AC grid voltage
$V_{g-\mathrm{ref}}$	The reference AC grid voltage
V_{g}	The AC grid terminal voltage
V_{dc}	The measured DC voltage
V_{W}	The wind speed
Vs	The voltage at a remote point
ΔV	The voltage deviation
ω	The angular frequency of the grid voltage.
ω_{r}	The electrical rotor speed
ω_{m}	The mechanical rotor speed
ω_{H}	Angular hub speed
X_{g}	The AC grid reactance
Z_{g}	AC grid impedance
ψ	The rotor magnetic flux
λ	Tip speed ratio
θ	The angle of AC grid voltage

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Chapter 1

Introduction

1.1 Background of wind energy systems

As a result of environmental concerns and the quest for energy security, wind energy systems have become crucial in the development of renewable energy resources and they play a significant role in the world power sector, particularly in European power sector. One of the scenarios from the European Wind Energy Association shows that over the next ten years, wind energy could meet one-fifth of the electricity demand in Europe by 2020, one-third by 2030, and half by 2050, as shown in Figure 1-1 [1], [2]. In the past, wind power capacity was a small portion of power systems and the continuous connection of a wind farm to the AC grid was not a major concern. With an increasing share of wind power sources, the continuous connection of wind farms to AC grids has played an increasing role in allowing continuous power supply to AC grids, even in the case of small disturbances. Therefore, it is essential to address some practical challenges associated with increasing scale of wind power such as reduction of power quality, high power fluctuations, and connection of weak AC grids when maintaining the stability and reliability of power system [3].

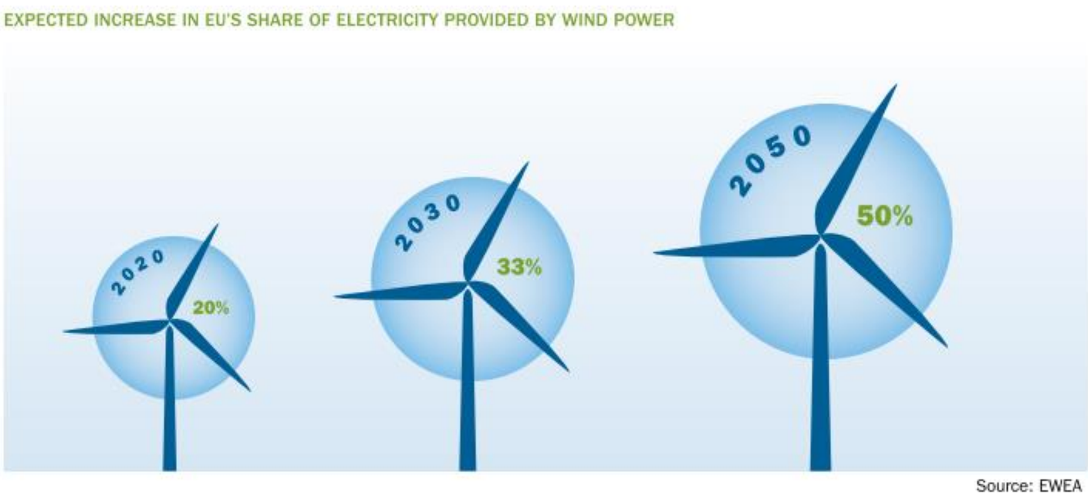


Figure 1- 1: European Wind Power Forecast for 2050 [2]

1.2 Wind energy in power systems

1.2.1 Wind energy

Wind has a kinetic energy that can be converted into mechanical power by wind turbines. The mechanical power can be used by generators to generate electric power. However, there are several difficulties related to the variability of wind power impacts on the delivered electrical power such as the magnitude of the wind power fluctuations [4]. Therefore, wind turbines have been designed to operate only within certain limits of wind energy availability (wind speed) and they tend to avoid extreme conditions that can destroy the turbines [5]. In addition, power electronic converters are used to improve the efficiency of wind energy conversion and to mitigate the difficulties of wind power variability [5].

1.2.2 Wind turbines and weak AC grids

There are many wind turbine manufacturers, and these produce different wind turbine technologies in different MW ratings and technical specifications. The early technology used in wind turbines was based on fixed speed. However, the technology has since developed towards variable-speed wind turbines. Fixed speed wind turbine technology is composed of squirrel-cage induction generator (SCIG) directly connected to the AC grid and a gearbox to match the rotor speed with that of the wind turbine, as shown in Figure 1-2. This technology has the advantage of simplicity, robustness, reliability and inexpensive [6], [7]. However, an uncontrollable reactive power consumption, limited power quality control and mechanical stress are the main disadvantages of this technology [6], [8].

The variable speed wind turbines are currently the most dominant wind turbine technology, since it increases energy capture from the wind, reduces mechanical stress on the wind turbine and improves power quality. The drawbacks of variable speed are needed power converters that increase the number of components and make the control more complex, all of which possibly reduce reliability and increase cost [5]. Variable-speed wind turbines are used to drive induction and synchronous generators such as Doubly-Fed Induction Generators (DFIGs) and Permanent Magnet Synchronous Generators (PMSGs), as shown in Figures 1-3 and 1-4 respectively.

In DFIGs, wound rotor induction generators use, the generators' stator is directly connected to the AC grid and the rotor is connected to the AC grid through a back-to-back converter. DFIGs are simple in construction and inexpensive, but they needs slip-rings and gearbox, which are required frequent maintenance [8]. PMSGs are connected to AC grids through the full power converters, which decouple totally the generators from the AC grids. PMSGs have a high reliability because they are suitable for direct drive gearless operation and the absence of field losses and mechanical components such as slip rings [7], [9]. However, demagnetization of permanent magnets at high temperature and high cost of the permanent magnet material are the main disadvantages of the PMSGs [7].

The connection methods of the wind turbines to the AC grids, particularly to weak grids, is an important issue since wind turbines connected to weak AC grids have a significant effect on the power system's performance [2]. Wind turbine performance can affect the AC grid considerably, and the weakness of the AC grids has a significant effect on wind turbine performance as well [10]. The main issues that are related to the effects of wind turbines on the AC grids include the variations in the voltage and the power, and the harmonics when using power converters [11], [12]. In fixed speed wind turbines, wind fluctuations are transmitted as power fluctuations into the AC grid resulting in voltage variations. Voltage variations will be large in the weak AC grids [6]. In addition, fixed wind turbines cannot mitigate the negative effects of a weak AC grid such as the poor power performance and instability without any external support, such as reactive power compensators [11], [13].

Variable speed wind turbines are able to operate at variable speed and extract a maximum power for each wind speed by using maximum power point tracking (MPPT) technique [14]. MPPT produces when the power coefficient of wind turbine achieves the maximum tip speed ratio and the pitch angle is zero. Generally, the MPPT technique is applied when the wind speed is lower than the rated speed, and if wind speed is greater than the rated speed, then output power of the wind turbines is controlled by the pitch angle control. Pitch angle control is used to limit the output power of the wind turbines within their rating [15]. Power converters are used to regulate the frequency and the output voltage of wind turbine, such that it becomes equal to that of the AC grid, in the variable speed wind turbines [16]. Moreover, they provide a possibility for wind turbines to regulate active and reactive power to/from an AC grid, and improve the power performance and the stability of wind turbines [11]. In variable-speed wind turbines, use power converters can be assisted to mitigate power and voltage variations and improve the power quality to weak AC grid [12], and to reduce the impact of a weak AC grid on wind turbine performance. Hence, the impacts of weak AC grids on the performance of variable-speed wind turbines will be highlighted in detail in this work.

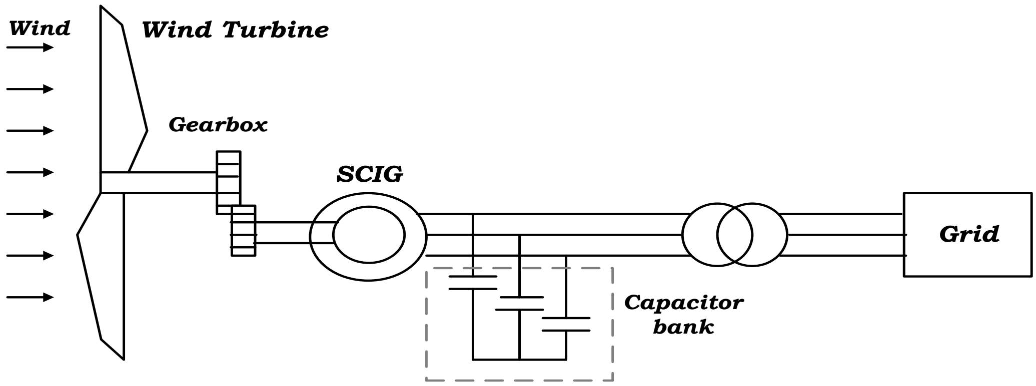


Figure 1- 2: Fixed-speed wind turbine with a SCIG

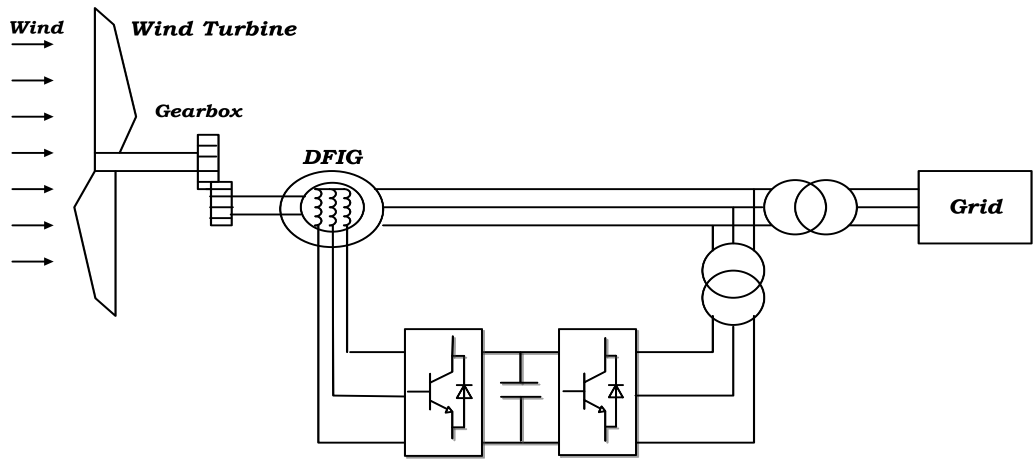


Figure 1- 3: Variable-speed wind turbine with a DFSG

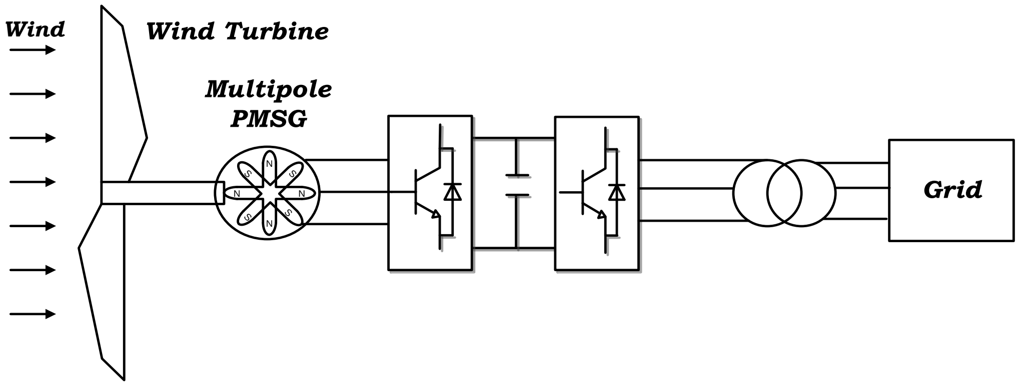


Figure 1- 4: Variable-speed wind turbine with a PMSG

1.2.3 Grid connection

Due to the fluctuation of wind power, the connection of wind farms to AC grids has become a crucial issue in the research of renewable energy. AC or DC transmission systems are used to make the connection to AC grids. Security, stability, power quality and the cost should all be considered in the transmission systems. The connection of a wind farm to the AC grid is possible at low, medium, high, as well as extra high voltage levels. This section will focus on high voltage systems that are used for grid connections.

A High Voltage Alternative Current (HVAC) transmission system can be used for connecting wind farms to AC grids such as sub-sea cable transmission used with distance less than 50 km. It is the most simple and cost-effective connection method [17] [18]. However, HVAC systems have drawbacks, mainly relating to distances of more than 50 km [18], where it is likely that the power losses and costs will increase, and dynamic reactive power compensation will be requested if the AC grid is relatively weak to maintain the AC voltage magnitude within the acceptable limits [1], [12], [19]. Thus, the HVAC transmission systems for the AC grid connection of large-scale wind farms that are located more than 100 km away from the AC grid are not preferred [19], [20], [21].

High Voltage Direct Current (HVDC) transmission systems are preferred over HVAC transmission systems for transmission distances greater than 100 km because they have lower power losses [22]. Further, they can transfer large-scale power over long distances [3]. HVDC transmission systems allow connections to be made to AC grids with different fundamental frequencies [23]. Therefore, they are suitable to connect different countries and continents, and to improve the trade of electric power markets. In HVDC systems, AC grid disturbances are not directly affected by wind farm performance as a result of the decoupling between the wind farm and AC grids [18]. Two different HVDC transmission systems are considered: the first is a Line Commutated Converter HVDC (LCC-HVDC) using thyristors and the second is a Voltage Source Converter HVDC (VSC-HVDC) using Insulated Gate Bipolar Transistors IGBTs. Hybrid HVDC transmission systems using LCCs and current source converters (CSCs) have been used to connect offshore wind farms to AC grids. The CSC is connected to the offshore wind farm and a LCC connects the onshore grid. The CSC has the same features that the VSC for offshore applications, such as reactive power control capability, the ability to operate without an external commutation voltage, a relative small footprint and good performance to AC fault. The LCC has low power losses, low cost, and high possibility to DC faults compared to the VSC, thus the hybrid topology combines advantages from the CSC and the LCC. Moreover, both the CSC and the LCC are current source converters and hence the coupling can be smoothly done [24]. Multi-terminal HVDC technologies based on VSCs or LCCs have also been used to connect large offshore wind farms to main power systems. Those technologies have high reliability and good performance during the steady state and even for severe conditions, such as AC side three-phase faults [25].

Regarding the connection wind farms to weak AC grids, the VSC-HVDC system is a better solution for that connection than the HVAC and the LCC-HVDC systems. The VSC-HVDC system allows active and reactive power to be regulated independently, with the related advantages such as the inherent capability to provide dynamic support to the AC grids, thus it is possible to connect to weak AC grids, and it can provide black start and support system recovery in faults [22]. In addition, the VSC-HVDC system is able to provide a variable active power of the wind farm to the weak AC grid and keep the fluctuations of AC voltages at the point of common coupling (PCC) within acceptable limits [26], [3]. The VSC-HVDC system is more feasible for weak AC grids since VSCs can operate without external commutation voltage like LCCs that are required a robust synchronous voltage for the commutation process, which is provided by a synchronous compensator or a static synchronous compensator (STATCOM) [18]. STATCOM can normally offer fast control and low losses compared with the synchronous compensator [26], [27]. In LCC–HVDC system, the risk of commutation failures is the main problem in connecting to weak AC grids [1], and the large AC harmonic filters, causes over-voltages during fault recovery [12]. Moreover, LCC stations occupy twice of the foot-print of two-level VSC stations due to the size of harmonic filters [24], [28]. The VSC-HVDC system is suitable for connecting two weak ac grids with a novel power synchronization control [23].

1.2.4 Reliability and stability considerations

The existence of wind turbines in a power system causes serious concerns related to the reliability, stability, and security of power systems. Further, power quality problems such as continuous power variations, voltage variations, flicker, and harmonics are another serious concerns that should be considered. Moreover, interruptions of wind turbines and frequency deviations that are associated with both steady state and transient conditions should be taken into account in connection wind turbines to AC grids. Most of these problems can be overcome by carefully choosing the type of wind turbine and its control.

Since most wind farms are located in remote rural sites and are connected to electrically weak AC grids, they are frequently prone to voltage sags, faults and unbalances. Therefore, another issue related to the reliability and stability that should be considered is the strength of the AC grid connected to the wind farm. Power system stability analysis, including voltage, frequency, and angle stability, are essential to the successful operation for that connection in power system. Stability problems increase in weak AC grids [29] as a result of the connection not being reliable, and it is difficult to re-establish the voltage and frequency during a sudden change and/or a large disturbance. In addition, there is constant a risk of voltage and frequency instability. Therefore, some measures should be carried out to improve system stability and reinforce the strength of weak grids [2]. There are two key control methods in wind turbine control systems to improve the integration of the wind farms to weak AC grids: turbine-based control and substation-based control. In turbine-based control, each wind turbine has to have a specific control, such as voltage or power control to enhance the wind farm’s capability in a weak AC grid. In substation-based control, reactive power compensation is either provided by static compensation or dynamic compensation can be used to enhance the integration of wind farms into weak AC grids [30]. Furthermore, there are some regulations for connecting wind farms, which are known as grid codes [31], [32]. Most grid codes require that wind turbine generators be treated as a conventional generator and participate in AC grid voltage and frequency regulations.

1.2.5 Power and voltage performance

The wind is an intermittent and unstable power source, so when wind farms feed weak AC grid, the power supplied to the AC grids becomes difficult [26]. Hence, effective power control and AC voltage control are essential for the connecting wind farms to weak AC grids. As power electronics is not involved in wind farms based on fixed speed induction generators (FSIGs), it is impossible to control either transferred power or voltages without using external reactive power compensators [6]. In a DFIGs system, the converter rating is related not to the total power of the wind generator, but to the slip power; hence, only the slip power is controlled by the converters [11]. In full power converters, the rated power is controlled, and the voltage can be regulated by exchanging the reactive power with the AC grids [33]. However, the main concern of the full power converters is the low reactive power support capability in response to grid faults and an increase wind generation [34]. The importance of power and voltage control emerges when the system is exposed to disturbances, whereby the voltages of the wind farms and the AC grids will be changed; this depends on the type and location of the disturbances. Wind generators may be unable to transfer all of their generated power, and this may result in an imbalance between input mechanical power and output electrical power. This imbalance can make the system unstable. Therefore, an accurate power control is necessary to keep the power equilibrium in the system [12]. Due to the high transmission impedance of weak grids, reactive power support is important to maintain the system's stability. Wind turbine generators may need supplementary control equipment to improve power and voltage control in steady state and transient conditions [35]; this is what will be verified in this thesis.

1.3 Research objectives

Recently it is recognised that the integration of wind power to AC grids is an important, particularly the amount of wind power that can be integrated to the AC grids. So far, there is no specific definition of an acceptable level of integration of wind power into AC grids in the literature. The strength of AC grids may be a standard that defines the acceptable limit of wind power integrated, and it should be taken into consideration when connecting wind power to AC grids. The short circuit ratio (SCR) is an indicator that represents AC grid strength with respect to the amount of wind generation that is interconnected. When the SCR of the AC grids is lower than 3, the AC grids are weak grids. Most of the rich wind sources are far from the infinite bus bar of the interconnection power system, and weak AC grids are electrically far away from that bus bar, thus, wind farms can be classified as being connected to weak AC grids. High impedance with low SCR and low inertia of weak AC grids can limit the amount of wind power that can be connected to AC grids and makes the recovery of the stable operation difficult after fault clearing. Thus, the main aim of this research is to develop a reliable model for wind farms with different control techniques to mitigate negative effects of weak AC grids and to ensure a reliable connection during the increased wind power generation and after the fault clearing with the AC grids. A full power converter-based direct drive PMSGs has been considered in this research. Specific objectives towards achieving the aim are as follows:

- Investigate the main characteristics of weak AC grids and compare to that in the strong AC grids. And investigate the voltage stability limits of the AC grid under different short circuit levels during an increase in the grid load or active power injection from energy source. And also explore how the active and reactive power injection can increase voltage stability limits of AC grids, particularly weak AC grids with low short-circuit level.
- Compare the impacts of the increased wind power generation on the voltage stability of weak and strong AC grids, to identify technical factors of weak AC grids that are limited the transfer of wind power.
- Investigate different control modes in wind farms and various modelling and control issues for reactive power compensation, which include static and

dynamic compensation to accommodate a high amount of wind power generation to weak AC grids.

- ❖ Design a reactive power versus AC voltage control for a STATCOM connected to a weak AC grid to accommodate a high amount of wind power generation.
- ❖ Identify the technical factors that limit wind farms' capability to voltage recovery and to deliver reactive power to the AC grid after a fault has been cleared.
- ❖ Investigate the impacts of the SCR values of AC grids on wind farms during and after a three-phase to ground grid fault. And offer an insight into the capability of the wind farms under different control modes to participate in AC grid voltage support during and after a fault.
- ❖ Design DC chopper control and proposed a new supplementary control for wind turbine's grid side converters for improving transient performance and enhancing Fault Ride Through (FRT) capability of the wind farms are connected to very weak AC grids.
- ❖ Investigate the application of STATCOM on wind farms to achieve the FRT. The results will be compared with the case without employing STATCOM under the same grid faults.

1.4 Thesis outline

The thesis consists of six chapters, as follows:

Chapter 1 outlines the background of wind energy in power system. The effects of wind turbine performance and weakness of AC grid are considered. The AC grid connection is described. Requirements and considerations, such as reliability, stability, power, and voltage performance of connecting a wind farm into an AC grid are discussed.

Chapter 2 contains a literature review of the definition and modelling of weak AC grids. It explains the main factors that affect the performance of connecting a wind farm into a weak AC grid. Some of the challenges for integrating a large-scale wind farm into a weak AC grid are highlighted. The challenges of transient stability for wind turbines connected to AC grid are discussed.

Chapter 3 defines power system voltage stability and demonstrates the classifications of voltage stability. Tools for steady state voltage stability analysis are described, such as P-V and V-Q curves. These curves can be used for analysing a weak AC grid connecting with energy sources under different short circuit levels to determine the steady-state characteristics of weak AC grids.

Chapter 4 investigates the power transmission limitations analytically. The test system model is described in the static model and dynamic model. Definitions and impacts of the reactive power compensators, including static and dynamic compensators, as well as full power converters control are discussed and investigated to increase wind power generation. A reactive power versus AC voltage control is designed in a STATCOM to help a weak AC grid to accommodate a high amount of wind power generation.

Chapter 5 studies the transient stability of connecting wind farms into weak AC grids. Grid codes, including requirements of FRT capability as well as reactive power and voltage control capability—are demonstrated. DC choppers are employed to achieve FRT for wind farms connected with AC grids under different values of the SCR. A new supplementary control in grid side converters (GSCs) is proposed and investigated to improve post-fault restoration capability in very weak AC grids. The effectiveness of the Supplementary control of STATCOM is also investigated.

Chapter 6 outlines the conclusions from the research work in this thesis. It also gives several suggestions for future researchers who wish to continue this work.

Chapter 2

Literature Review

2.1 Introduction

Wind power generation has recently gained massive importance and it has made a rapidly growing contribution to total electricity production in the world. Consequently, the integration of wind power generation into the AC grid is a crucial issue, especially in a weak AC grid. Wind farms are geographically located in areas with rich wind resources which is typically distant from the main power system. Because the location of the wind farms in remote areas, they are typically connected to the AC grids that are relatively weak. Weak AC grids with a high impedance or low inertia can pose serious constraints on the effective utilization of the available wind power. Thus, there are many technical challenges to the successful integration of wind farms into weak AC grids, including power quality, stability, and security system. These challenges are related to the characteristics of the wind farms and weak AC grids.

This chapter has highlighted the definition of weak AC grids and their models. Several technical factors have summarised and discussed that affect the integration of wind farms into weak AC grids. A literature review of the connection of a large-scale wind farm/wind turbine into weak AC grids is presented. Some measures were used to increase the capacity of wind farms connected directly to weak AC grids. The challenges of transient stability of the wind farms connected to AC grids will be discussed, together with the technical solutions; depending on the type of wind turbines that were used.

2.2 Weak AC grids

2.2.1 Definition

Weak AC grids are a part of the power system, which is electrically far away from the infinite bus bar of the interconnection power system [36]. Weak AC grids can be defined as grids that are more susceptible to a sudden change in operating conditions. Any major change in the operating condition leads to a significant voltage and frequency deviation, which could make the system unstable [37]. Whereas strong AC grids have much higher capability to withstand any change in operating conditions, such as power demand and fault condition with a more robust capability to keep a stable operating condition and maintain its voltages, frequency, and other parameters within acceptable limits. Isolated grids can be considered as weak AC grids as well because they have a low inertia and a low regulation capability [38].

Weak grids have low short circuit level compared to strong AC grids, which have a high short circuit level. Weak AC grids can be characterised by a high impedance, low inertia, low damping and poor reactive power support [39], [40]. In AC/DC power systems, the strength of the AC grid is measured with respect to the rated DC power [41], while in wind energy conversion, is measured by the rating of the wind farm [42]. SCR or the Effective Short Circuit Ratio (ESCR) is used to define the strength of the AC grid. The SCR is defined as the ratio of the short circuit MVA of the AC grid at the AC bus bar with the rated DC power in AC/DC power systems. The ESCR takes into account the reactive power generation, due to AC filters. The SCR is a complex number that is inversely proportional to impedance system. However, given that the impedance system is usually highly inductive, the SCR is almost inversely proportional to the inductive impedance system [41]. The standard of values SCR with HVDC are: SCR greater than 3 (strong grid), SCR less than 3 and greater than 2 (weak AC grid) and SCR less than 2 (very weak AC grid), these standards are appropriate for high voltage (HV) [43]. In medium voltage (MV), the AC grid is considered strong for SCR values above 20 [44], [45] or above 25 [46], and the AC grid is considered weak for the SCR equal or less 10 [47].

2.2.2 Modelling

Weak AC grids can be modelled using the following methods:

- A weak AC grid is represented by a voltage source behind a high Thevenin equivalent impedance or long transmission line. The inductance of the weak

AC grid is significantly more than the resistance [48]. This representation is a large grid with infinite inertia.

- A synchronous generator together with a transmission line equivalent is used to represent a weak AC grid. The synchronous generator has quantified electrical parameters, such as rated power, direct/quadrature-axis sub-transient, transient and steady-state reactance. Moreover, the mechanical parameters—such as the moment of inertia, AVR/exciter control system, governor model—must also be specified for dynamic/transient studies [49].

- A weak AC grid can be modelled as a radial grid which introduces a very high impedance [50], this model is usually operated at medium voltage levels with long radial feeders and low X/R ratios [51], [52], [53].

2.3 Factors affecting wind farms connection to weak grids

The most of the previous studies were constrained by the factors such as the SCR, X/R ratio, PLL performance and gains of the controllers, as well as the interaction between the controllers and the interaction between VSCs and weak AC grids that affect the performance in the integration of wind farms to weak AC grids. These factors have a significant impact the stability and security of that integration. Some of the solutions have proposed to mitigate the negative effects of these factors and solutions demonstrated a positive effect.

2.3.1 Short circuit ratio

The SCR represents the amount of active power that can be accommodated by AC grids without affecting the power quality and stability. The SCR has been used to assess the AC grid’s strength for the connection of power electronic converters. Thus, the integration of wind farms to weak AC grids that have a low SCR has led to negative effects, including:

- ❖ To decrease voltage stability limits (critical voltage, maximum active power, and reactive power margins) because voltage stability is affected by both active and reactive power, which is injected into AC grid [54].

- ❖ To limit the generation power capability of the wind farm: An AC grid with a low SCR value has a negative effect on wind farm capability as a result of limiting the transmitted active and reactive powers from the wind farm into the AC grid. The PQ capability of the wind turbine generator is greatly limited compared to the AC grid, which has a high SCR [11], [55] as shown in Figure 2-1. Furthermore, it can be observed that for an AC grid with an SCR of 1.1, it is impossible to transfer rating power if reactive power is not provided by the external reactive power source and/or increasing the power converter rating.

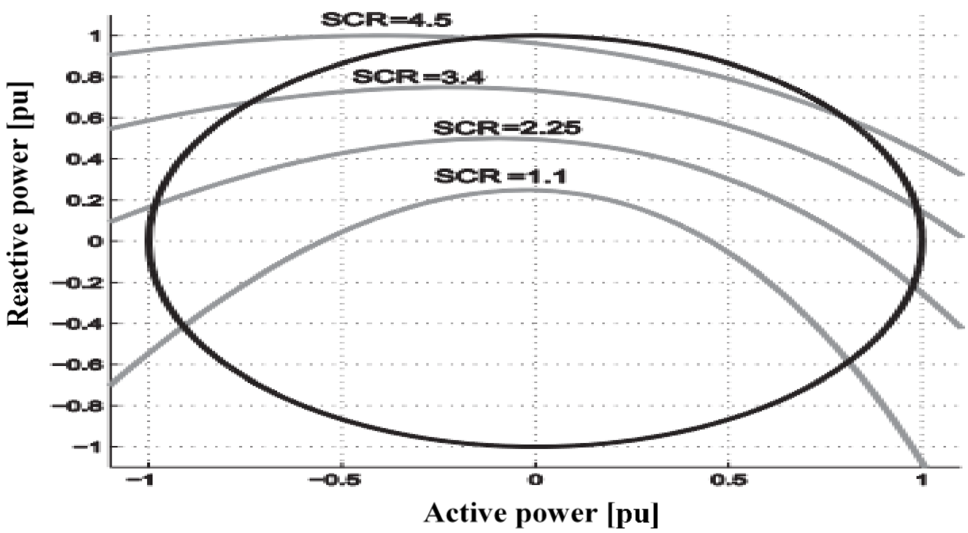


Figure 2- 1: PQ chart for different SCR values at AC grid voltage of 1pu [55]

- ❖ To cause a poor voltage regulation due to large voltage deviation that may result in instability and tripping wind generators, especially in a large-scale wind farm [56], [57].
- ❖ To affect the performance of the converters: The converters that are connected to AC grids can either be a LCC or a VSC.

1) LCCs are current source converters that are made from thyristors that can only be turned on. The term ‘line commutated’ indicates that the conversion process depends on the line voltage of the AC grid to activate the commutation from

one switch to another. LCCs need a strong AC grid to operate properly [58], [17]. The long fault recovery times, high temporary overvoltage, the risk of commutation failure, and low-frequency resonances were consequences of connecting the wind farm to an AC grid that has a low SCR through the LCCs [59], [60], [61] and the system was more prone to voltage instability [42], [62].

2) VSCs can be connected to weak AC grids and that awards them a better advantage compared to LCCs. When the AC grids have a high SCR, VSCs of the wind farm are robust with vector current control strategy, have good performance, and the tracking of their controllers (the power and voltage references) is quick and precise [63]. On the other hand, AC grids with low SCR values influence the stable performance of wind farm converters. One essential issue for the performance of a VSC is the stability of the DC voltage control, which is influenced by the dynamics of the PLL [64]. This issue will be explained in detail in the section, which describes the performance of the PLL and the interaction between the controllers. In addition, the operation of the VSC is greatly influenced by the gains of the PLL. Large PLL gains were detrimental to the VSC stability for the SCR less than 1.6 [65] and it was very difficult with a very low SCR such as 1.3 [66]. Furthermore, the low SCR of the AC grid destabilised the PLL as a result of the complex dynamics of terminal voltage. The fast control and large angle of AC voltage grid result in difficulty for the PLL to track the AC voltage angle correctly, which may make the wind farm grid side converters unstable [63].

- ❖ Transient stability can be endangered in weak AC grids that have low SCR during an AC grid fault. The magnitude of the voltage dip following a fault is too high at the connection point with the AC grid. As a result, the wind farm generators have to be immediately disconnected from the weak AC grid. Thus, the fault ride through (FRT) of the wind generators is a serious challenge, particularly with AC grids that have a low SCR and in large wind farms. To enhance the wind generators’ FRT, the grid codes recommend that wind farms should support the AC grid by producing reactive power during faults and provide fast control to recover normal operation [67]. However, the capability of the wind farm is limited by low SCR.

2.3.2 X/R ratio

The X/R ratio is another factor that can impact on the performance of wind farms with weak AC grids. The X/R ratio is the ratio of the reactance to the resistance of the grid impedance. For a certain SCR, the voltage at the connection point of a wind farm with an AC grid can encounter increment or decrement, based on the X/R value [46]. The voltage at that point is a function of the power flow (active and reactive powers) and the AC grid impedance, which can be represented by the SCR or X/R ratio [46]. The AC grid voltage increases with the growth of the active or reactive power of the wind farm but is more sensitive to an increase in active power with the resistive grid when the X/R ratio is low [37], [68]. The situation is reversed in an inductive grid that has high X/R, where the AC grid voltage readily goes beyond the voltage safe margins, and the system could become unstable when the X/R ratio is more than 2 [53]. In this case, a high reactive power support is necessary to maintain the AC grid voltage within acceptable limits [69].

Flicker is defined as unsteadiness in the R.M.S value of the AC voltage and it is related to power quality [16]. The X/R ratio of the AC grid has a considerable influence on the power quality from wind generators. The risk of flicker increases at low X/R ratio. Depending on the SCR, an X/R ratio of 1.3–2.8 is the most suitable to connect a wind farm into a weak AC grid with fewer flickers and an acceptable voltage level [68].

2.3.3 Performance of PLL

Grid variables such as voltage, phase angle and frequency should be continuously monitored to guarantee correct operation and synchronisation of power converters with the AC grid. Several synchronisation methods have been presented over the years to address concerns such as unbalanced condition and frequency deviation. Vector current control strategy is one of the main strategies of the control for the VSCs. The principle of that strategy is to use a synchronisation unit to track the angle of the AC grid voltage and achieve synchronisation between the converter and the AC grid voltages. The PLL achieves the synchronisation process in vector current control strategy [70]. PLL performs Park transformation to decouple active and reactive components of the voltages and the currents of the converters [63]. PLL can offer fast and accurate synchronisation with a high degree of immunity and insensitivity to disturbances, harmonics, and unbalances for the input signals.

Various modification techniques have been done in PLL to facilitate the appropriate synchronisation technique selection for certain applications. For instance, classic PLL dynamics have a negative impact on the performance of VSC when connected to weak AC grids. Nevertheless, the classic PLL is still well accepted because of its simplicity. Some modifications have been done to improve the performance of PLL in the synchronisation of converters with weak AC grids.

The poor performance of PLL limits the range of power transfer stability for VSCs that are connected to weak AC grids with high impedance. A virtual impedance term in the voltage was introduced in the PLL to virtually synchronise for converter voltages with the AC grid voltages at a stronger point in the grid. The synchronisation has been done to the voltage behind the corresponding virtual impedance. The proposed approach was verified by an analytical model of the system to calculate the achievable steady-state power transfer capability. Small signal stability is also ensured in this approach. Time domain simulations have also been used to verify the proposed control in the Simulink/Matlab tool [71].

Classic PLL causes fake transient frequency when the phase angle of AC grid voltage is changed. Fake transient frequency reflects back on the phase voltages and a delay in the estimation and synchronisation process leads to instability [72]. The reason for this is that the detection of the phase angle and frequency is achieved in the same loop in classic PLL. This may also occur during the start-up operation of the PLL if the initial phase angle of the input signal is far from the initial phase angle of the PLL integrator. Therefore, efficient methods for the detection of phase angle and frequency variation is required to create synchronisation between VSC and weak AC grid voltages [73].

The fast performance of PLL deteriorates the stability of the DC voltage control in VSC when connected to weak AC grids [64]. Therefore, the slow performance of PLL could improve the stability and increase power transfer capability of very weak grid [66]. On the other hand, the slow performance of the PLL allows a large transient phase angle deviation between the PLL and the voltage at the capacitor filter in the case of connecting VSC to a weak AC grid through a LC filter. This results in a slow and less precise dynamic performance for the VSC control. Furthermore, VSCs are unstable due to the destabilisation of the reference voltages of the PLL as a result of the complex dynamics of the weak AC grid voltages [74].

The poor performance of PLL increases the oscillations in output signals of VSC when connected to a weak AC grid with low SCR. In time domain eigenvalue analysis, it has been proven that the damping of the oscillation modes that related to the PLL was the weakest one in that analysis [63], [75].

2.3.4 The controllers' parameters

The vector control technique is based on proportional integral PI controllers, which have been widely used in the industry. PI controllers can successfully eliminate the steady state error in the control system of wind farm converters. Suitable proportional and integral gains of PI controllers are required to achieve better control performance for the wind farm. However, the coordinated tuning of PI controllers is a challenging issue. The gain values of the PLL and outer PI controllers have a significant effect on the performance of wind farm integrated to weak AC grids compared to the gain values of the inner PI controller, which have a limited impact on performance [66], [62]. High gains in the PLL controller lead to the VSCs of the wind farm becoming unstable when connected to weak AC grids. One of the measures that was used to improve and enhance that integration was a reduction the values of PLL gains [76], [44], [58]. The high proportional gain of the AC voltage control and fast power ramp can improve the stability of the active power output of the wind farm converters [77], [78].

2.3.5 Interaction between the controllers

The interaction between the VSC controllers is another technical factor that impacts the performance of a wind farm connected to weak AC grids. Vector current control strategy in VSC includes outer loop control and inner current loop control. The performance of this strategy predominantly depends on the performance of the inner current control. The performance of the inner current controllers depends on the interaction of the outer loop control and the PLL control [79]. In a weak AC grid, the voltages of the point of connection of the wind farm with the AC grid are more susceptible to disturbances from either VSCs side or a weak AC grid side. The VSCs control can affect the AC grid voltage dynamics, which in turn influence on the VSCs control. In spite of DC Voltage control of grid side converter is designed independently without considering the AC grid characteristics but the dynamics of DC voltage control are influenced by other control loops, such as PLL control, reactive power control and AC voltage control, which are related to the AC grid characteristics. However, when the bandwidth of the reactive power controller is closer to that of the DC voltage controller, the impact of reactive power control on the stability of DC voltage control is a maximum and the DC voltage controller becomes unstable. To get a good dynamic performance of DC voltage control, the bandwidth of reactive power control should be a greater or lower bandwidth than the DC voltage control [80]. In addition, the interaction between PLL and DC voltage control is a serious issue in the loss of stability in weak AC grids. The dynamic of PLL is affected by the small signal stability of the DC voltage control. The terminal voltage of VSCs is more sensitive to the power flow variation in a weak AC grid, as well as in VSCs. PLL is influenced by the variations of the terminal voltage of VSCs. DC voltage is controlled through the regulation of d-axis current, which is aligned to the reference voltage of PLL. The active power that is transmitted from the VSCs to AC grid depends on the phase angle of the PLL. Generally, when the phase angle is small, the PLL effect is insignificant. Meanwhile, when the phase angle is around 50°–60° with low SCR of about 1.5, a fast PLL deteriorates the stability of the DC voltage control [64]. In weak AC grids, convergence in the bandwidth of PLL and AC voltage control to DC voltage control in VSCs makes the system unstable because PLL and AC voltage control impact on the active power output and the stability of DC voltage control [81].

2.3.6 Interaction between the controllers and AC grids

The VSC control system should be designed for stable operation under every AC grid condition. The interaction between the AC grid and the VSC controllers is largely dependent on the strength of the AC grid. The strength of the AC grid is a suitable index to predict that interaction [41]. A high grid impedance in a weak AC grid can destabilise the grid side converters’ current control loop and lead to harmonic resonance or instability [82]. Active damping has been used to stabilise the AC grid and avoid harmonic resonance in different AC grid conditions [50].

2.4 Technical issues of connecting large wind farms into weak grid

The Most technical issues of connecting small-scale wind farms into weak AC grids can be overcome by selecting an appropriate wind turbine type and/or by adjusting the wind turbine control parameters. On the other hand, connecting a large wind farm into a weak AC grid has more technical issues such as the reactive power issues, voltage control issues, and dynamic stability [83].

Integrating a large-scale wind farm into a weak AC grid with a high impedance results in the steady-state voltage level falling beyond its acceptable limits and reduces the AC grid stability margin [84], as well as increasing voltage regulation control difficulty [85], [86]. Thus, voltage control and reactive power compensation need to be addressed in planning and developing large-scale wind power plants in areas distant from the main transmission system and load centre [83]. Furthermore, the connection of large wind farms to AC grids through long transmission lines may result in wind power generator supply voltages become unbalanced. Unbalanced voltages in the generator lead to fluctuations in its current, power and torque. These fluctuations can be caused to overcurrent, overheating, and extra mechanical stresses. In this case, wind generators may need to be disconnected from the AC grid. Therefore, a rebalancing control is necessary to improve the wind power generation system in the AC grid.

The FRT of wind generators is also more challenging in connection of weak AC grids with high capacity wind farms. There was a risk of voltage instability that may be initiated by the fault and the AC grid voltage cannot be re-established after removing the fault. The wind farms were disconnected when the uncontrollable voltage dip was developing. In this case, the control of wind farms should be contributed to regulate the reactive power and AC voltage at the fault. The wind generators must be restarted quickly, perhaps before the AC grid voltages have been re-established to contribute to the reactive power control in maintaining transient voltage stability [38].

Recent developments in wind energy conversion systems have resolved some of the problems that were posed from the connection of large wind farms to weak AC grids. Some solutions increase capacity transfer but with very slow response time and some do not guarantee a wide range of operating conditions. Meanwhile, others have neglected important considerations, such as the capacity of the collection system. Several technologies have been used to increase the limit of transferred wind power to weak AC grids, which will be described in the following subsections.

2.4.1 Grid reinforcement

Grid reinforcement is capital intensive but may be unavoidable if required [87], [88]. Grid reinforcement can be used to overcome the voltage fluctuations and maximise the wind power generation [47], [89].

2.4.2 Static reactive power compensation

The two main types of static compensators reported in the literature are: mechanically switched capacitors (MSC) banks and transformer tap changers (TCs) that are used to control voltage profiles through the exchange of reactive power between the wind farm and AC grid [61], [90]. MSC and TCs are relatively inexpensive [91] and they can enhance the AC grid’s voltage stability limit and increase power transfer capability [42], but they are not very sensitive to voltage variations and slow response in the reactive power exchange as a result of absence a controller [92].

2.4.3 Dynamic reactive power compensation

The combination of power electronic converters and control technology with wind generators enables variable-speed wind turbines to work together with weak AC grids. The GSCs' control of wind farms has been used to enhance the stability of weak grids in large wind farms. Reactive power regulation is necessary to stabilise the connection point voltage and allow for high wind power integration into weak AC grids [46], [93]. However, the limited ability of wind farm converters to stabilise AC grid voltage is the main drawback.

Synchronous condensers are shunt compensating devices that use synchronous machines for the provision of dynamic reactive support to AC grids. They have been used to support the integration of large-scale wind generation in weak grids [60], [94] by enhancing the AC system strength and injecting reactive power to support AC grid voltages. Further to this, synchronous condensers enable maintenance of AC frequency deviations under contingency conditions. One potential concern with the application of synchronous condensers is their relatively slow response times [55].

Static VAR Compensators (SVCs) are power electronic components that have proven robustness and which can supply dynamic reactive power with a fast response time. The SVCs are a common solution to the fault ride through and voltage stability issues that are associated with large-scale wind generation integration into weak AC grids [84], [95]. However, an SVC does not decrease the equivalent system impedance and it cannot improve the system strength. Furthermore, the reactive power support provided by the SVC is dependent on the AC grid voltage and thus SVC capability is reduced at low voltages [96].

STATCOMs have been used to enhance the dynamic and steady-state stability of a large scale doubly fed induction generator based wind farm connected to a weak grid [59] and to improve the power quality in a weak AC grid [97].

2.4.4 Energy storage systems (ESSs)

ESSs were used in addition to dynamic reactive power compensation equipment to connect large wind farms to very weak AC grids because they can reduce the challenges of increasing wind power generation and provide smooth output power [98]. However, the cost will be higher than the dynamic reactive power compensation.

However, the serious difficulties posed by large wind farms that are connected to very weak AC grids still required solutions. Research in this area has made slow progress and the need to understand the implications of connecting large wind farms to very weak AC grids is becoming essential.

2.5 Transient stability challenges in wind farms connection

The strength of AC grids has a significant influence on the security and stability of connecting wind farms to AC grids. Grid connection codes in most countries regulate the connection of wind farms to AC grids during a transient condition. For example, during a fault, the wind farm should remain connected to the AC grid to maintain reliability during and after a fault. In transient operation, FRT techniques are necessary to maintain the connection between wind farms and AC grids, and to ensure that there is no generation loss. The quick disconnection of wind generators has a negative impact on the AC grids, particularly with a large wind farm. FRT techniques have to cover several issues, such as AC grid support capability, fault ride through capability, voltage and frequency operating range, and power factor regulation. Therefore, wind farms should contribute to maintain the AC grid voltage and frequency stability by delivering active and reactive power to the AC grids. However, if the wind farms are connected to weak AC grids, the possible disconnection and loss of generation might threaten the wind farms and AC grids stability [99]. Robust techniques for FRT are required to prevent disconnection of wind farms that are connected to weak AC grids during and after the fault. The following subsection will discuss the various challenges of integrating various types of wind turbine generators to AC grids.

2.5.1 FRT Capability of wind turbine generators

Currently, three main types of wind turbine generators technologies used: FSIGs, DFIGs and PMSGs. FSIGs use squirrel cage induction generators that are connected directly to the AC grids. The squirrel cage induction generators absorb more reactive power from the AC grid during a fault and the rotor of the generator will accelerate due to the unbalance between mechanical power extracted from the wind and the electrical power delivered to the AC grids. Hence the generators suffer significantly from AC grid fault conditions. This situation will become worse if these generators connect to weak AC grids. In the removal of the faults more reactive power will be consumed by the generators, preventing the AC grid voltage restoration. If the AC grid voltage cannot be restored rapidly, then the generators will continue to accelerate and consume more reactive power. This process eventually leads to voltage and rotor speed instabilities [100] and the disconnection of the wind generators is required in these conditions. To avoid instability and maintain the wind generators connected to AC grids during and after the fault, reactive power is required to support the AC grid voltage and enhance FRT capability of wind turbine generators. The amount of required reactive power depends on the SCR value and the X/R ratio of the AC grid [101]. In addition, fast control strategies for reactive power support are required to improve restoration normal operation after fault clearing [102].

In DFIGs, there are some drawbacks such as a deficit to provide reactive power to AC grids during the fault. Due to the direct connection of the DFIG stator to the AC grid, the converters are designed to have a slip power equal to 25–30% of the rated power [103], [21]. The second drawback is sensitivity to the AC grid faults; the current passing through the stator winding will be high as a result of the voltage dip in the AC grid voltage during the fault. Due to the magnetic coupling between stator and rotor windings, the rotor currents are also high. High rotor currents could cause problems in the rotor winding as well as in the converter switching. The rotor side converter (RSC) and grid side converter (GSC) are prone to over-currents and over-voltage. These problems cause a blocked rotor side converter [104], [105]. Another drawback in DFIGs is that the overvoltage across DC link generates during the fault as a result of the unbalanced active power in the system [106]. Hence, to minimise the influence of the AC grid faults, FRT techniques and reactive power requirement are required to improve the performance of DFIGs during and after the AC grid fault.

In PMSGs with a full power converter have better FRT capability in comparison with the direct connection of induction generators to AC grids, and DFIGs connection because the wind generator’s operation is completely decoupled from the AC grid. Therefore, AC grid disturbances have no direct impacts on the wind generators. The only essential problem is the overvoltage in the DC link when connected to a strong AC grid. During the fault period, the GSC's capability to transfer the active power from the DC side to the AC grid side decreases proportionally to the AC grid voltage dip, whereas the active power introduced from the wind generators stays at a constant value. Due to the imbalance between the input and output powers of the DC capacitor, the DC link voltage is able to exceed its safety limits and this results in damage to the DC capacitor, and over-voltage pressure on both converters. Therefore, these consequences can force the wind generators to disconnect from the AC grid. Several techniques have been introduced in the literature, mostly by enhancing the FRT capability of wind turbine generators that are connected to strong AC grids. Whereas the techniques of enhancement the FRT capability for wind turbine generators that are connected to the weak AC grids are limited. The next section will describe and demonstrate the benefits and drawbacks of each technique that has been used to prevent disconnection of wind farms from the AC grid and to improve transient performance of the system.

2.5.2 FRT techniques

FRT techniques are required to improve the performance of wind turbine generators during and after the AC grid fault. These techniques include modifying the control of the wind farms' power converters or using external devices to enhance FRT capability of wind turbine generators and to provide sufficient reactive power to support grid voltage during and after the grid faults.

2.5.2.1 Modified power converter controllers

In DFIG system, reactive power support without a voltage dead band and high proportional gain (beyond the current minimum of 2 in German grid code) has been proposed to help to restore the AC grid voltage after fault clearing [107]. Different proportional gains have been investigated to reduce the voltage recovery time, and an increase of the gain of up to 6 is a significant value [77], [108]. Another modification of back-to-back converter control with the DFIGs has been done in the literature—a coordination of reactive and active power injection has been used to improve AC voltage recovery after a fault [109]. Coordination depends on the characteristics of the

AC grid—where the grids have a low X/R ratio, a prioritising active current is used to give AC grid voltage support by injection power during faults. On the other hand, a reactive current prioritises injecting when the AC grid has a high X/R ratio while keeping the rated current of the converter within maximum acceptable limits [109].

Power-synchronisation control strategy has been used to integrate wind farms based on DFIGs in weak AC grids. It contains a power synchronisation loop (PSL) to achieve the synchronisation with weak AC grids at normal operation. During severe AC grid faults, the PSL is unable to substitute for the role of a conventional PLL. Therefore, a backup PLL is necessary to complement the PSL functions during the fault [110].

Full power converters used to connect synchronous or induction generators to the AC grids. In full power converters, WSC control basically regulates the operation of the wind generator [111]. Decoupling the dq axes stator current components manages the active and reactive power of the wind generator independently. Cascaded control loops are used for the inner control and outer control loops. The d-axis reference current is set to zero to get maximum torque at minimum current to reduce the resistive losses in the wind generator, while the q-axis reference current is obtained from the outer active power control, as shown in Figure 2-2. The reference active power (P_s^*) can be determined according to Equation (2.1) [112].

$$P_s^* = P_{max}\frac{v_{sq}}{v_{qe}} \tag{2.1}$$

where P_{max} the maximum power of wind turbine v_{sq}actual AC grid voltage in q-axis, v_{qe} is rated AC grid voltage in q-axis. Thus, P_s^* would be a function of the AC grid voltage and it changes according to the AC grid voltage magnitude. The objectives of the GSC are to adjust the DC voltage and reactive power demand of AC grid. The limitations of this method are that it is used to limit over voltage through the DC link and for strong AC grids.

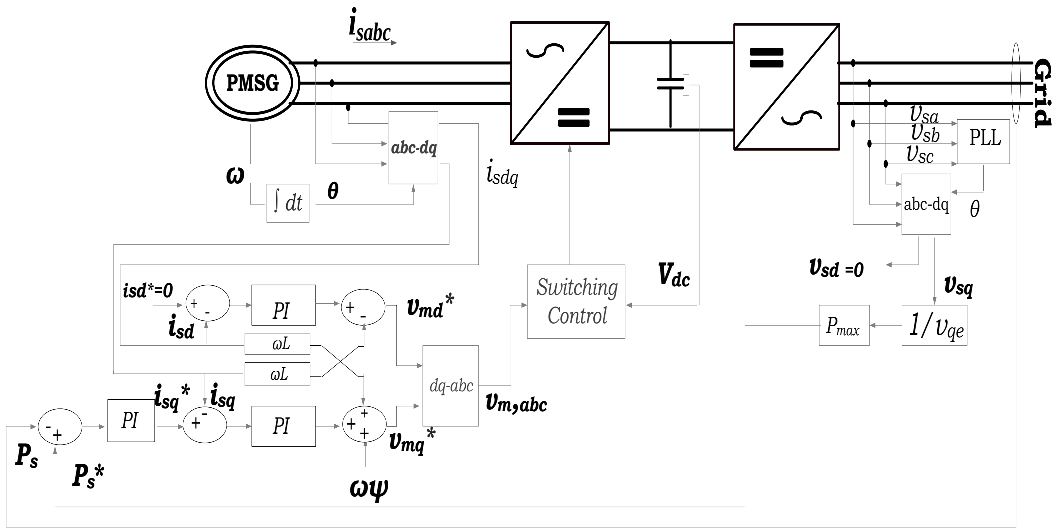


Figure 2- 2: Full power converter control block diagram [112]

Another modification has used in WSC to reduce the generator active power when the DC link voltage reaches a certain threshold by reducing the torque of the generator. The d-axis reference current is set to zero to obtain maximum torque, while the q-axis reference current is obtained from the outer speed control. The DC power at the DC link is used to get a reference speed of the controller from the power-speed characteristic of the generator. The reference torque of the generator is obtained when the error of the reference and actual speed is regulated by a PI controller, as shown in Figure 2-3 [99]. The control is activated when the AC grid power reduces and DC voltage increases. The GSC is responsible to regulate the DC voltage by d-axis current, while the q-reference current is set to zero. The limitations of this method are that it was used to limit overvoltage through the DC link and for strong AC grids.

A boost DC/DC converter was also added in the DC link to maintain a constant DC voltage [113]. Boost converters are used when the WSC designed by diode switching. The boost converter is composed of one power switching device and it uses two control loops. The inner loop regulates the current i_L and the outer loop is used to generate the DC current reference i_L^* and to make the DC voltage constant. The function of GSC control is to track the power reference P_S^* to capture the maximum energy from the wind. The GSC uses two control loops, the inner loop is used to regulate the grid side current while outer loop is used to regulate the output of the wind generator P to track the optimal power P_S^* in order to extract maximum energy from the wind as shown in Figure 2-4 [114].

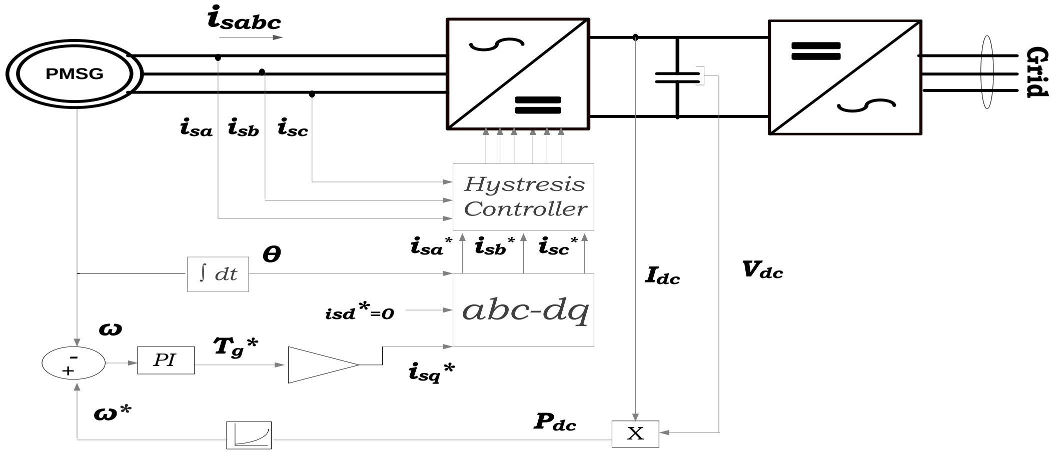


Figure 2- 3: WSC control block diagram [99]

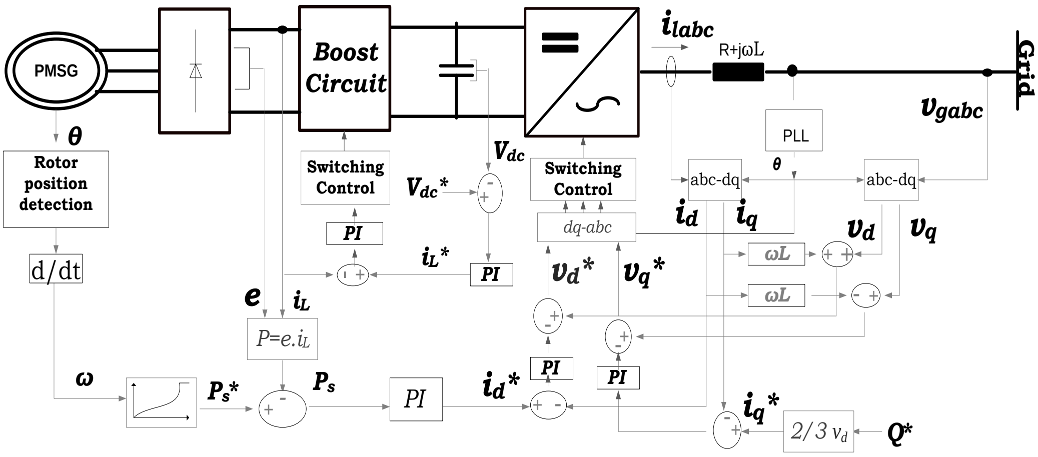


Figure 2- 4: Full power converter control block diagram, including boost converter [114]

An ultra-capacitor bank in parallel with battery storage has been used in the DC link of a full power converter to integrate fixed speed wind turbines into a weak AC grid. AC grid voltage was supported during a fault, and power flow was ensured under normal operation by GSC control. The functions of the WSC control are to limit the generator starting current, provide reactive power, and adjust rotor speed. The current ripples that originate from the switching frequency are reduced and power overshoot is absorbed rapidly by the battery storage [39].

Resizing capacitor is another technique to reduce the extra power at the DC-link during a fault. That power is storing in a larger capacitance, the extra power stored in the capacitor can be explained by Equation (2.2):

$$\int P_C dt = \frac{1}{2} C(V^2 - V_0^2) \tag{2.2}$$

where P_C is the power stored in the capacitor, C is the value of capacitance in Farad, V is the value of capacitor voltage at fault and V_0 is the capacitor voltage pre-fault. Using the numerical example in [115], it is observed that the required capacitance size is directly proportional to the voltage dip magnitude. In addition, the required capacitance size increases when the voltage dip duration increases, which makes the capacitor sizing technique expensive and an impractical solution [99].

2.5.2.2 Using external devices

- Crowbar resistors

A crowbar resistor is inserted into the DFIGs rotor circuit and activated at fault detection to mitigate over-currents and over-voltage of converters [116]. During the fault, the rotor side converter is blocked through the short circuit to the rotor circuit; hence, the control of active and reactive power in the RSC is inactive [117]. In this case, DFIGs operate like a typical induction generator and absorb a large amount of reactive power, which can be risky to the AC grid. Meanwhile, a suitable control strategy in the GSC can improve the AC grid voltage profile and contribute to restoring normal operation before the disconnection of the crowbar circuit.

- Pitch angle control

Control of blade pitch angle is most commonly used to mitigate the power imbalance at fault condition by reduction the wind power in variable-speed turbines. When a reduction of AC grid voltage is detected by the protective relay system, the pitch controller is activated to increase the pitch angle of the blades, β, in order to reduce the power imbalance to the value that can restore the power balance again.

Hence, an increase in β leads to a decrease in the reference active power in the machine side converter control in accordance with the decrease in wind power [11], [112]. Although the pitch control system is the cheapest solution, it has a slow dynamic response due to the mechanical constraints of the actuator and the blade pitching limits. Since the requested β is not delivered immediately, an overvoltage of the DC link is reduced but is not reasonably eliminated to enhance fault ride through [115].

- The DC chopper (braking resistors)

In this technique, a resistor is inserted in the DC link of the converters to dissipate the extra power and restore the power balance at the fault. The resistor is typically controlled using a power electronic switch such as IGBTs [115], [100]. The control scheme for the DC chopper in a wind turbine must be carefully designed to avoid large transients or resistor/switch overheating occurring [115]. The advantages of DC chopper are its low cost and simple control structure [118]. A DC chopper can only dissipate extra power and it cannot increase the reactive power injection to the AC grid. To improve the system performance, DC chopper can be combined with other techniques to improve the fault ride through of wind generators [119], [118].

- Energy storage systems (ESSs)

Generally, ESSs can be added to the DC link by a buck-boost DC-DC converter. When an AC grid fault happens, ESSs can absorb additional power from the DC-link, preventing overvoltage. After fault clearance, the saved energy is injected into the AC grid. Thus, ESSs can be enhanced the FRT capability of wind generators by providing an alternative path for the wind generator currents [120]. In particular, ESSs are more sensitive to fault severity than the type of the fault. When the fault voltage is too deep, high capacity ESSs are required and the cost will be more expensive, which is the main drawback of this technique [99], [9].

- Dynamic reactive power compensators

In wind farms based on FSIGs that are connected directly to weak AC grids, Particular Custom Power System devices (CUPS), such as Unified Power Quality Compensators (UPQCs), have been used to enhance the fault ride through capability of wind generators, and mitigate the voltage instability which result from wind power fluctuations, as well as the load changes [45]. Another compensation strategy based on the Flexible Alternating Current Transmission Systems (FACTS) such as SVC or STATCOM have used to facilitate and mitigate the challenges of integration of wind farms based on FSIG into weak AC grids [121], [102]. SVC can provide a reactive power support to the direct connection between the wind farms and weak AC grids [122]. STATCOM is also used to ensure stable operation and enhance transient voltage and rotor speed stability of wind farms [123]. In addition, STATCOMs connected at the point of common coupling to prevent offline DFIGs during and after the fault, and also to mitigate the effects of transient disturbances [57]. A mechanically switching capacitor bank has also been combined with STATCOM to make the compensation system economical in DFIGs system with the weak AC grids [124]. A coordinated control of the reactive power between the STATCOM and the GSCs of full power converters was proposed to support AC grid voltage and enhance the fault ride through of the wind farm. The GSCs are fully used to provide the reactive power for the AC grid during the fault before activating the STATCOM. Low reactive power of STATCOM capacity was used to enhance fault ride through capability of the wind farm [125]. Another proposed control strategy for supercapacitor energy storage based STATCOM has been used to enhance the fault ride through capability of a wind farm based on variable-speed wind turbines with a full power converter, to mitigate the power quality as well, and to reduce the dip AC grid voltage level during the AC grid fault [7]. For FRT of the wind farm, the most relevant feature of the STATCOM is its inherent ability to increase the transient stability margin by injecting a controllable reactive current independently of the AC grid voltage [126], [121], [120].

Dynamic voltage restorers (DVRs) have also used to enhance FRT capability of wind farms based on variable-speed wind turbines with a full power converter. DVR consists of a three-phase voltage source inverter, an energy storage device, and low pass filter connected in series with AC grid by the transformer. The high voltage side of the transformer is connected to the AC grid, while the low voltage side is connected to the DVR devices. The function of the transformer is to regulate the voltage supplied by DVR converter to the desired level and to keep the DVR isolated from the AC grid. In normal operation, the DVR may either charge the energy storage or inject a small voltage to compensate for the voltage drop on the transformer reactance. In a fault condition, when a voltage dip is detected, the DVR injects a synchronised voltage that is the difference between pre-fault voltage and fault voltage by supplying the real and reactive powers from the energy storage. The injected voltages are synchronised with the AC grid voltage by the PWM applied control strategy. Thus, DVR compensates for AC grid voltage dips and improves FRT capability [127]. In this situation, the GSCs do not sense to AC grid fault using the DVR. However, the DVR is not suitable for deep voltage sag because its capability is not good enough [127] and a specific design is required for the injection transformers which differs from that of a conventional transformer to avoid saturation and high inrush current [128].

In the literature, most investigations of the FRT capability of full power converters into AC grids have not considered the strength AC grids. Thus, investigations of the FRT capability of full power converter based wind turbines to weak AC grids are limited and rare. Consequently, this work will address this topic.

2.6 Summary

This chapter has reviewed the various definitions of weak AC grids that are given in the literature. Weak AC grid models were represented using several different methods, taking weak AC grid specifications into consideration. Several different factors impact on the integration of a wind farm into a weak AC grid and the effect of these factors were studied and summarised. The technical issues of integrating large-scale wind farms into weak AC grids were discussed and the existing solutions were reviewed. A review of the literature related to challenges of transient stability for wind turbines connected to AC grids was highlighted according to the type of the wind turbine. A number of alternative measures to enhance the connection and improve the transient stability of wind farms connected to AC grids were presented. Most of the literature has concentrated on DFIG system or/and direct connection wind turbines to weak AC grids. Whereas, studies of the connection full power converter based wind turbines to the weak AC grids are limited and needed more investigation.

Chapter 3

Voltage Stability Analysis of Weak AC Grid Connections

3.1 Introduction

Power systems operation should be stable and meets the various operational criteria at any time, particularly in the contingency events. The stable and the secure operation of the power systems become an important and challenging issue. Voltage instability is one of the main concerns of the power system, and it is often related to weak AC grids and a heavy load. This chapter will investigate the steady-state characteristics of weak AC grid that limits the voltage stability of the grid and compare to those in a strong AC grid. Voltage stability analysis has been done for the AC grid with different short-circuit levels by using P-V, and V-Q curves. During the grid load increases, comparisons have been done for AC grid under different short-circuit levels with and without an energy source which injects an active power to the AC grid. Weak AC grids can be identified through a low short-circuit level compared to the strong AC grids. Weak AC grids have low voltage stability limits compared to the strong AC grids. The high impedance of the weak AC grids leads to a large voltage variation that limits the stable operation region of the AC grids. Furthermore, an energy source power can help to improve voltage stability limits of the AC grids, particularly the AC grid that has a low short-circuit level.

Grid load is constant, the transferred active power is increased from an energy source, in order to analyse the impact of that increase on the reactive power margin of the AC grid under different short-circuit level. The increase of the active power injected leads to reduce a reactive power margin of the AC grids. However, strong AC grids have a higher reactive power margin compared to that in weak AC grids. The use of reactive power compensators can help to increase reactive power margin of weak AC grids.

This chapter contains the definition of voltage stability and its classifications. Tools for steady-state voltage stability analysis are highlighted such as P-V, V-Q curves. The analysis of the voltage instability of weak AC grids is studied. The test system is described. The simulation results and discussion are demonstrated.

3.2 Power system voltage stability

Voltage stability is defined as the ability of a system to maintain the voltage at all buses within acceptable limits under normal operating conditions and subjected to disturbances [85]. A voltage stable power system is capable of maintaining the post-disturbance voltages near the pre-fault value.

A consequence of an increase in load or a change in system conditions may result in voltage instability of the system. In such a case, the voltage declines or increases progressively and uncontrollably, which may lead to voltage collapse. One of the main reasons for voltage instability is the inability of the system to meet the demand for reactive power [85].

3.2.1 Classification of voltage stability

The classifications of voltage stability are as follows [85]:

- Static voltage stability refers to the ability of a system to maintain steady voltages when subjected to small perturbations, such as incremental changes in the system load. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes. The study period may be a few seconds.
- Dynamic voltage stability refers to the ability of the system to maintain steady voltages following large disturbances, such as system faults, loss of generation, or circuit contingencies. Determining the dynamic voltage stability requires the examination of the nonlinear response of the power system for periods of around several seconds to tens of minutes to capture the performance and interactions of devices, such as motors, on load transformer tap changers and generator field current limiters.

3.3 Tools for steady-state voltage stability analysis

Voltage stability depends on the relationships between P, Q, and V. Therefore, there are different methods for static voltage stability analysis [86], [129]. They are P-V and V-Q curves.

3.3.1 P-V Curve

This is one of the most widely used methods of voltage stability analysis. This gives the available amount of active power margin before the point of voltage instability [86], [129]. A typical P-V curve for the system circuit diagram in Figure 3-1 is shown in Figure 3-2. It represents the variation in voltage at a particular bus as a function of the total active power supplied to the loads. The value of the load active power increases while the value of the load reactive power remains constant in order to plot the P-V curve. It can be seen that at the "nose" of the P-V curve, the voltage drops rapidly when there is an increase in the load demand. Power flow solutions do not converge beyond the critical point, which indicates that the system may become unstable.

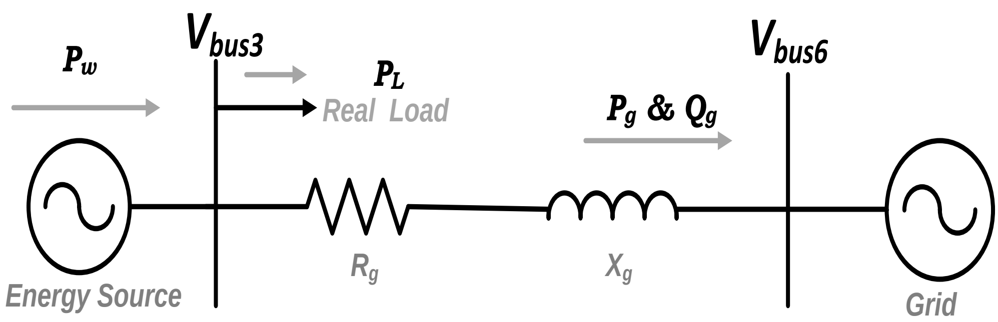


Figure 3- 1: System circuit diagram

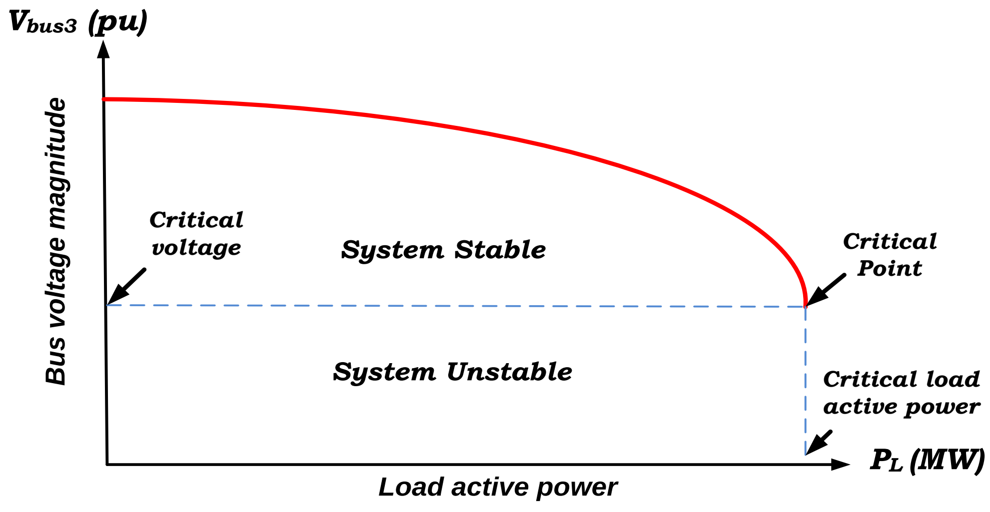


Figure 3- 2: Typical P-V Curve

3.3.2 V-Q Curve

The V-Q curve is a powerful tool to determine reactive power margins of the AC grid. The V-Q curve plots the voltage at a critical bus versus reactive power support on the same bus. A fictitious synchronous condenser with zero active power and no reactive limit is connected to the critical bus. The voltage at a critical bus is scheduled, and the amount of reactive power support from the fictitious synchronous condenser is recorded [86],[129].

The fictitious synchronous condenser is connected to bus 3. Figure 3-3 shows the system circuit diagram. A typical V-Q curve is illustrated in Figure 3-4. The operating points corresponding to zero reactive power are represented; there is no need for reactive power compensation. The reactive power margin is the MVAr distance between the operating point and the nose point of the V-Q curve where dQ/dV becomes zero. When the nose point of the V-Q curve is above the zero horizontal axes, the system is unable to provide reactive power, and so additional reactive power is needed to prevent a voltage collapse [129]. V-Q curves help to determine the stiffness of the bus from the slope of the right portion of the V-Q curve. The high slope is for weak buses whereas the strong buses have a low slope. The V-Q curve also helps to determine the amount of reactive power needed to obtain the desired voltage.

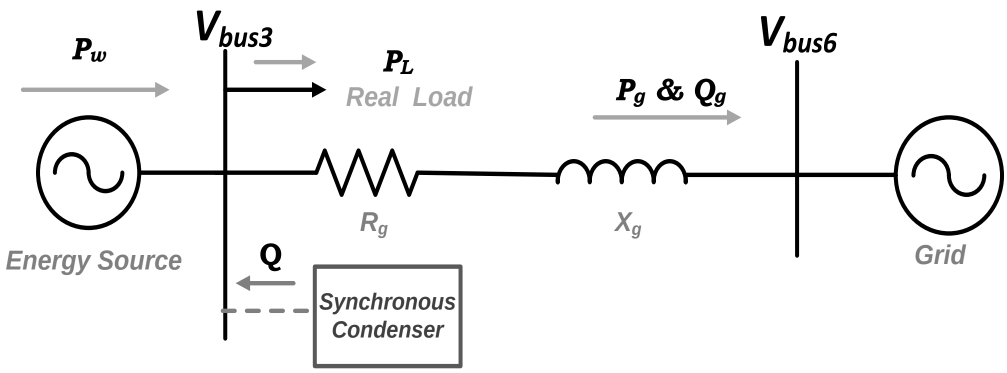


Figure 3- 3: System circuit diagram

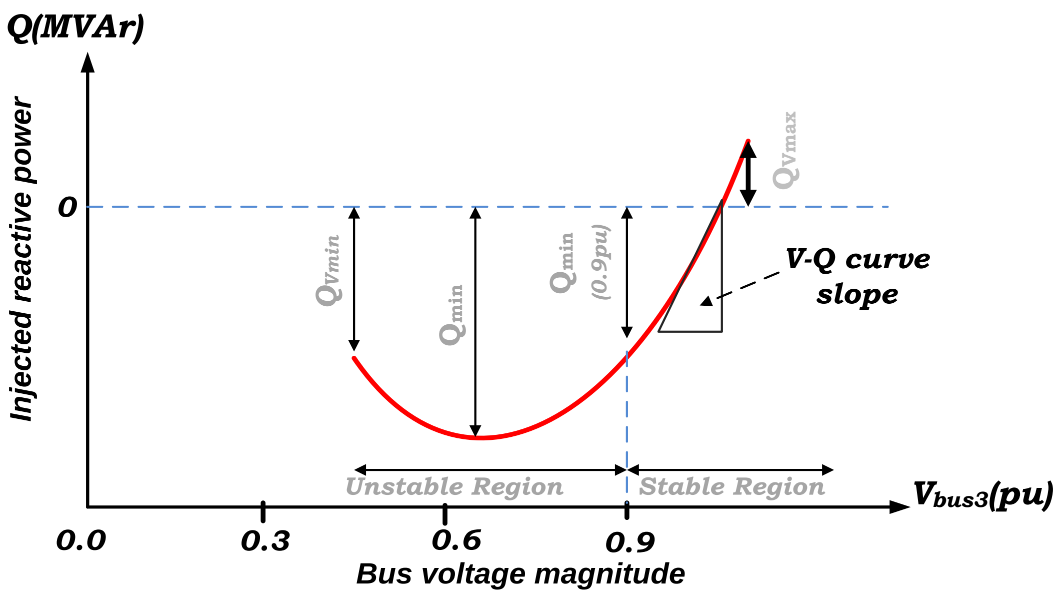


Figure 3- 4: Typical V-Q Curve

3.4 Voltage stability analysis of weak AC grids

AC grids can be characterized by a short-circuit level that is the MVA corresponding to short-circuit current. The short-circuit level is a common measure of the strength of the AC grid to which the energy source is connected [130], [5]. The short-circuit level depends on the rated voltage and the absolute value of AC grid impedance, which can be determined at the connection point with the energy source. A high impedance of AC grids results in the low short-circuit level at a constant rated voltage of a connection point. Thus, a low short-circuit level is usually referred to a weak AC grid [104] while a high short-circuit level is referred to a strong AC grid. In wind power application, the SCR uses as a metric that represents AC grid strength with respect to the amount of wind generation that is interconnected. The SCR is defined as a ratio of the short-circuit level (MVA) of an AC grid (S_{sc}) divided by the nominal MVA rating of the wind farm (S_{WF}) [42].

$$SCR = \frac{S_{sc}}{S_{WF}} \tag{3.1}$$

If system parameters are measured in per unit (pu), the nominal rating of the wind farm is chosen as a base MVA. The SCR can be expressed as shown in Equation (3.2):

$$SCR(pu) = S_{sc}(pu) \tag{3.2}$$

The short-circuit level of AC grid can be written as follows:

$$S_{sc} = \frac{V_g^2}{|Z_g|} \tag{3.3}$$

where V_g is the AC grid terminal voltage in pu (assumed to be 1 pu), and Z_g is the magnitude of AC grid impedance in pu; hence, S_{sc} is

$$S_{sc} = \frac{1}{|Z_g|} \tag{3.4}$$

The AC grid impedance is given by:

$$Z_g = R_g + jX_g \tag{3.5}$$

The magnitude of AC grid impedance is

$$|Z_g| = \sqrt{R_g^2 + X_g^2} \tag{3.6}$$

If the grid resistance is neglected, then the short-circuit level of the AC grid is

$$S_{sc} = \frac{1}{|X_g|} \tag{3.7}$$

Substituting Equation (3.7) in Equation (3.2) yields

$$SCR\ (pu) = \frac{1}{|X_g|} \tag{3.8}$$

Depending on the AC grid reactance, the AC grid is weak with a high reactance resulting in a low SCR. On the other hand, a strong AC grid has a high SCR with a low reactance magnitude. A low SCR or low short-circuit level makes weak AC grids more sensitive to the magnitude and direction of the power flows. The change of power flow causes a progressive and uncontrollable fall of grid voltage that may then lead to a voltage collapse. Therefore, the voltage stability analysis of the weak AC grid connections is an important issue in power system operation and planning. Two aspects of the voltage stability analysis are considered [86].

1. Proximity to voltage collapse
- How close is the system to voltage instability?

Physical quantities are used as a measure of how close the system is to voltage instability, such as load levels, the critical active power flow, and the reactive power reserve.

2. The mechanism of voltage instability is considered in the voltage stability analysis, such as:
- How and why does instability occur?
- What are the key factors contributing to instability?
- What measures are most effective in improving voltage stability?

Weak AC grids have low stability margins compared to strong AC grids; hence, weak AC grids are close to voltage instability [131]. Regarding the mechanism of voltage instability, the main reason behind the collapse of the weak AC grids is insufficient reactive power support. Improving the power factor at the terminal of a weak AC grid by injecting an amount of reactive power from reactive power compensators can enhance the static voltage stability margins of the weak AC grid.

3.5 Simulation results and discussions

In this simulation study, an energy source connected to a power grid having different short-circuit levels was considered. The energy source could be a conventional energy source or a renewable energy source such as a wind farm. The energy source used to inject an active to the AC grids. The effects of the energy source power on voltage stability limits of the AC grid was explored. In order to evaluate the voltage stability limits of the AC grid with respect to the critical voltage variations, critical load active power, and reactive power margin, power flow studies were carried out in the IPSA package. Two case studies were considered. These case studies are an increase of AC grid load with and without the energy source, and an increase in active power of the energy source with keeping the AC grid load constant.

3.5.1 Test System

Figure 3-5 shows the simplified diagram of the test system. It has 6 buses operating at the voltages of 33 kV, 132 kV and 220 kV. The 33 kV energy source bus is connected to the point of connection at 132 kV by a collector cable 10 km long and a 33/132 kV transformer. A load connected to the 132 kV busbar was used to investigate the effect of loading on the transmission network. The 132 kV transmission line of 100 km long is used to connect the energy source and the load to the 220 kV grid. The short-circuit level of the grid bus (bus 3) was varied (150 MVA, 300 MVA, 500 MVA, and 1000 MVA) to investigate the effect of the energy source power on voltage stability. The energy source was represented by a coherent universal machine of 50 MVA rating at unity power factor. In this case, it was assumed that the energy source does not provide any reactive power output. The grid load has increased in P-V curves analysis while active power injection was increased in V-Q curve analysis.

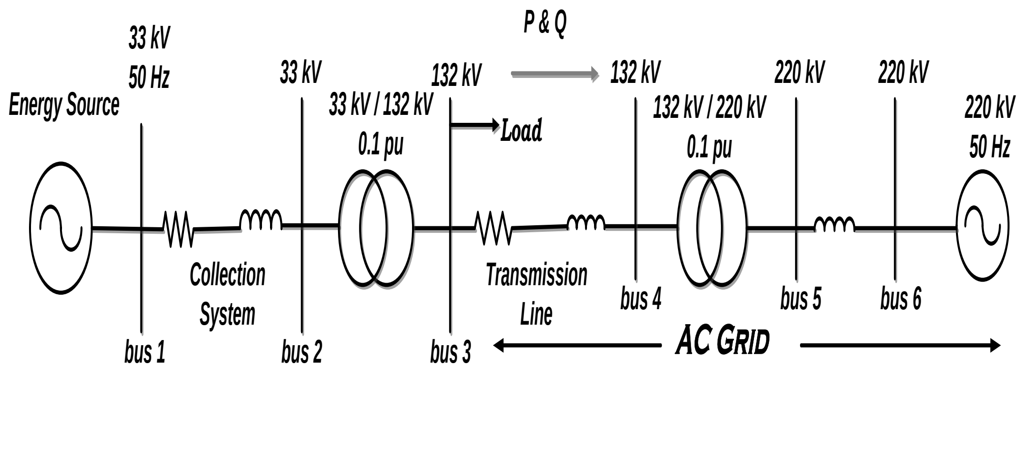


Figure 3- 5: Diagram of the test system

3.5.2 Case studies for the AC grids under different short-circuit levels

3.5.2.1 Case 1: Increase AC grid load

A set of PV curves were generated by carrying out a series of load-flow studies. The active power of the load was increased by keeping the power factor at unity until the power flow no longer converges. Figure 3-6 shows that there has been a steady reduction in the grid bus voltage as a result of increasing the real power demand. Further, it can be seen that the critical load active power and critical voltage significantly varies with the grid short-circuit level. The low short-circuit levels have a minimum critical load active power of 50 MW whereas the critical load active power of the 1000 MVA grid is 114 MW. The voltage variation in weak AC grid with a low short-circuit level is greater than that in strong AC grid with a high short-circuit level grid, thus the weak AC grids have a poor voltage stability limit compared to the strong AC grids. More explanation is given in Appendix A.1.

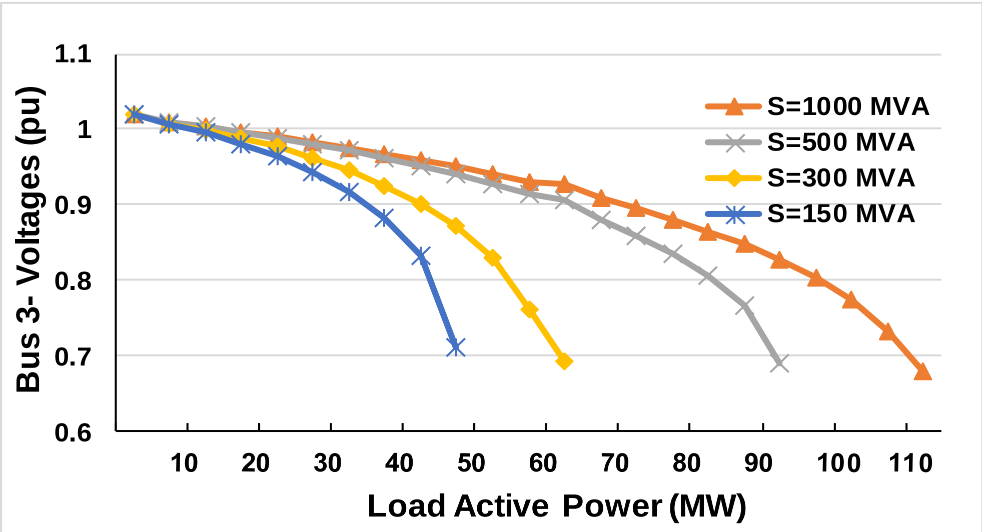


Figure 3- 6: P-V curves of the AC grid without an energy source for different short-circuit levels

Figure 3-7 reveals simulation results with an energy source, it can be seen that there has been a gradual decrease in the voltage of the grid bus bar with the increase in the load active power. However, in a weak AC grid with 150MVA short-circuit level, a different trend has seen at the low load active power levels. The reason why the grid bus voltage has increased with the increase in load active power from 10 to 35 MW in the low short-circuit level grid is described in Appendix A.1.

Moreover, the obtained curves demonstrate the significant influence of the grid short-circuit level on the critical load active power and critical voltage. A grid that has a high short-circuit level has the highest critical load active power and the lowest critical voltage. In contrast, the lowest critical load active power and highest critical voltage are seen in a grid that has a low short-circuit level. The most likely causes of this difference are the level of a short circuit, the voltage variation, and the impedance of the grid as explained in Appendix A.1.

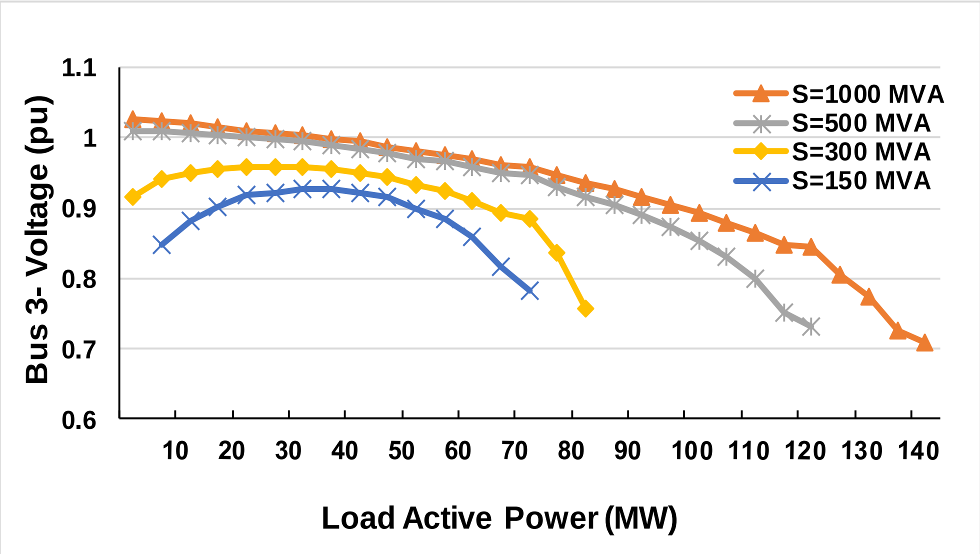


Figure 3- 7: P-V curves of the AC grid with an energy source for different short-circuit levels

Figure 3-8 compares the critical load active power with and without an energy source that injects an active power to the AC grid. As the figure shows, there is a substantial difference in the critical load active power in both cases. The critical load active power with the energy source is greater than without it. In other words, the connection of the energy source can improve the voltage stability of the AC grid by increasing the voltage stability limit. Furthermore, this increase in the voltage stability limit depends on the short-circuit level of the grid. For instance, in the 150 MVA AC grid, the limit of the critical load active power has increased by 44%, while in the1000 MVA AC grid, the limit has increased by 23%.

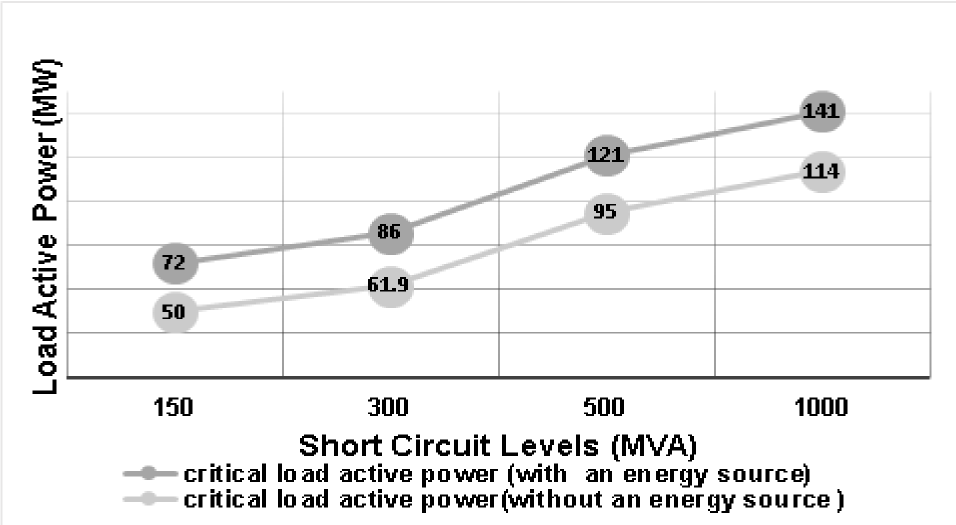


Figure 3- 8: Comparison of critical load active power with and without an energy source

As can be seen from Figure 3-9, the critical voltage with an energy source is higher than without it. It means the existence of the energy source that injects active power can support the voltage of the grid bus through increasing the limit of the voltage stability of the AC grid.

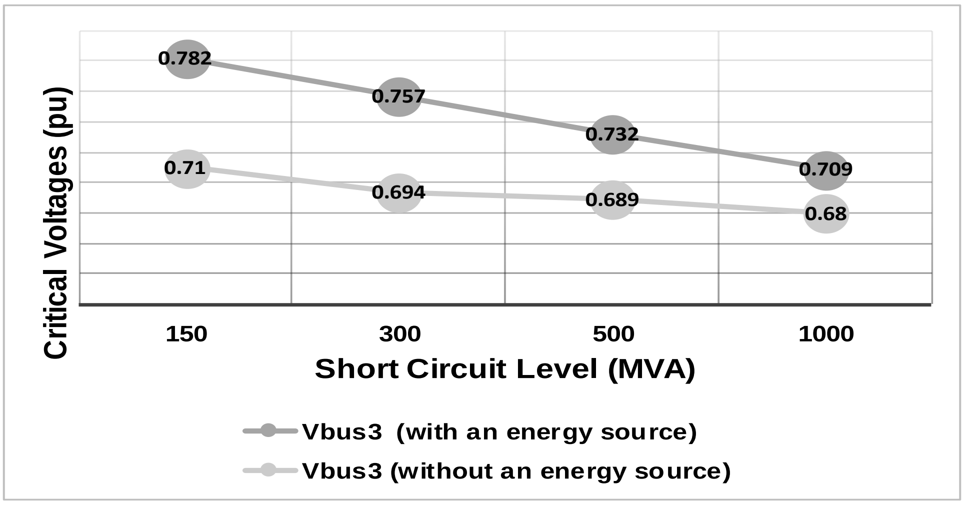


Figure 3- 9: Comparison of critical grid voltages with and without an energy source

3.5.2.2 Case 2: Increase active power generation

V-Q curves were generated by a series of load-flow solutions in the IPSA package. The energy source was connected to the AC grid, which has a short-circuit level of 1000 MVA and 150 MVA. The energy source power of 50 MW and 70 MW were tested, to evaluate the impact of the growth of power injection on the reactive power margin of the AC grid while keeping the load active power constant at 70 MW. The grid bus voltages were scheduled from 0.6 to 1.1 pu, and the reactive power which was generated by the synchronous condenser was recorded. Figure 3-10 shows the V-Q curves of the AC grid. It can be seen that the reactive power margin of the AC grid decreases at increase active power injection. The reactive power margin in active power of 70 MW is lower than in 50 MW for the AC grid, which has 1000 MVA. In AC grid with 150 MVA, the nose of the V-Q curve is above the zero axis (no compensation axis) when the active power injection is 70 MW. It means the system is unstable and cannot operate without any reactive power compensation. Whereas the reactive margin is 27.57 MVAr in a grid with 1000 MVA. Thus, AC grids with high short-circuit levels have a reactive power margin greater than the AC grid with low short-circuit level, that makes the capability of reactive power support of strong AC grids is better than weak AC grids capability.

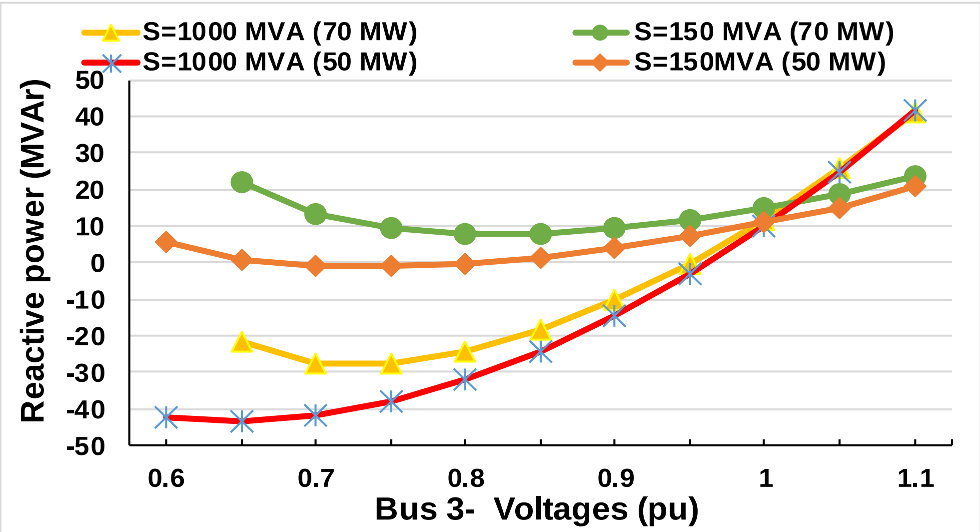


Figure 3- 10: V-Q Curves

Figure 3-11 shows the V-Q curves of a weak AC grid without and with reactive power compensators when the energy source power is 70 MW. A fixed capacitor is used as reactive power compensators in different sizes. It can be seen that the nose of the V-Q curve is above the zero axis in cases of capacitor size is 10 MVAr and without the capacitor, and the system needs more reactive power to operate in a steady-state condition. When the capacitor size is 30 MVAr, the reactive power margin of the weak AC grid has increased to 15.185 MVAr. That means the reactive power injection by the capacitor can contribute to enhance the capability of the weak AC grid in reactive power support.

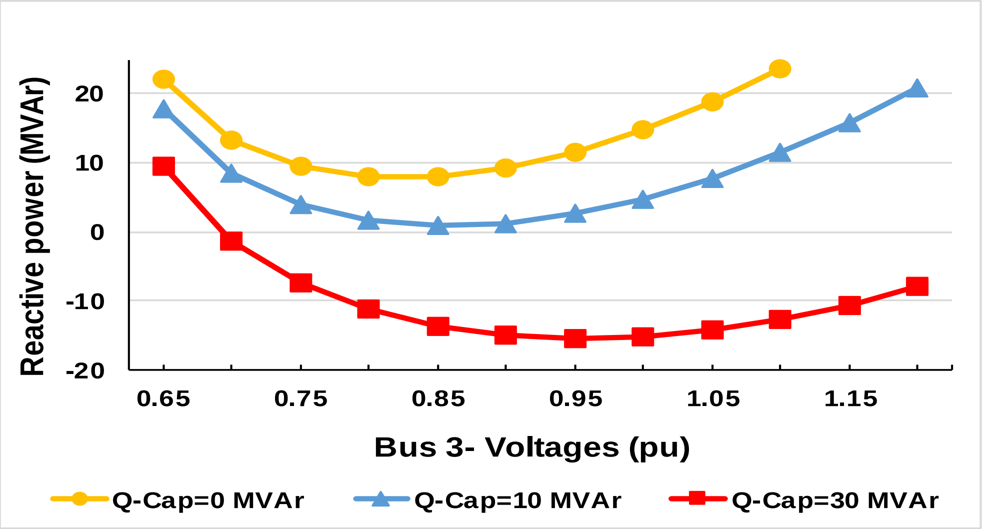


Figure 3- 11: V-Q Curves of weak AC grids

3.6 Summary

A voltage stability of power system has been defined with the classification of voltage stability according to the type of disturbance. Tools that used for voltage stability analysis such as P-V and V-Q curves were highlighted. The voltage stability of weak AC grids was studied. The test system was described and simulation results were discussed. The AC power flow solution was done to analyse the voltage stability of the AC grids under different short-circuit levels. Two case studies were tested: an increase in AC grid load with and without an energy source, and an increase in active power of the energy source with keeping AC grid load constant. Weak AC grids with a low short-circuit level have a poor voltage stability limit compared to that in strong AC grids. A comparison study of the impact of power injection on the voltage stability limits of the AC grid with and without an energy source was presented. The injected active power can help to increase the voltage stability limits of the AC grid, particularly, in a weak AC grid.

Regarding the influence of the increase power injection from an energy source, there was a reduction in a reactive power margin of the AC grid when the active power increases. The strong AC grid has a high reactive power margin compared to that of the weak AC grid. Thus, the strong AC grid has a capability of reactive power support greater than weak AC grids. Weak AC grids suffer from a shortage of reactive power support. The stable operation cannot be achieved for weak AC grid connection in specific operating conditions. Reactive power compensators can be used to support the capability of the weak AC grids and increase grid reactive power margin.

Chapter 4

Steady State Voltage Control of Wind Farms connected to Weak AC Grids

4.1 Introduction

With the increasing connections of large wind farms that comprise of variable-speed wind turbines with a full power converter to weak AC grids, the steady state characteristic of a wind farm connected to a weak AC grid is an important topic for research. Furthermore, integrating wind farms into weak AC grids which are characterized by a high grid impedance with low SCR and its corresponding control system design offers a challenging task for the researchers. Hence, the steady-state analysis of wind farms connected to strong and weak AC grids is analysed and compared in order to identify the factors limiting the transfer capability of the wind farm output. Weak AC grids have not enough support capacity to maintain the operation stability of wind farms. Low SCR of the AC grids is a main technical factor to constrain voltage stability. The steady-state control of full power converters and the reactive power compensators, including the static and dynamic reactive power compensation technologies are investigated to transfer more active power and voltage support in weak AC grids. The full power converters under different control modes were used. Sufficient and local control of the reactive power compensation is required to reduce the voltage stability constraints by the weakness of the AC grids, which can be provided by using external compensators, such as a STATCOM and a SVC.

A STATCOM was connected to AC grids. A reactive power versus AC voltage droop was proposed as an alternative control for the AC voltage control in STATCOM. The AC grids are represented in two models: as the voltage source behind a Thevenin impedance and as a hydro-synchronous generator.

In this chapter, the limiting factors of the AC grid are also discussed analytically and considering the thermal limits and specifications of the converter as well. Static and dynamic simulation models of the test system were developed. The test system including a wind farm, an AC grid, and reactive power compensators. Variable-speed wind turbines with a PMSG and full power converters were used in the wind farm. Reactive power compensators such as a STATCOM, a SVC and fixed capacitor are highlighted. PSCAD simulation results and discussions are also presented.

4.2 Power transmission limitations

The study of the power transmission from the wind farms to AC grids is an important issue when the variable-speed wind turbines with a full power converter are connected to the AC grids. Different limitations for the AC grids and the power converters can limit the transferred power of the wind farm as the following is shown:

4.2.1 AC grid limitations

The strength of the AC grids and the angle of the AC grid voltage play a significant role in the amount of power transferred from the wind farm. The power transfer from the wind farm power is given by (the derivation is given in Appendix A.2). Equation (4.1) shows that the amount of active power transfer to the AC grid is limited by the AC grid impedance. Furthermore, the active power delivered to the grid depends on the angle of the AC grid voltage.

$$P = \frac{|V_g|}{{R_g}^2 + {X_g}^2}[R_g|V_g| - |V_s|.R_g cos\theta + |V_s|.X_g sin\theta] \tag{4.1}$$

where P is an active power transfer to the AC grid. V_s and V_g are a remote point voltage and an AC grid voltage. θ is the angle of AC grid voltage, R_g and X_g are AC resistance and reactance of the AC grid.

4.2.1.1 Angle stability limits

The power transfer is limited by the angle of the AC grid voltage. Using Equation (4.1), the active power transfer with the angle θ for different grid resistance values with X_g, $|V_s|$ and $|V_g|$ equal to 1 pu was obtained and shown in Figure 4-1. The AC grid with

$X_g = 1$ pu is weak according to Equation (3.8), SCR of the AC grid is 1. The reduction in the resistance value limits the power transferred into the weak AC grid.

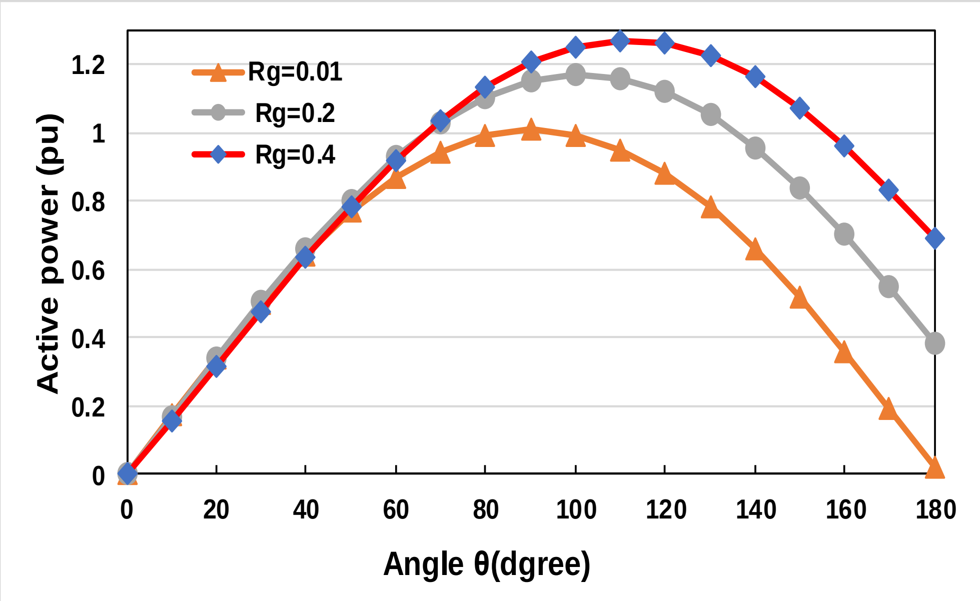


Figure 4- 1: Transferred active power for different grid resistance values

Figure 4-2 shows the active power transfer with the angle θ for different SCR while keeping R_g at a constant of 0.01 pu and $|V_s|$ and $|V_g|$ equal to 1 pu. It is worth noting that the SCR is inversely proportional to grid reactance X_g, as mentioned in Chapter 3. As can be seen, the amount of active power is limited with a low SCR (high grid reactance). Moreover, the angle of AC grid impedance is a function of the grid resistance and the grid reactance, the impedance angle increases with the reduction of the grid resistance or with the increase of the grid reactance. From Figures 4-1 and 4-2, the transferred power is limited by the increase of the angle of the AC grid impedance [55], [44]. However, the effects of the impedance angle and voltage angle of the AC grid are not considered in this work.

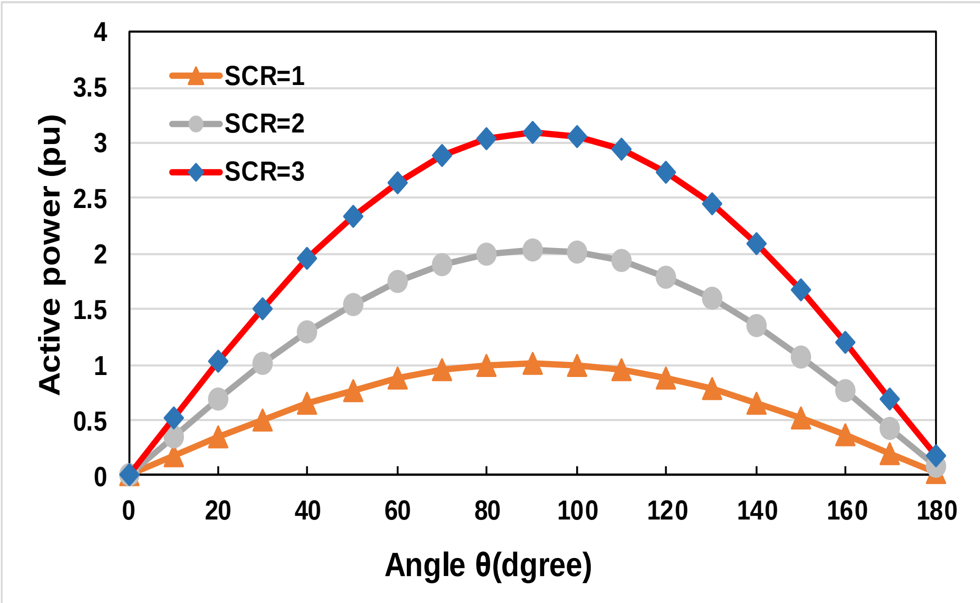


Figure 4- 2: Transferred active power for different grid reactance values

4.2.1.2 Voltage stability limits

To study the voltage stability limits, the voltage operational area for a given grid voltage should be obtained. The reactive power as a function of the transmitted power, grid voltage, and grid impedance, as given in Appendix A.3, is

$$Q = \frac{1}{{R_g}^2 + {X_g}^2}\left(|V_g|^2 . X_g - \sqrt{|V_g|^2\left(2R_gP + |V_s|^2\right)\left({R_g}^2 + {X_g}^2\right) - |V_g|^4 . {R_g}^2 - P^2\left({R_g}^2 + {X_g}^2\right)^2}\right) \tag{4.2}$$

By using Equations (4.2) and (3.8), the PQ curve of the AC grid under different SCRs while keeping R_g at a constant of 0.01 pu and $|V_s|$ and $|V_g|$ equal to 1 pu was obtained and shown in Figure 4-3. As can be seen, very weak AC grids need more reactive power to support their voltage and to accommodate more active power.

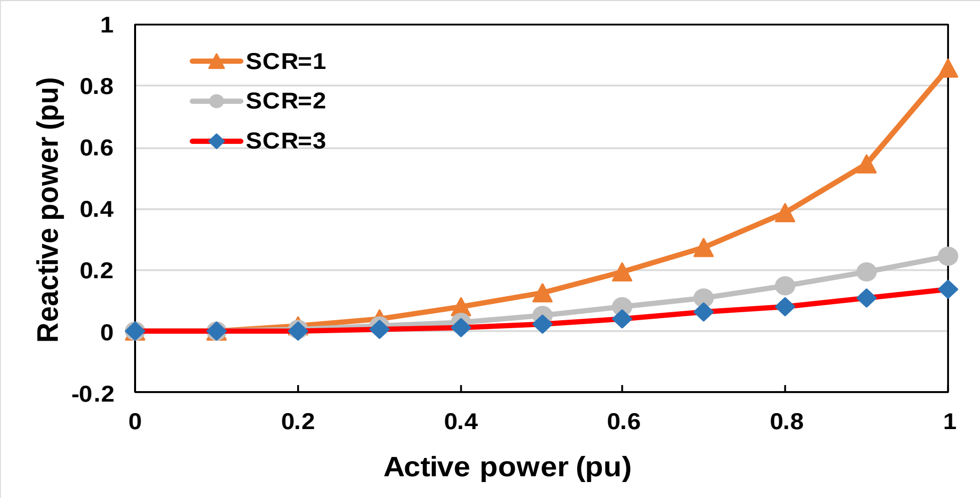


Figure 4- 3: The PQ curve for different SCR values

Figure 4-4 shows the PQ curve for a very weak AC grid with SCR=1 and the grid voltage limits with $\pm$ 10% of the nominal value of 1 pu. The maximum acceptable grid voltage limit required more reactive power compared to the minimum limit, as shown in that figure. In addition, the increase of the wind farm's output required more reactive power to set the AC grid voltage to a certain level. From Figure 4-4, for instance, to transfer 1 pu active power and set the grid voltage to 1 pu, the amount of reactive power required is about 0.9 pu at SCR =1. The AC grid is responsible to generate this quantity of reactive power when the wind farm operates in unity power factor control and it is connected directly to the weak AC grid. If the weak AC grid is unable to provide the required reactive power, it is necessary to use an external source to support the weak AC grid voltage. It can conclude that wind farm is unable to transfer the rated power to very weak AC grids without using an external reactive power compensator. In the case of the wind farm working with a leading power factor or set point AC voltage and connected directly to AC grid, it is impossible to transfer the rated active power because the rating of the wind farm converter is limited according to Equation (4.3).

$$S^2 = \sqrt{P^2 + Q^2} \tag{4.3}$$

where S, P, and Q are power rating, active power, and reactive power of wind farm respectively.

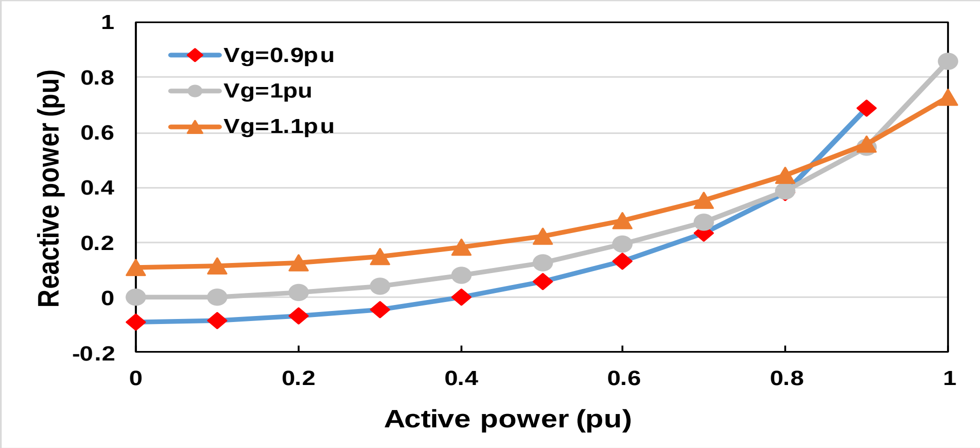


Figure 4- 4: The PQ curve for different grid voltages

4.2.2 Power converter limitations

4.2.2.1 Thermal limits

Power electronic converters are basically made up of power semiconductor devices, which can conduct the electric current and works mainly as switches. These switches have a limited current carrying capability. In the case of it is being exceeded, could lead to the failure of conduction and result in damage to the converter. The increase of the converter's active power results in an increased converter current, which is key to the thermal limits of the converter. Therefore, the maximum current of the converter should be selected at least to supply nominal power in the steady state [132]. In order to avoid the thermal limits being exceeded, the current limiters are used in converter control to limit converter currents within acceptable limits of nominal power.

4.2.2.2 Converter requirements

Typically, the power converters are connected to the AC grid through the phase reactor, which is also used as a filter. High reactance values are necessary to prevent the harmonics from spreading into the AC grid and to improve the dynamic response of the converter [133]. However, the active power injected into the AC grid decreases with the increase of series reactance [134].

4.3 Steady state voltage control and reactive power compensation

Voltage control in the power system is a crucial issue for proper operation and for preventing damage to the electrical power equipment. In addition, it is required to maintain the ability of the power system to withstand and prevent voltage collapse. Full power converters in wind farm and reactive power compensators are important technologies that are used to regulate AC voltage and reactive power control, and to improve stability and the power system performance, especially in weak AC grids [135], [125].

4.3.1 Full power converters control

Variable-speed wind turbines use full power converters to generate active power from the available wind interface of the wind generator terminals to the AC grids. The wind generators can be either induction or synchronous generators. The full power converter provides full control capability for the active and reactive power obtained from the wind generators. Full power converters include two converter station: WSC and GSC. WSC's control regulates the performance of wind generators while GSC's control regulates the operation of wind farms with the AC grids. The GSC can regulate active and reactive power within the apparent power limits of the converters to improve the voltage of AC grids, particularly in weak grids [11]. Thus, the full power converters can be used as a reactive power compensator and they exchange the reactive power with AC grids to regulate grid voltage. Different control modes can be applied in the GSC to regulate the connection point voltage with AC grids, such as a constant reactive power control mode, a power factor control mode, and an AC voltage control mode [136].

- Constant reactive power control mode, which aims to set a quantity of reactive power, which is transmitted to the AC grid to support the grid voltage [137].
- Power factor control mode, which aims to regulate the reactive power of the wind farm according to the magnitudes of the wind farm active and the power factor [136], [137]. A wind farm can operate either at unity power factor or at a leading or lagging power factor.

- Voltage control mode, which aims to keep the wind farm voltage at a set point by the contribution of sufficient reactive power to achieve the desired voltage level [137].

4.3.2 Reactive power compensators

The reactive power compensators can be categorised into static and dynamic compensators.

4.3.2.1 Static reactive power compensators

Mechanically switched capacitor (MSC) bank is one of the static reactive power compensators, which is used to provide fixed reactive power. The MSC is connected in parallel with the AC grid. Their reactive power output is controlled by switching the groups of capacitors in or out of the service. Static compensators are used to achieve local voltage control [138]. The clear limitation of MSC is that the reactive power output is proportional to the square of the voltage of the associated bus [86].

4.3.2.2 Dynamic reactive power compensators

Dynamic reactive power compensators can be changed their output according to the associated bus voltage. They include SVCs and STATCOMs.

- **Static VAR compensators (SVCs)**

SVCs are shunt compensating devices that use power electronic components for the provision of reactive power support [84]. They contain a combination of a capacitor bank or reactors; the capacitor bank is split up into small capacitance stages and is switched on and off individually by a thyristor valve [102]. SVCs regulate locally its bus bar voltage by injecting or absorbing reactive power. However, the disadvantage of using SVCs is that they become less effective with the reduction of the AC voltage level of the AC grid, because SVCs have a constant impedance and their reactive power output decreases in proportion to the square of the AC grid voltage. [139], [140].

- **Static synchronous compensators (STATCOMs)**

STATCOMs are shunt compensating devices that use voltage source inverter to convert a DC input voltage into an AC output voltage in order to compensate the active and reactive power required by the system. Most STATCOMs can inject or absorb reactive power assuming that no active power is exchanged between the STATCOM and the system.

STATCOMs offer fast and continuous control of reactive power for AC voltage support compared with SVCs. Harmonics from STATCOMs are lower than from SVCs' of the same rating. Since STATCOMs do not include large passive components, they have a small physical size. In general, STATCOMs are more expensive than SVCs, but the civil engineering cost of STATCOMs is 80% that of SVCs of the same electrical characteristics as a result of the physical size of the installation of SVCs that influence civil engineering cost [141]. At present, the STATCOM cost seems to be competitive with the SVC [141]. Furthermore, the STATCOM applications have demonstrated a more robust than SVC. By comparing the I-V characteristic of the STATCOMs (red) and the SVCs (green) shown in Figure 4-5. It can be seen that the voltage profile of the AC grid with the SVC and the STATCOM is the same when the SVC and the STATCOM operate in the linear region of their I-V characteristics. When the maximum current limits are reached, the SVC behaves exactly like a fixed shunt capacitor and the maximum compensating current of the SVC decreases linearly with the AC grid voltage. Whereas, the ability of the STATCOM to maintain maximum current limits at low grid voltage is sufficiently more than the SVC. Thus, the operating zone of the STATCOM is greater than in the SVC of identical rating. The STATCOM has better reactive power control than the SVC and it can support AC grid voltage at very low voltage conditions. That makes STATCOM more effective than the SVC in improving the transient stability. Furthermore, STATCOMs have independent control of active and reactive powers, hence they can regulate the active and reactive power of the AC grid.

In wind power applications, the total compensation capacity of the required reactive power can be determined by the desired power factor at the connection point of wind farms to AC grids in normal operation condition, but it is more difficult to determine in fault conditions. The total compensation capacity of the required reactive power depends on the ratio between short-circuit of the AC grids at the connection point to the rated power of the wind farms. However, a required reactive power compensator rating such as a STATCOM rating varies between 30% and 100% of the wind farm power rating to guarantee a stable operation and a successful voltage recovery [123] [142]. In this thesis, the rating of STATCOM is 50 MVA according to Equation (A.16).

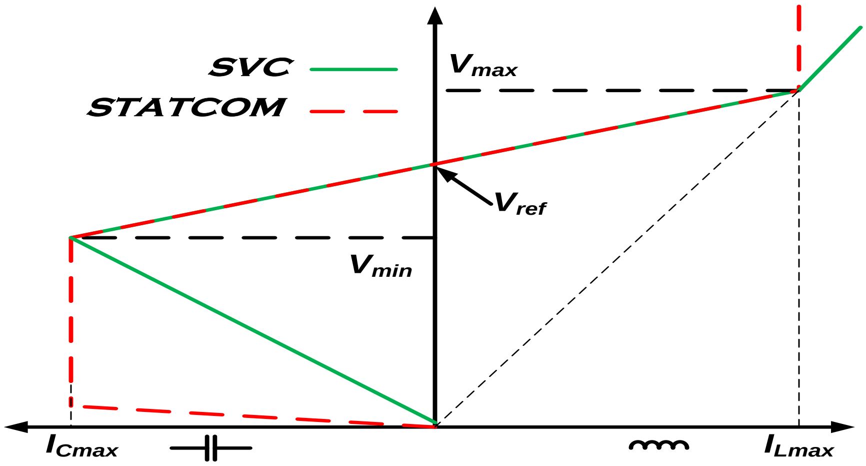


Figure 4- 5: I-V Characteristic of SVC and STATCOM

4.4 Configuration system model

Modeling is a method of simulating real-life situations with mathematical equations to predict the situation’s performance. A system model is a theoretical representation that describes the performance of the system. The system model can be classified into either static or dynamic model as follows:

4.4.1 Static model

A static (or steady-state) model evaluates the system in the time-invariant. The system frequency is also assumed to be constant. Many aspects of the problem can be effectively analysed by using static models, which examine the viability of the equilibrium point represented by a specified operating condition of the power system. The static analysis techniques can provide much insight into the nature of the problem and identify the key contributing factors. The static model of the test system can be described as follows.

- ❖ Wind farms that comprise of variable-speed wind turbines with a full power converter are able to actively take part in the AC grid operation because they can independently control active and reactive power generation; they can operate as a PQ bus, or they can generate active power with AC voltage control as a PV operating bus [143]. Consequently, a wind farm can be assumed to be a PQ bus or a PV bus, depending on the control strategy that the wind farm adopts [144]. This representation of steady-state wind farm models is suitable to load flow analysis [145].
- ❖ Transmission lines are modeled using a constant resistance and inductance.
- ❖ The AC grid is used as a voltage source behind the Thevenin impedance.
- ❖ A STATCOM is represented as a voltage source for the full range of operation, making possible a more robust voltage support mechanism [146]; thus, the STATCOM is operating in voltage control mode. The STATCOM is modeled as a PV bus with the active power output set to zero in steady state analysis [147].
- ❖ A mechanical switched capacitor is modelled by a fixed capacitor with constant reactive power.
- ❖ A static VAR compensator is modelled by several banks of capacitors and reactors switched by thyristors.

4.4.2 Dynamic model

Dynamic models describe the time-varying state of a system. They are typically represented by differential equations.

4.4.2.1 Wind turbine model

In this study, the standard model of a wind turbine available in the PSCAD, wind turbine MOD2, with three blades was used. The power captured by the wind turbine is written as Equation (4.4):

$$P_{Turbine} = \frac{1}{2}\rho\pi r^2 C_P(\lambda,\beta)V_W^3 \tag{4.4}$$

where ρ is the air density [kg/m^3], r is the radius of the wind turbine rotor [m], C_P is the power coefficient, λ is the tip speed ratio of the wind turbine, β is the blade angle with wind speed and V_W is the wind speed [m/s]. The C_p is defined by the following formulae [148], [149]:

$$C_p = \frac{1}{2}\left(\lambda - 5.6 - \frac{\beta^2}{45}\right)e^{-\frac{\lambda}{6}} \tag{4.5}$$

and

$$\lambda = \frac{2.237 * \; V_W}{\omega_H} \tag{4.6}$$

where ω_H angular hub speed

$$\omega_H = \frac{\omega_m}{GR} \tag{4.7}$$

ω_m is the mechanical rotor speed [rad/s], GR is the gearbox ratio.

4.4.2.2 Wind turbine governor model

The wind turbine governor is designed to enable the pitch control to function when necessary. The output is the pitch angle β [150]. The wind turbine governor in the PSCAD library was used, the block diagram of the transfer function is described in Appendix C.

4.4.2.3 PMSG model

The PSCAD/EMTDC software library provides a model of the PMSG. This model is described by the following equations [151]. The voltage equations from the main stator windings in the dq reference frame are as follows:

$$v_{sq} = \mathrm{r_s} \,.\, i_{sq} + \frac{\mathrm{d}}{\mathrm{dt}} L_q \,.\, i_{sq} + \omega_r L_d \, i_{sd} \tag{4.8}$$

$$v_{sd} = \mathrm{r_s} \,.\, i_{sd} + \frac{\mathrm{d}}{\mathrm{dt}} L_d \,.\, i_{sd} + \omega_r L_q \, i_{sq} \tag{4.9}$$

where v_{sd}, v_{sq}, i_{sd} and i_{sq} are the instantaneous stator voltages and currents in the dq-axes reference frame, ω_r is the electrical rotor speed [rad/s], r_s is the stator winding resistance. L_q , L_d Quadrature and direct axes are the stator winding inductance. The motion equation of the generator is given from the equation as [152]:

$$J\frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \tag{4.10}$$

where J is the total moment of inertia [kg.m^2], B is the friction coefficient [N.m.s], T_m and T_e are the mechanical and electromagnetic torque of the turbine [N.m].

4.4.2.4 Full power converters model

The PMSGs are linked to the AC grids through the full power converters; they are a simple structure and have few components, which contribute to a well-proven robust and reliable performance. Vector control techniques have been well developed for full power converters [153]. The proportional integral (PI) controllers are used to regulate the voltages and the currents of the converters. Two vector control schemes are designed for the WSC and GSC. The objective of the WSC controllers is regulates the PMSG speed to achieve the desired power transfer under a given wind condition .This is normally achieved following the MPPT algorithm, while the objective of the GSC control is to keep the DC-link voltage constant and control the reactive power of the AC grids [132].

- **Wind turbine side converter controllers**

Figure 4-6 illustrates the control scheme of the WSC. The dynamic model of the converter in the synchronous dq reference frame is described by the following equations.

$$v_{cd} = Ri_{sd} + L\frac{di_{sd}}{dt} + \omega_r L i_{sq} + v_{sd} \tag{4.11}$$

$$v_{cq} = Ri_{sq} + L\frac{di_{sq}}{dt} - \omega_r L i_{sd} + v_{sq} \tag{4.12}$$

where v_{cd}, v_{cq}, are the instantaneous converter voltages in the dq-axes reference frame, and R and L are the resistance and inductance of converter reactor. It is possible to rewrite Equation (4.10) as follows [154].

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e - B\omega_m}{J} \tag{4.13}$$

The electrical torque of the generator can be expressed as [152]:

$$T_e = -p\psi i_{sq} \tag{4.14}$$

where p is the pole pair number, and ψ is the rotor magnetic flux generated by the permanent magnet. According to the relations stated in Equations (4.13) and (4.14), the speed regulator generates the reactive current reference whereas the active current reference is zero [153], [116], [155], [118].

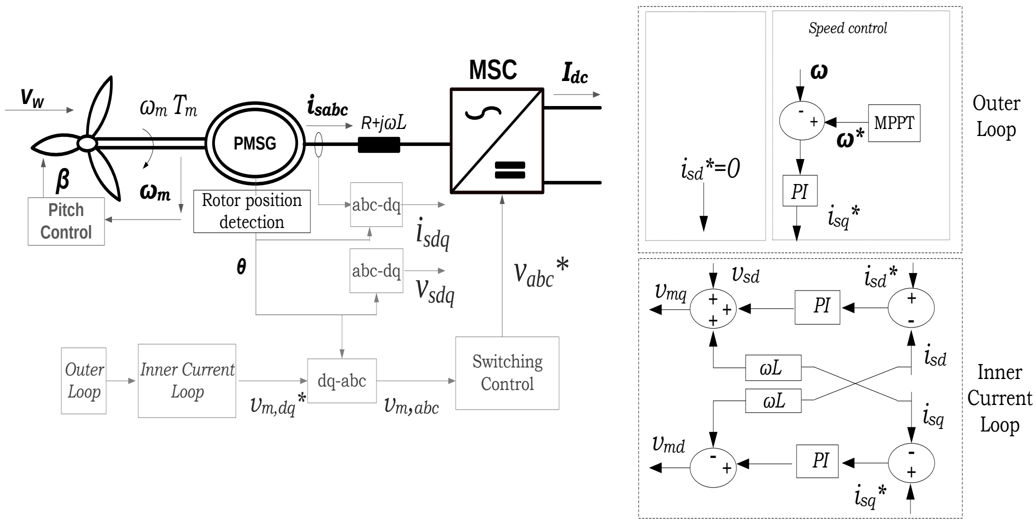


Figure 4- 6: Wind Turbine Side Converter Control Scheme

- **Grid side converter controllers**

The control functions of the GSC are to regulate the DC link voltage and to manipulate the reactive power output to the AC grid. The control scheme is shown in Figure 4-7; a phase-locked loop (PLL) is employed to create synchronization between the voltages of the converter and the AC grid. The dynamic model of the GSC connection, in the dq rotating reference frame, is represented as follows:

$$v_{iq} = Ri_{gq} + L\frac{di_{gq}}{dt} + L\omega i_{gd} + v_{gq} \tag{4.15}$$

$$v_{id} = Ri_{gd} + L\frac{di_{gd}}{dt} + L\omega i_{gq} + v_{gd} \tag{4.16}$$

where v_{id}, v_{iq}, are the instantaneous GSC voltages in the dq-axes reference frame, v_{gd}, v_{gq}, i_{gd} and i_{gq} are the instantaneous grid voltages and currents in the dq-axes reference frame, ω is the angular frequency of the grid voltage. Reactive power control can be achieved by controlling the reactive current reference. An outer DC voltage control is used to set the active current reference for active power control. The DC voltage control is supervising the voltage of the DC link and regulating it to its reference value in keeping the balance of the AC/DC power transformation between the wind generator and the grid converters according to Equation (4.17) [156], [155].

$$C\frac{dV_{dc}}{dt} = \frac{P_s - P_g}{V_{dc}} \tag{4.17}$$

where C is the DC capacitor, P_s is the wind generator power, and P_g is the grid power. The full control parameters of the GSC and WSC, including PI gains, are found in Appendix B.

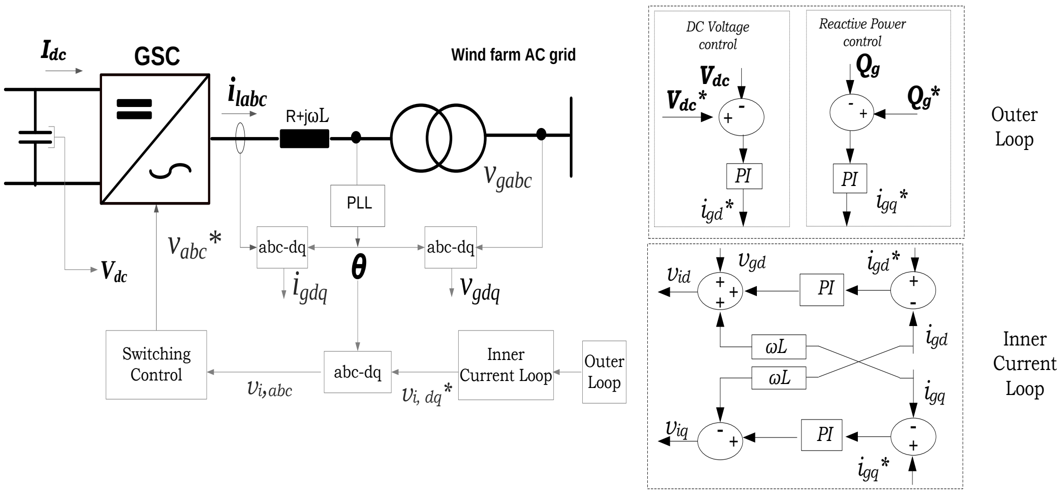


Figure 4- 7: Grid Side Converter Control Scheme

4.4.2.5 Aggregated wind farm model

To reduce the complexity of the analysis, the aggregated wind farm model was used. The wind farm comprises a number of wind turbine generators (WTGs) of the same type. AWTG is usually rated at a low voltage output (690 V). The voltage is stepped up to the medium voltage (33 kV) by a transformer located at each WTG.

Many closely located WTGs are connected in parallel in a group. This group is connected to the collection system, and then to the AC grids through a step-up transformer to the transmission level (132 kV) [157].

4.4.2.6 AC grid model

In the power system analysis, there are two methods to model the AC grids in the simulation of the power system.

- **As voltage source**

An ideal voltage source behind a Thevenin equivalent impedance can be used to represent AC grids and simulate a real-world source of electrical energy [158]. The strength of AC grids is an important property in power system applications. A strong AC grid condition is simulated by low Thevenin impedance while a weak AC grid condition is simulated by high impedance. This model of an AC grid is considered a large grid with infinite inertia.

- **As a synchronous generator**

An AC grid can be represented as a synchronous generator [39] with specified electrical parameters, like a power-rated MVA, and the mechanical parameters, such as the moment of inertia. The automatic voltage regulator, exciter control system and governor model are also specified. Typically, the strength of the AC grid is dependent upon the selection of the rating of the synchronous generator for several reasons. The power rating of a synchronous generator is defined as the maximum power which can be delivered by the synchronous generator safely and efficiently under certain conditions. The high rated synchronous generators can generate more power in a safe and efficient way compared with low-rated synchronous generators; thus, high rated synchronous generators can be referred to as strong AC grids while low-rated synchronous generators can be referred to the weak AC grids. Depending on the transmission impedance, and the voltage regulation of the AC grid bus, The high rated synchronous generators can regulate the grid bus voltage by generating a required reactive power while low-rated synchronous generators are unable to regulate the grid bus voltage [159]. High transmission reactance causes undesirable voltage drops with the increase in the generation; this reduces the AC grid voltage, forcing generators to supply more reactive power to the grid bus to meet the demands of the AC grid. In this situation, the low-rated generators linked to the grid bus will suffer from being overloaded or under-excited. The degree of suffering depends upon the magnitude and direction of the AC grid voltage change [160]. In this way, low-rated generators can behave like weak grids. In addition, the generator rotates at a constant speed corresponding to the base angular frequency to ensure sufficient power quality and to maintain the frequency at a specific value of 50 Hz since the frequency stability is not considered in this work.

4.4.2.7 STATCOM model

The STATCOM is modelled as a three-phase voltage source converter. The control scheme of the converter is shown in Figure 4-8. The dynamic model of the STATCOM converter, in the dq rotating reference frame, is represented as follows

$$v_d = Ri_{ST-d} + L\frac{di_{ST-d}}{dt} + L\omega i_{ST-q} + v_{ST-d} \tag{4.18}$$

$$v_q = Ri_{ST-q} - L\frac{di_{ST-q}}{dt} + L\omega i_{ST-d} + v_{ST-q} \tag{4.19}$$

where $v_{ST-d}, v_{ST-q}, i_{ST-d}$ and i_{ST-q} are the STATCOM voltage and current in the *dq*-axes. ω is the angular frequency of the AC grid. v_d and v_q are the STATCOM converter voltage in the *dq*-axes reference frame. The STATCOM's active (P_{ST}) and reactive power-(Q_{ST}) can be described by the following equations:

$$P_{ST} = v_{ST-d}i_{ST-d} \tag{4.20}$$

$$Q_{ST} = v_{ST-d}i_{ST-q} \tag{4.21}$$

The *d*-axis of the STATCOM control regulates the DC link voltage, and the *q*-axis is used for reactive power control or AC voltage control. A reactive power versus AC voltage droop was designed as an alternative control for the AC voltage control in STATCOM. The magnitude of the terminal grid voltage is measured and compared to the setpoint value. The error voltage is multiplied by a gain constant to obtain the droop control of the STATCOM. The magnitude of the droop K_{VQ} is determined according to Equation (4.25).

$$K_{VQ} = \frac{\Delta Q}{\Delta V} = \frac{Q_{rating}}{V_{rating}} \quad (4.25)$$

where Q_{rating} is the rating of the STATCOM, and V_{rating} is the rated voltage of the STATCOM. The output of the voltage regulation provides the reactive power that needs to be injected to maintain and improve the voltage profile of the AC grid according to the droop set value. The benefit of the droop control strategy is to extend the linear operating range of the STATCOM through the operating slope of reactive power deviation to voltage deviation whereas the AC voltage control operates to set the AC grid voltage to a certain value. Hence it improves the effectiveness of the STATCOM control. However, the AC voltage control is regulated the grid voltage to a certain value such as a 1 pu, and weakness of the AC grid could be limited the possibility to reach to 1 pu, and the voltage controller will be unstable, resulting in the system becoming unstable too.

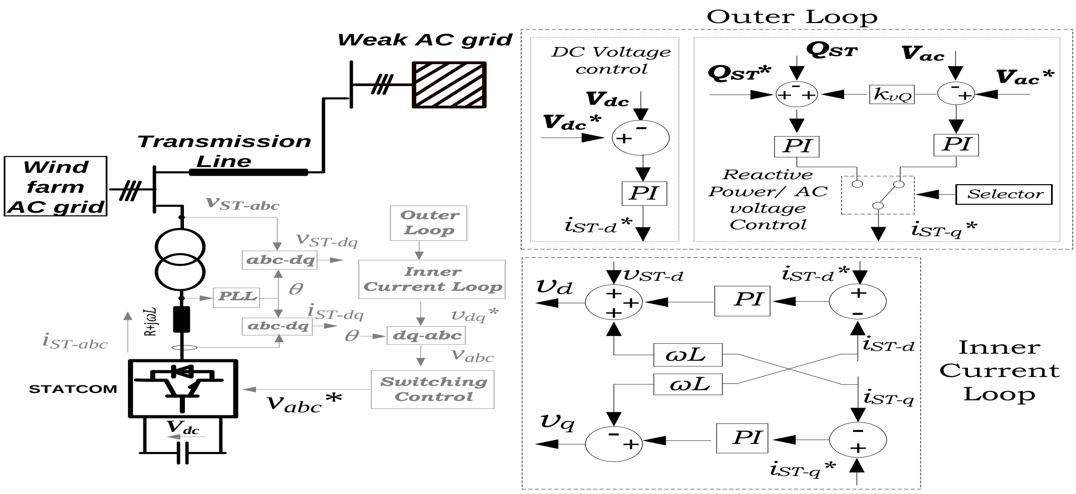


Figure 4- 8: Control structure of the STATCOM

4.5 Simulation results and discussions

Both static and dynamic models of the test system have been applied in analysing the problems of increased wind power generation to the weak AC grids. The test system was modeled using the IPSA simulation tool to simulate the static model. The dynamic model of the test system is simulated by PSCAD simulation tools.

4.5.1 Static model

Power flow solutions have been used in the static simulations to investigate the impact of the capability of GSC control under different control modes on the steady state characteristics of AC grids, especially weak ones, and to demonstrate the effectiveness of the control of reactive power compensation on the voltage profiles of weak AC grids. The capability of reactive power compensators was also tested. The static model was used to establish the initial conditions for the dynamic simulations as well. Figure 4-9 shows the test system which includes wind farm, different reactive power compensation technologies, and an AC grid. Wind farm comprises of variable-speed wind turbines with a full power converter. The test system has 6 bus bars operating at voltages between 33 kV, 132 kV and 220 kV. A 33 kV /132 kV transformer is used to interphase the wind farm (at bus 3) to the weak AC grid through a collection system with a length of 10 km. A 132 kV transmission line with a transmission distance of 100 km is used to connect the wind farm to the 220 kV AC grid.

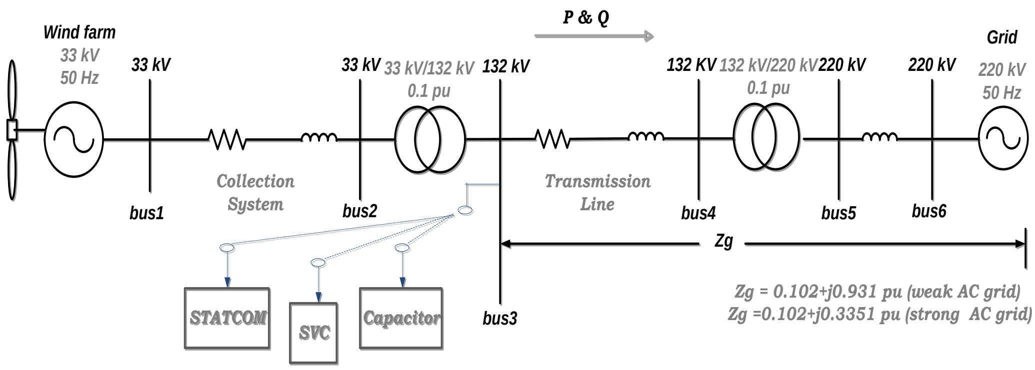
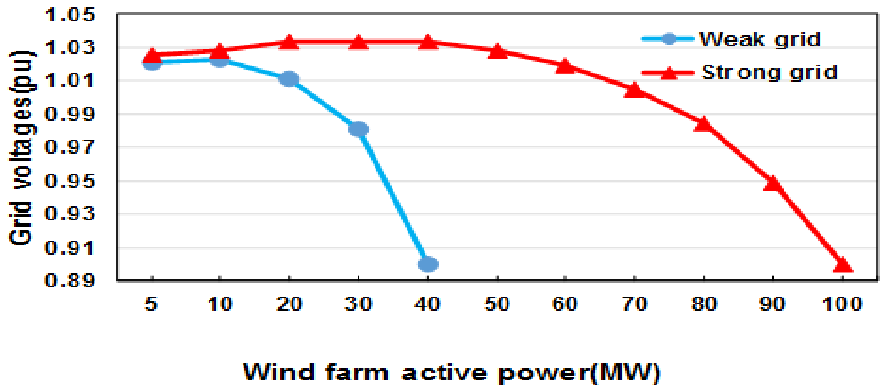


Figure 4- 9: Static Model of Test System

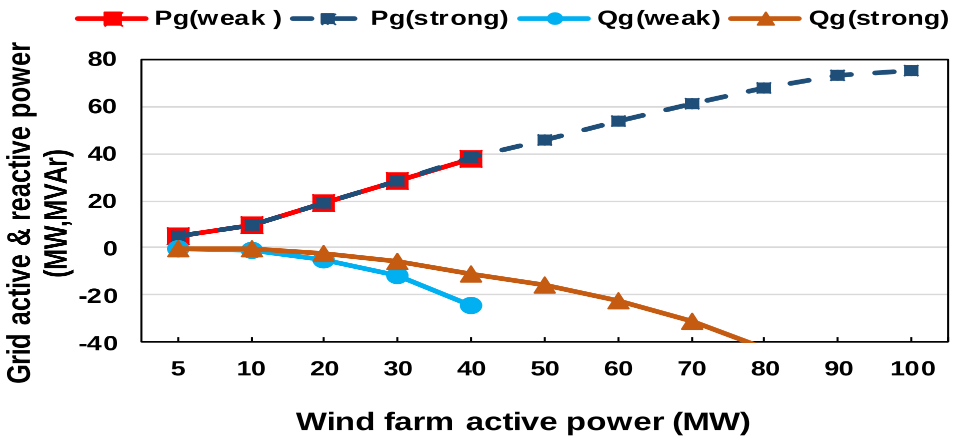
The impedance of the AC grids is 0.102+j 0.931 pu and 0.102+j0.335 pu for weak and strong AC grids respectively. The short circuit ratio at the connection point of the weak AC grid is 1.1 and of the strong AC grid is 3, representing AC grids as a Thevenin impedance behind voltage source [55].

4.5.1.1 Comparison of weak and strong AC grids

The wind power transfer capability is limited by the AC grid voltage. Figure 4-10 shows the P-V curves and the active and reactive power of the AC grids. The PV capability curve is usually presented to measure the proximity of the rated operating condition of a wind farm to the voltage collapse. From Figure 4-10(a), it can be seen that the AC voltage reduces with an increase in the wind power generation. The weak AC grid has a maximum wind power transfer capacity of 40 MW compared with the strong AC grid, which has 100 MW. The rating of a wind farm with the weak AC grid, which can lead to system collapse, is less than the one with the strong AC grid as a result of high transmission impedance with low SCR in weak AC grids. Figure 4-10(b) shows the active and reactive power variation on the AC grid. As wind power capacity increases, the weak grid consumed more reactive power compared to the strong AC grid, whereas the grid active power is approximately the same in both grids. Reactive power variation is the most significant parameter which affects the voltage stability on the test system.



(a) P-V curves for the weak AC grid & the strong AC grid



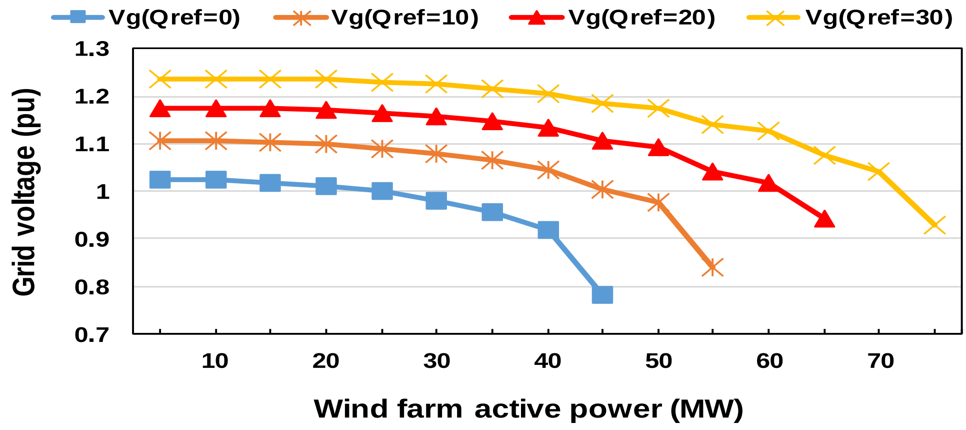
(b) Grid active & reactive power

Figure 4- 10: Simulation results of comparison weak and strong AC grids with unity power factor wind farm

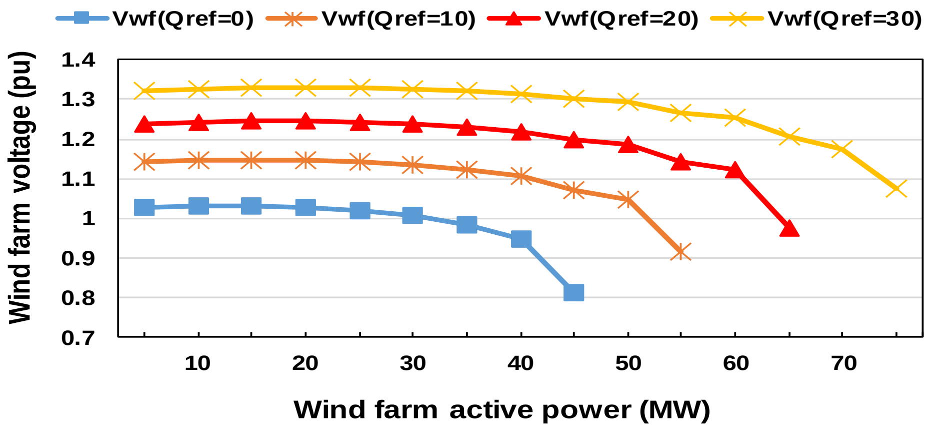
4.5.1.2 Weak AC grids with full power converter control

- **Constant reactive power control mode**

Wind farm operates as a PQ bus. Figure 4-11 shows the PV curves of the weak AC grid and the wind farm voltages with constant reactive power control, the reference of the reactive power for the wind farm is set at 30 MVAr, 20 MVAr, 10 MVAr, and 0 MVAr and wind power was increased. In general, there is a reduction in the grid and wind farm voltages with an increase in wind power generation at fixed reactive power control. It can be seen the high reactive power reference of the reactive power control is allowed to increase the transferred power, but the AC voltage of the weak grid and wind farm will exceed the upper allowable limit. The acceptable values of the grid and wind farm voltages are at a reactive power reference of 0 MVAr, but the amount of power transferred is low compared with the high reference reactive power.



(a) P-V curves of weak AC grid

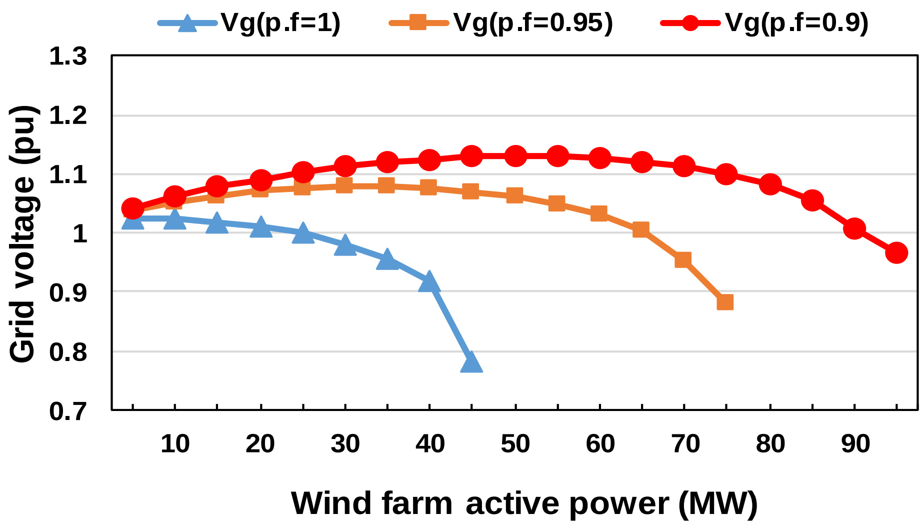


(b) Wind farm voltage

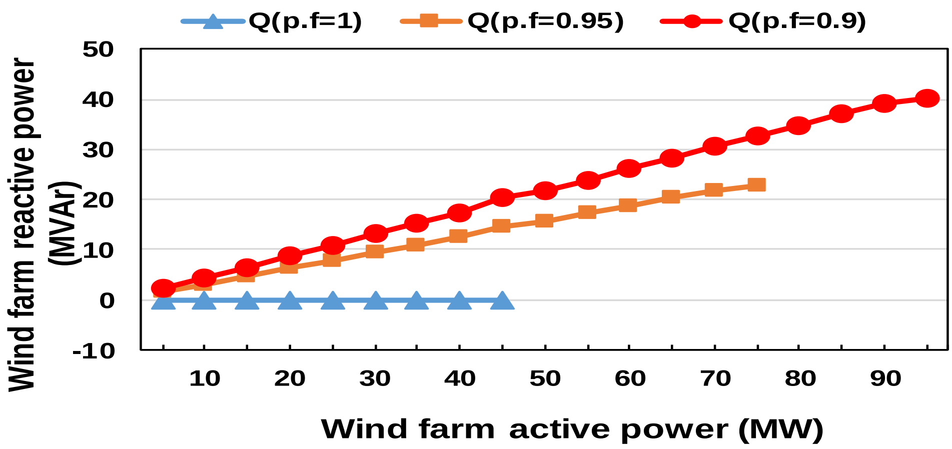
Figure 4- 11: Simulation results of the weak AC grid with reactive power control wind farm

- **Power factor control mode**

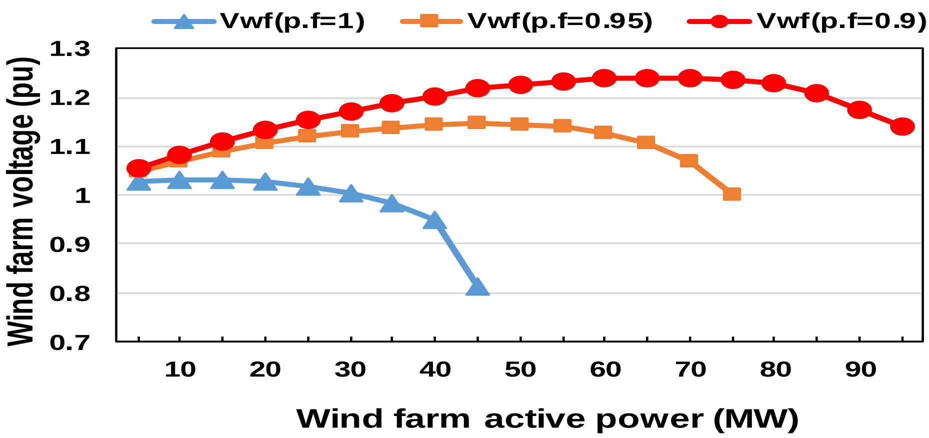
Wind farm operates as a PQ bus. Figure 4-12 shows the simulation results of the effect of increased wind farm output on a weak AC grid voltage when the wind farm is operated with a different power factor control. Figure 4-12(a) shows the P-V curve for a weak AC grid; it can be seen that the capacity of transferred power with a 0.9 power factor control is higher compared to the other values of power factor control, and the critical voltage, which is equal to 0.967 pu, is higher than those at unity and at 0.95 power factor controls. The reason for this is that the wind farm's reactive power under the 0.9 power factor control is more than the power factor control of the others, as shown in Figure 4-12(b). Although the 0.9 power factor control increases the amount of transferred power to the weak AC grid, the weak AC grid voltage go beyond the acceptable limits for the range 25 MW -70 MW wind farm active power. In addition, the wind farm voltage exceeds the allowable limit with a 0.9 power factor control as shown in Figure 4-12(c). The weakness of this strategy of control is that the amount of reactive power that is generated by the wind farm does not take into account the grid reactive power required, or the wind farm and the AC grid voltage levels; thus, overvoltage may occur at the terminal of the wind farm and the AC grid.



(a) P-V curves of weak AC grid



(b) Wind farm reactive power

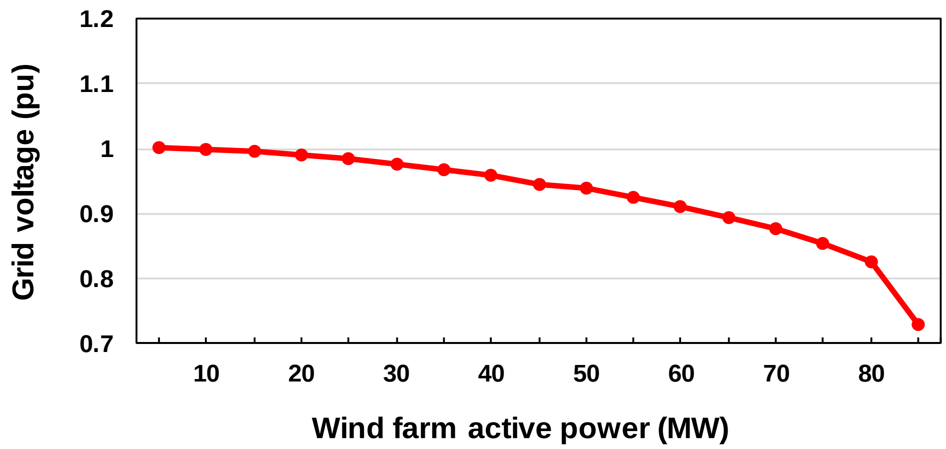


(c) Wind farm voltage

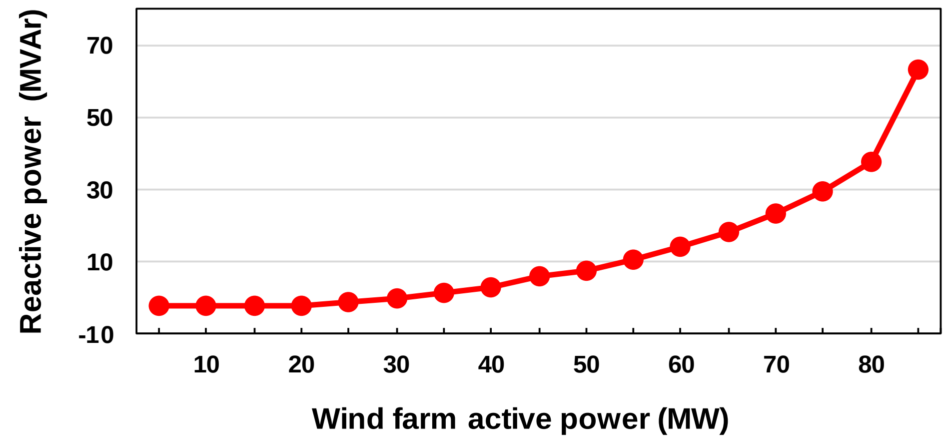
Figure 4- 12: Simulation results of the weak AC grid with power factor control wind farm

- **AC voltage control mode**

Wind farm operates as a PV bus. Figure 4-13 shows the simulation results of the impact of increased wind power generation on the weak AC grid voltages when the wind farm operates with a set point AC voltage control. The P-V curve of the weak AC grid is shown in Figure 4-13(a); as the output of wind farm increases, the weak AC grid voltage reduces. In addition, the reactive power which is generated by the wind farm increases with the growth in wind power generation to set the wind farm voltage to 1 pu, as shown in Figure 4-13(b). The weak AC grid voltage will reach a critical voltage point of 0.73 pu when the real power of the wind farm is increased up to 85 MW and the reactive power of the wind farm is increased up to 63 MVAr. However, the maximum power that can transfer to the weak AC grid within an acceptable limit of grid voltage is 65 MW, and the amount of the wind farm reactive power is 18 MVAr.



(a) P-V curve of weak AC grid



(b) Wind farm reactive power

Figure 4- 13: Simulation results of the weak AC grid with AC voltage control wind farm

4.5.1.3 Weak AC grids with different reactive power compensators

- **Static reactive power compensators**

A fixed capacitor with different sizes was connected to the weak AC grid bus to explore the impact of an increase in wind power generation on the AC voltage of a weak grid. Figure 4-14 shows the voltage of a weak AC grid with an increase in the wind farm output; the AC voltage of the weak grid has been reduced with the increase in output of the wind farm. The maximum connected capacity of the transmitted power from the wind farm increases with a high capacitive compensation, such as 25 MVAr and 50 MVAr, but the weak AC grid voltage is beyond the acceptable limits. On the other hand, 8 MVAr of static compensation enables the capacity of the wind farm to be increased to 55 MW. At the same time, the weak AC grid voltage is maintained within acceptable limits. Thus, fixed capacitors can help to improve the capacity of transferred power into weak AC grid, but they do not have the repeatability of operation that is normally required for the dynamic compensation of the AC grid and absence of the accurate and reliable control. For instance, when capacitor's size is the same as the size of the SVC and the STATCOM, as will be discussed later, the capacitor provides only reactive power without controlling the voltage magnitude at the AC grid bus lead to overvoltage.

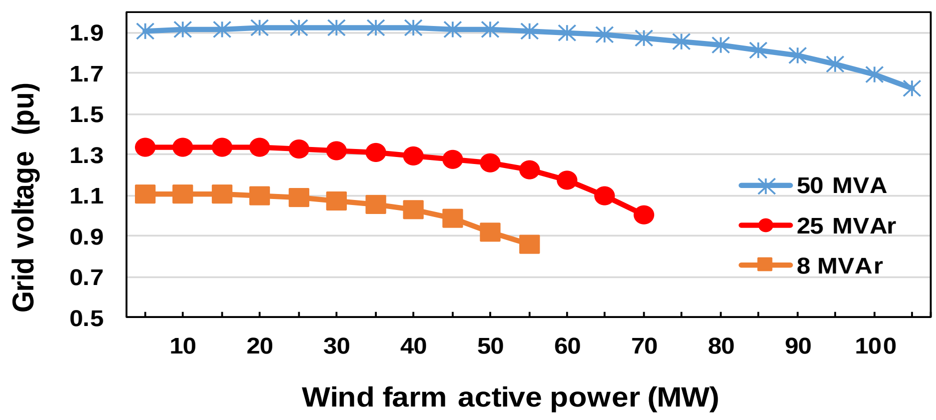


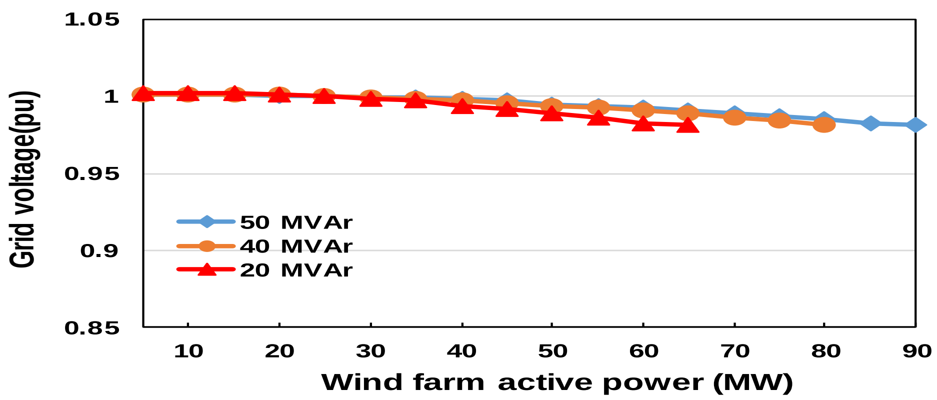
Figure 4- 14: Simulation results of the weak AC grid with fixed capacitors

- **Dynamic reactive power compensators**

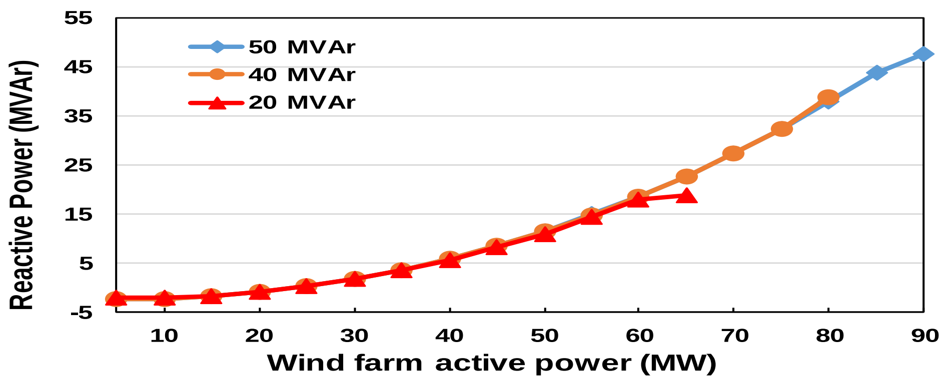
A. SVC

A unity power factor wind farm equipped with a SVC and connected to weak AC grid was simulated. A static model of the SVC was used. The SVC is linked to the weak AC grid bus in order to provide AC voltage support to the weak grid since that location is more appropriate because the voltage deviation is high and needs more reactive power support; 50 MVA, 40 MVA, and 20 MVA is the rating of the SVC. The SVC regulates the AC voltage of the weak grid within a range of 2%.

Figure 4-15 shows the simulation results of the weak AC grid with a wind farm including the SVC. The P-V curves of the weak AC grid with the SVC are illustrated in Figure 4-15(a). In the application of the SVC, the voltage profile of the weak AC grid has improved, and the capacity of a wind farm that is transmitted to a weak AC grid reached 90, 80, and 65 MW with the 50 MVAr, 40 MVAr, and 20 MVAr SVC; beyond these values, no active power can be transferred into the weak AC grid with these rating of the SVC. When the rating of SVC is 50 MVAr, the transferred wind power is greater than in the rating of SVC 40 MVAr and 20 MVAr. Figure 4-15(b) shows the reactive power transferred from the SVC to the system to support the weak AC grid voltage. Due to increased wind power generation, the reactive power that is injected by the SVC increases.



(a) P-V curves of weak AC grids



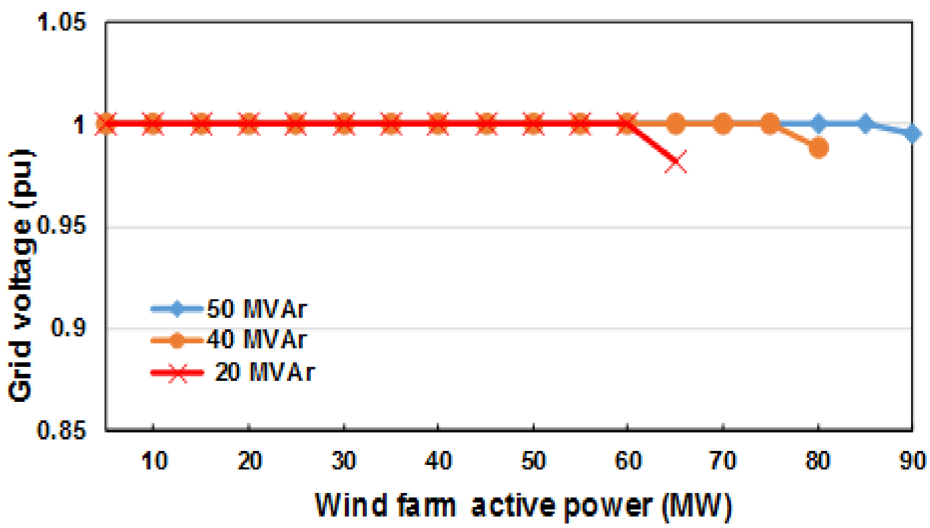
(b) SVC reactive power

Figure 4- 15: Simulation results of weak AC grid with the SVC

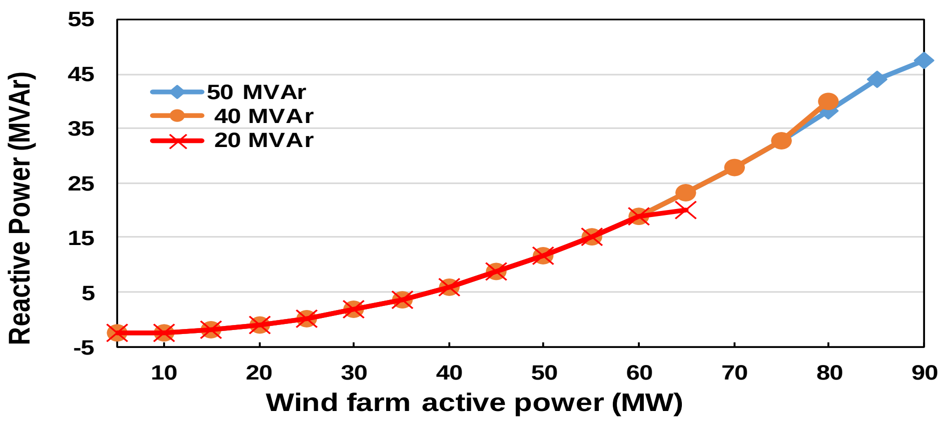
B. STATCOM

The SVC has been replaced by a STATCOM for the purpose of testing STATCOM control in transmitting more active power to weak AC grids. A PV bus was used to simulate the STATCOM with regulating the AC voltage of the weak grid within a range of 2%. The 50, 40, and 20 MVA the rating of the STATCOM were used to mitigate the negative impact of low SCR of weak AC grid in increase the limit of transferring power.

Figure 4-16 shows the simulation results of the weak AC grids with a wind farm including the STATCOM. The P-V curves of the weak AC grid with the STATCOM are illustrated in Figure 4-16(a). In the application of the STATCOM, the voltage profile of the weak AC grid has improved significantly, and the capacity of a wind farm that is transmitted to a weak AC grid increased to 90 MW with the rating of 50 MVAr. Figure 4-16(b) shows the reactive power transferred from the STATCOM to the system to support the weak AC grid voltage. The reactive power that is injected by the STATCOM increases the output of wind farm, but in different values depending on the rating of the STATCOM. From the results in Figures 4-15 and 4-16, in steady state operations, STATCOM produces controlled reactive power similar to SVC.



(a) P-V curves of weak AC grids



(b) STATCOM reactive power

Figure 4- 16: Simulation results of weak AC grid with the STATCOM

Different voltage control technologies were enabled in order to test the effectiveness of these controls in mitigating the negative impact of weak AC grid in increase the limit of transferring power. Voltage control technologies were selected that would achieve the maximum transmitted power and the permissible values for the voltages of the weak AC grid and the wind farm. The allowed values for the weak AC grid voltage were 10% of the 1 pu. The maximum transferring power is summarised in Table 4-1

Table 4- 1: The maximum transferred power with different control technologies

Full power converter control		
Constant reactive power control mode (Qref=0)	Power factor control mode (pf=1)	AC voltage control mode
40 MW	40 MW	65 MW
Reactive power compensation technologies		
Fixed capacitor (8 MVAr)	SVC (50 MVAr)	STATCOM (50 MVAr)
55 MW	90 MW	90 MW

According to the above simulation results of this study, it can be concluded that local AC voltage control of a STATCOM or a SVC is a better option to increase the limit of the transferred power to a weak AC grid. The maximum wind power transferred limit is 90 MW at an acceptable grid voltage value. However, a STATCOM has advantages over the SVC in reactive power compensation as mentioned in section 4.3.1.2 of the STATCOM. Therefore, The STATCOM was used and verified its performance to simulate a dynamic model of the test system and also in Chapter 5 with transient stability.

4.5.2 Dynamic model

Figure 4-17 shows a test system to connect a wind farm with a STATCOM to an AC grid. The PSCAD simulation tool was used to simulate a dynamic model of the test system. Simulation studies were carried out to investigate how a weak AC grid can be strengthened through the use of an enhanced STATCOM with different control modes, and to demonstrate the effectiveness of the STATCOM controls on the AC voltage regulation of weak grids to accommodate more power from wind farms.

The same specifications as given in Figure 4-9 were used in the dynamic simulation of the test system. The test system for the connection of an 85 MVA offshore wind farm, which comprises of full power converters with the PMSGs, was located 100 km from the AC grid. The wind farm contained 17 wind turbines with a rating of 5 MVA. The collection system was used to connect the wind farm to the point of connection with AC grids. The AC grid was modelled in two methods as discussed before. When the AC grid was modelled as a voltage source with a Thevenin impedance, the impedances of 0.102+j 0.931 pu and 0.102+j0.335 pu for the weak and strong AC grids respectively were selected. Thus, SCR is 1.1 for the weak AC grid and 3 for the strong AC grid. Regarding the AC grid as a synchronous generator, the weak AC grid was modelled as a hydro-synchronous generator with a rating of 85 MVA and of 300 MVA for the strong AC grid. The synchronous generator, hydro turbine, governor, and the exciter models are available in the PSCAD library. The hydro turbine model is the TUR1 (Non-Elastic Water Column with Surge Tank) type, the governor model is the GOV1 (Mechanical Hydraulic Controls) type, and the exciter model of IEEE AC1A (Alternator Supplied Rectifier) type were selected. The specifications of these models are shown in Appendix B. The transfer function of these models is described in Appendix C. The reasons for selecting the hydro-generators are that they have a lower rating and slower response compared to others, such as the steam generator [161], [162]; thus, it is easier for it to behave like a weak AC grid.

A STATCOM is connected to Bus 3 through another 33 kV /132 kV transformer in order to improve voltage stability and provide reactive power compensation on the weak grid during wind power generation. The technical parameters of the test system are included in Appendix B. The direction of the active and reactive powers is assumed to be from the wind farm into the AC grid as shown in Figure 4-17.

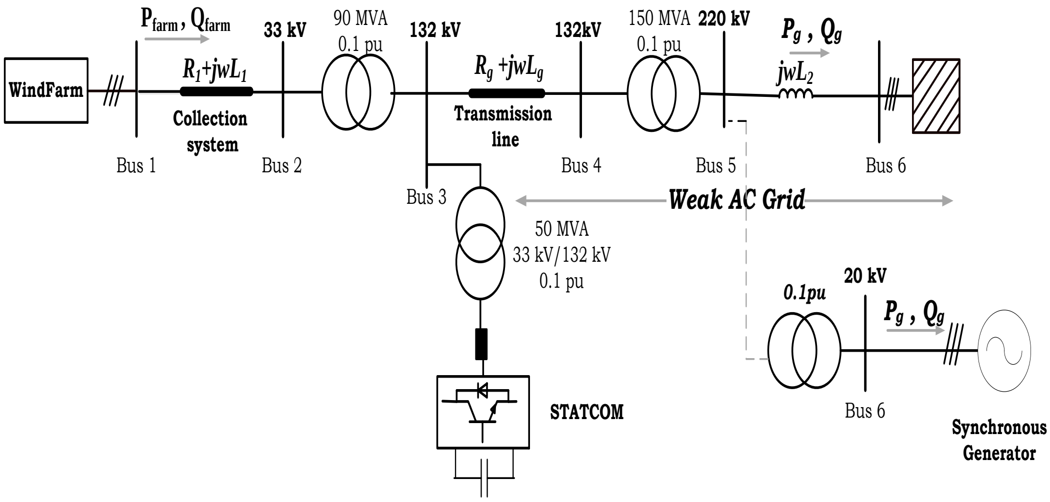
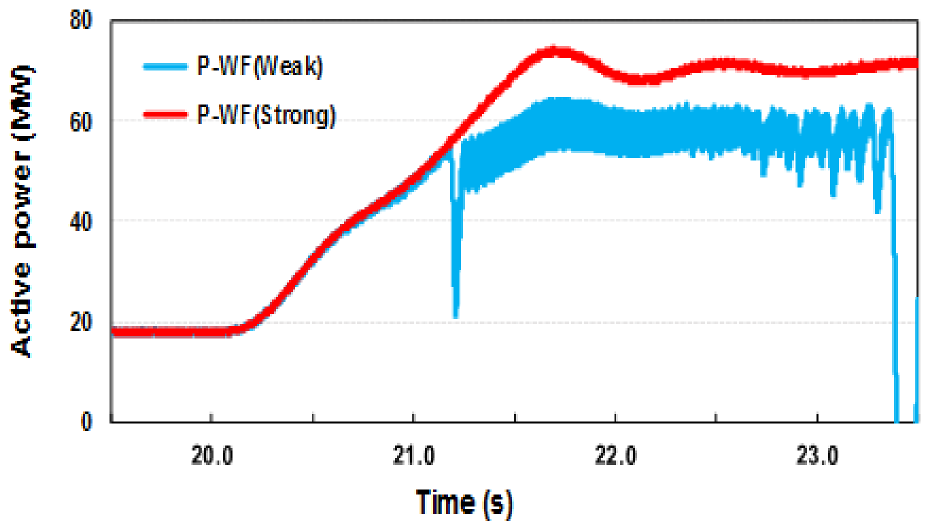


Figure 4- 17: Dynamic Model of Test System

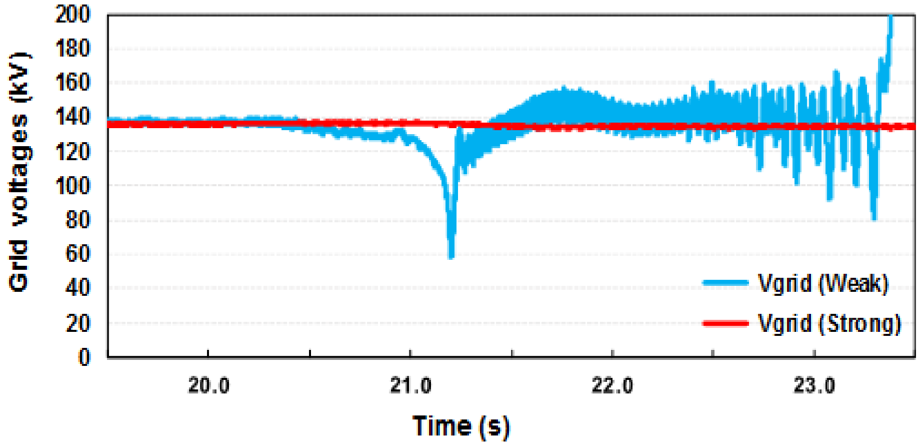
4.5.2.1 AC grid as a voltage source

- **Comparison of weak and strong AC grids**

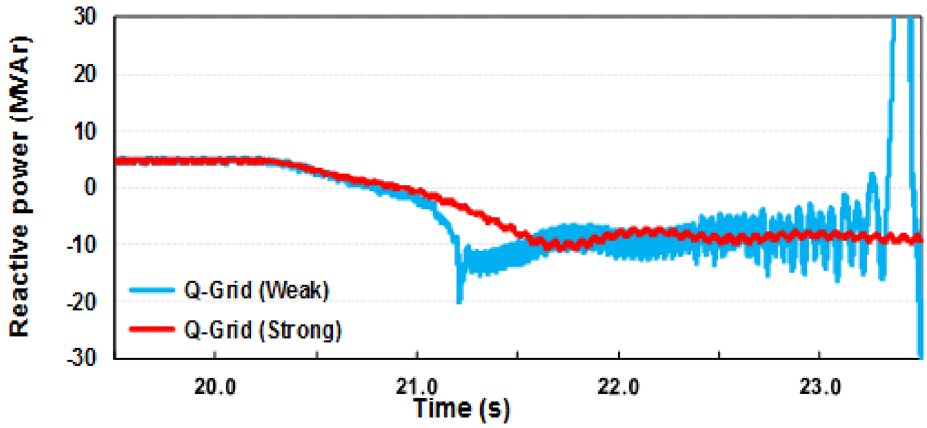
Figure 4-18 shows the simulation results of the comparison weak and strong AC grids with an increased wind farm output. Figure 4-18(a) shows the simulations of increased wind power generation from 18-70 MW in the strong AC grid with an SCR of 3 and in the weak AC grid with an SCR of 1.1. It is observed that the strong AC grid can accommodate 70 MW whereas the weak AC grid cannot accommodate this increase as a result of low SCR. The system of the wind farm connected to the weak AC grid becomes unstable compared with that with the strong AC grid. In addition, the AC grid voltages in Figure 4-18(b) are found to have an unstable response when simulated for a weak AC grid condition at low SCR while the response is stabilized as the SCR is high and simulated for a strong AC grid. Because of weak AC grids, which have a low SCR, consume a large amount of the reactive power when the wind farm power increases, and a reduction in the AC grid voltage, which may exceed the safe voltage margin and lead to voltage instability as a result of insufficient voltage and reactive power capability support. The plots in Figures 4-18(c) and (d) show the reactive powers for grid and wind farm during conditions of increased wind farm output. It can be seen that the strong AC grid can achieve the requirement of the reactive power grid and support its voltage during the increase in wind power generation in Figure 4-18(c). In contrast, the weak AC grid is unable to achieve this requirement of reactive power and to support its voltage. The amount of reactive power which the weak AC grid needs is greater than its capability and wind farm capability. Thus, weak AC grids need reactive power compensation technologies to support the voltage during increased wind power generation.



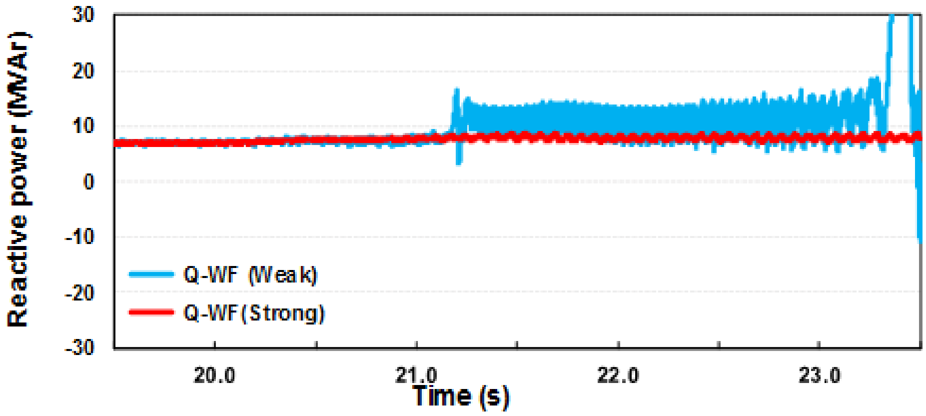
(a) Wind farm active power



(b) AC grid voltage



(c)Grid reactive power



(d) Wind farm reactive power

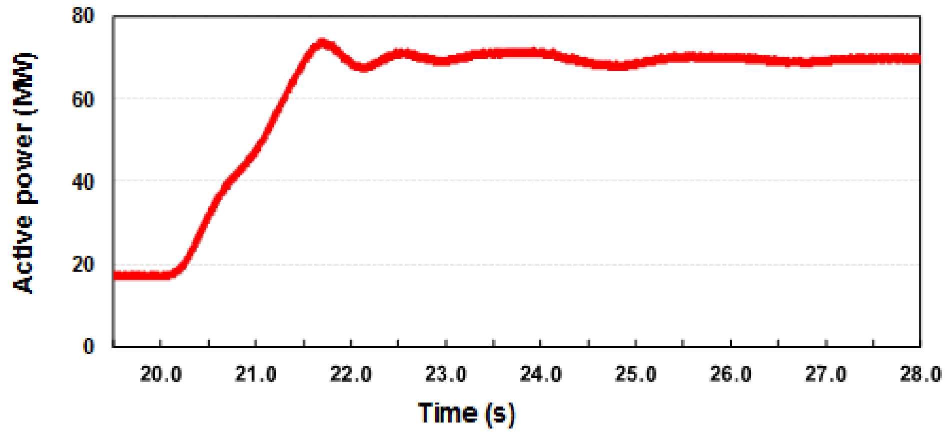
Figure 4- 18: Simulation results of comparison weak and strong AC grid

➢ Dynamic operation of Weak Grids with STATCOM

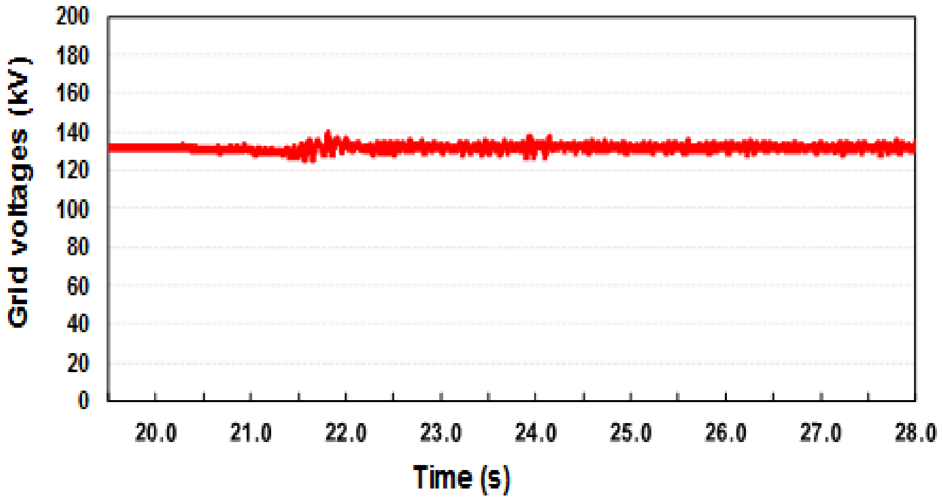
Using SCR 1.1, the wind power output was increased from 18 MW to 70 MW due to a variation of wind speed at time 20 s, in order to test the effectiveness 50 MVA STATCOM control schemes (see Figure 4-8). These are (i) AC voltage control and (ii) proposed reactive power versus AC voltage droop control.

(i) STATCOM in AC voltage control mode

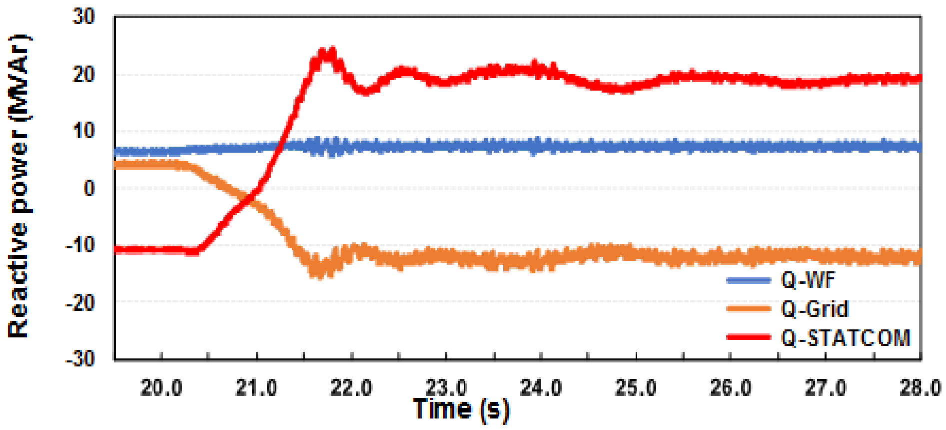
Figures 4-19(a)-(c) show the simulation results of wind farm active power, AC grid voltage, and reactive power (of the AC grid, STATCOM, and wind farm converter) in the case of a STATCOM in AC voltage control mode. It can be seen from the result that when the wind farm output increases, as shown in Figure 4-19(a), the weak AC grid voltage is reduced. The reduction in the AC voltage grid is detected by the controller of the AC voltage; the STATCOM injects fast reactive power and compensates for the voltage reduction to restore the grid terminal voltage, as shown in Figure 4-19(b). The STATCOM operation helps to stabilize the grid voltage during the change of wind power output. Figure 4-19(c) shows the reactive power of wind farm, grid, and STATCOM. The reactive power capability of the wind farm converters is limited to meet the requirement of the weak grid. Thus, AC voltage control of the STATCOM enhances the capability of the wind farm and the weak AC grid to support the voltage of the grid during the increase in wind farm output and help weak AC grid to accommodate more power from the wind farm.



(a) Wind farm active power



(b) AC grid voltage

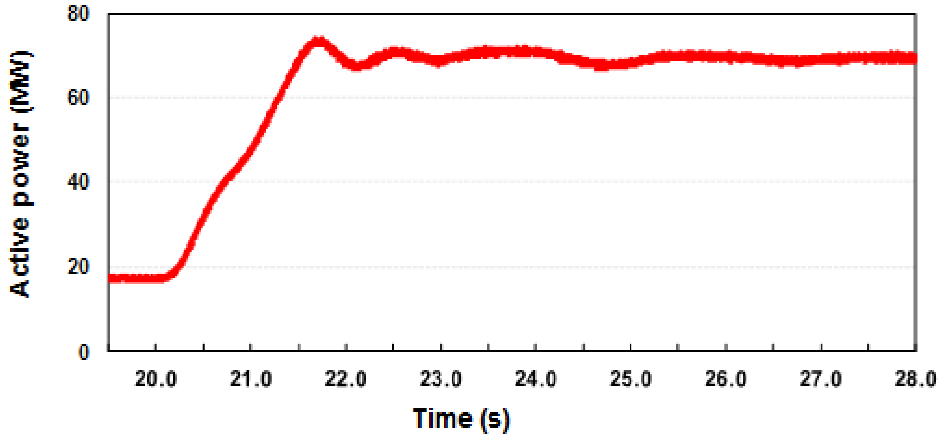


(c) Wind farm, grid, and STATCOM reactive power

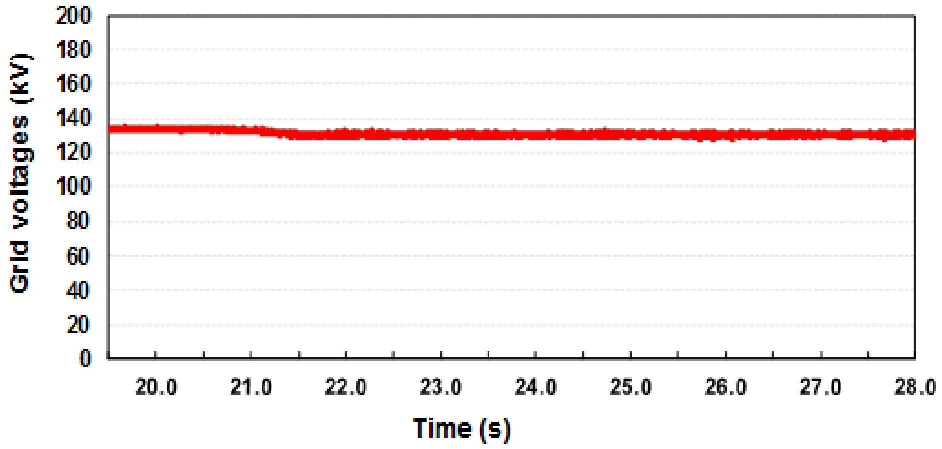
Figure 4- 19: Simulation results of STATCOM with AC voltage control

(ii) STATCOM in droop control mode

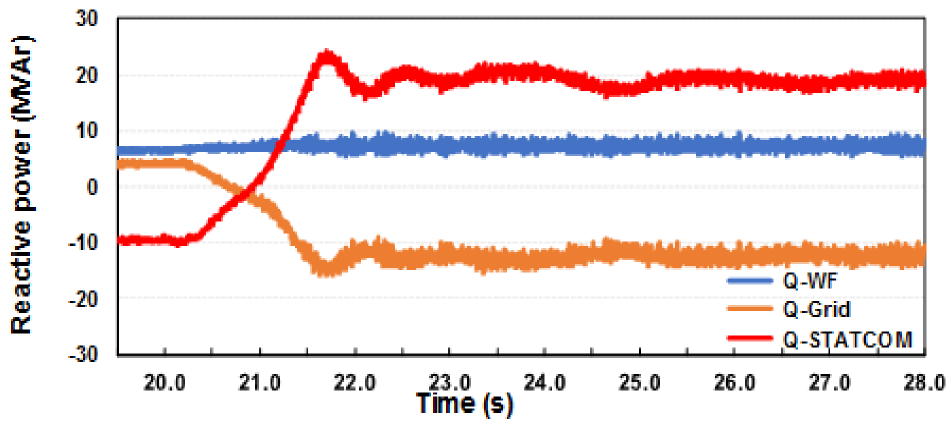
Figures 4-20(a)-(c) show the simulation results of wind farm active power, AC grid voltage, and reactive power curves, during the case of a STATCOM with the reactive power versus AC voltage droop control. In order to demonstrate the effectiveness and sensitivity of the proposed control scheme, the droop gain, K_{vQ}, is selected as 24.32. In Figure 4-20(a), the increase in wind farm output with STATCOM droop control makes the system stable and enhances the capability of the wind farm to transfer more power to the weak AC grid. Furthermore, the droop gain makes the performance of the droop control close to the AC voltage control (see Figure 4-20(b)). Also, the converter's capability of the wind farm to meet the requirement of the weak grids is very limited (see Figure 4-20(c)). Voltage regulation using droop leads to an increased reactive power contribution of the STATCOMS (see Figure 4-20(c)) and enhances the ability of the wind farm to transfer more active power to the weak grids. The advantages of this control are that it is possible to control the grid voltage level according to the characteristics of the droop K_{vQ}.



(a)Wind farm active power



(b) AC grid voltage



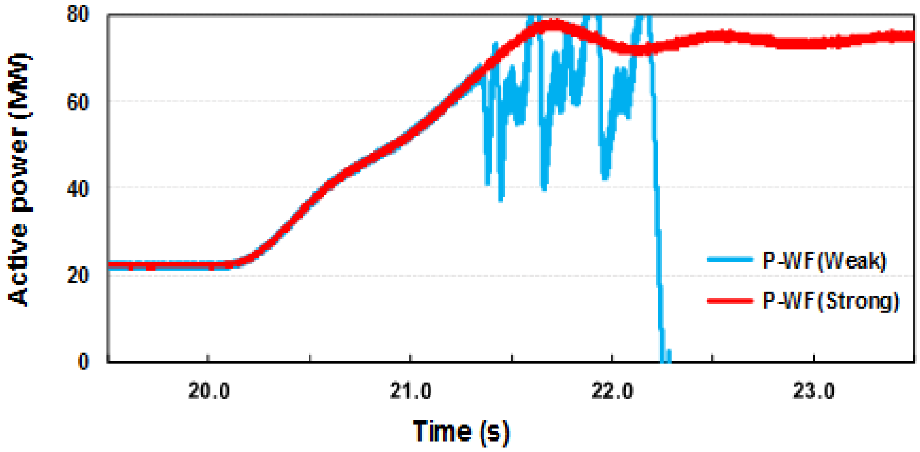
(c) Wind farm, grid, and STATCOM reactive power

Figure 4- 20: Simulation results of STATCOM with droop control

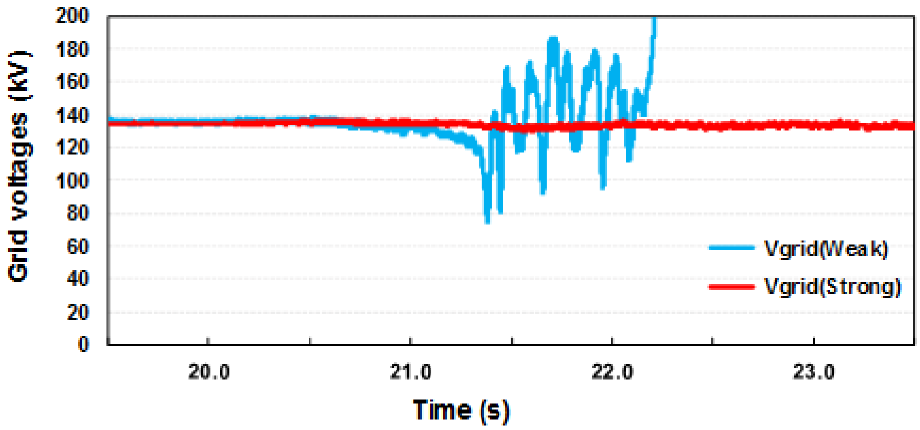
4.5.2.2 AC grid as synchronous generator

- **Comparison weak and strong AC grids**

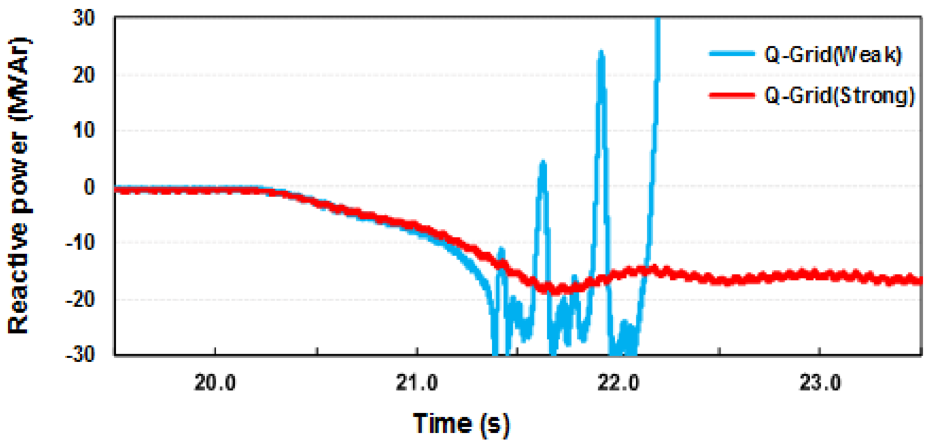
The comparison of the impact of the increase in wind power generation on weak and strong AC grids when the AC grid as a synchronous generator is shown in Figure 4-21. From Figure 4-21(a), it can be seen that the strong AC grid can accommodate the increase in wind farm active power while the weak AC grid is unable to receive this amount of wind farm output. The AC voltage of the strong AC grid remains constant throughout the increase in wind power generation. On the other hand, the weak AC grid voltage is declining over the period of increased wind farm generation, and then the voltage collapses as shown in Figure 4-21(b). A possible explanation for the collapse is that the weak AC grid has not the ability to support its voltage by generating the required reactive power as a result of high grid impedance, as shown in Figure 4-21(c) and because the enhancement of the wind farm is limited, as shown in Figure 4-21(d). The weak AC grid cannot produce more reactive power with the rating of 85 MVA to fit the increase in wind power generation, which means this rating of the weak AC grid is limited to the transferred power from the wind farm. In addition, a wind farm cannot provide suitable support to this AC grid. Conversely, the strong AC grid provides sufficient reactive power with the rating of 300 MVA to accommodate the increase in wind power generation.



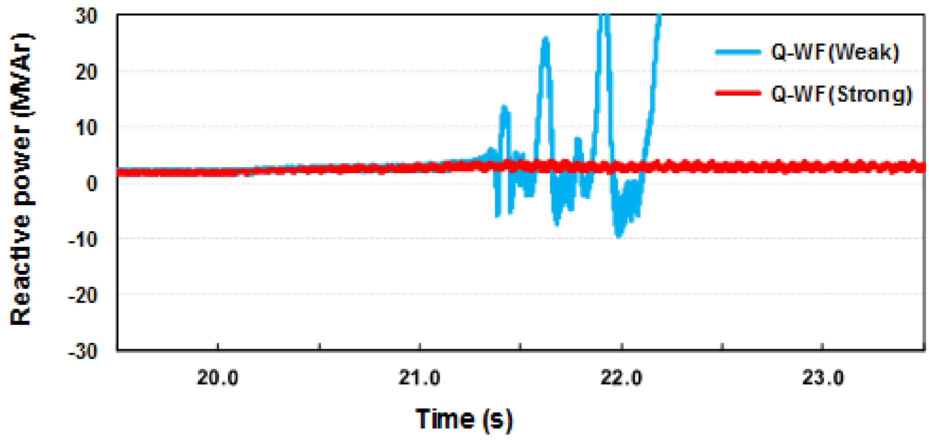
(a) Wind farm active power



(b) AC grid voltage



(c) Grid reactive power



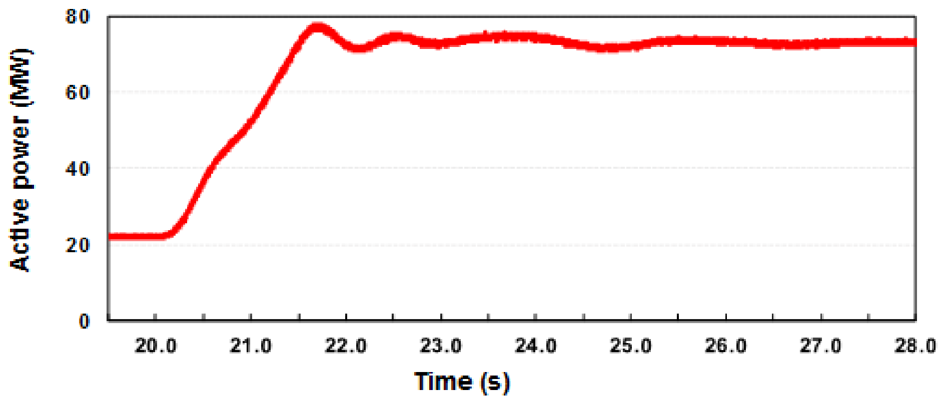
(d)Wind farm reactive power

Figure 4- 21: Simulation results of comparison of weak and strong AC grid

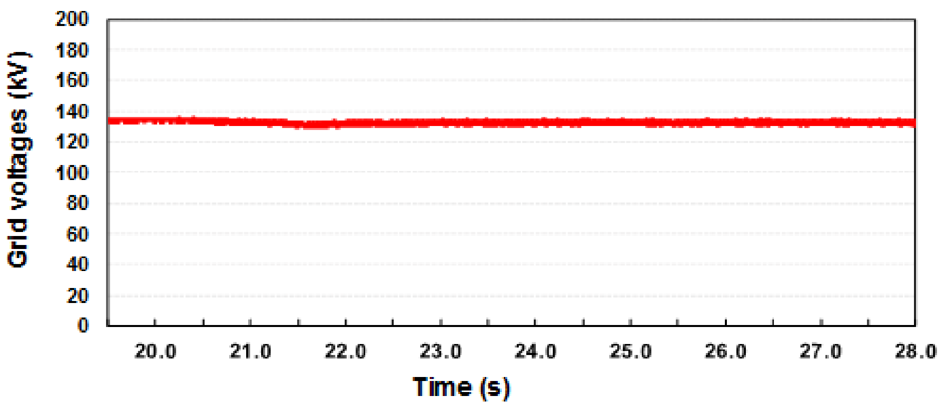
- **Dynamic operation of weak grids with STATCOM**

(i) STATCOM in AC voltage control mode

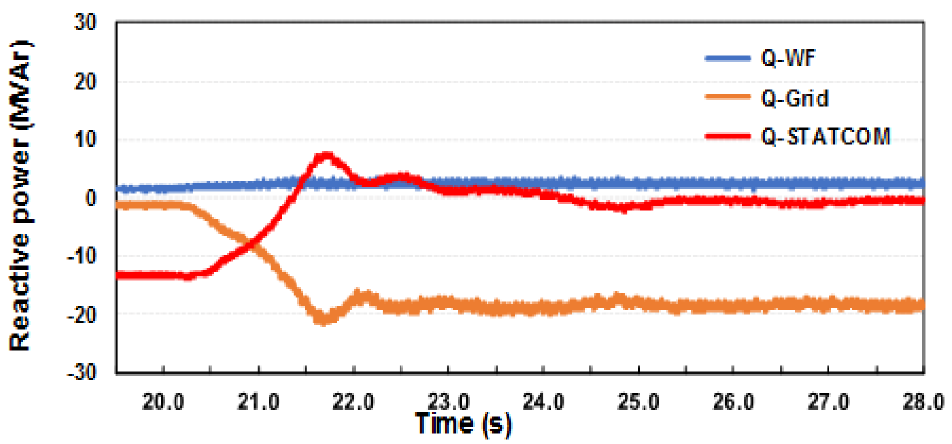
The dynamic reactive power compensation of the STATCOM contributes significantly to improve the performance of connecting wind farms to weak AC grids, as can be observed from the simulation results in Figure 4-22. Figure 4-22(a) shows the increase of wind farm active power. This increase was detected by the AC voltage controller of the STATCOM, and it responded rapidly to meet the set point voltage of the controller, as shown in Figure 4-22(b), by providing reactive power to support the weak AC grid voltage and compensate for the large amount of reactive power that is absorbed by the weak AC grid, as shown in Figure 4-22(c). The STATCOM is fast and effective in improving system stability and has a good performance in improving the voltage stability of the weak AC grid when there is an increase in the wind farm output.



(a)Wind farm active power



(b) AC grid voltage

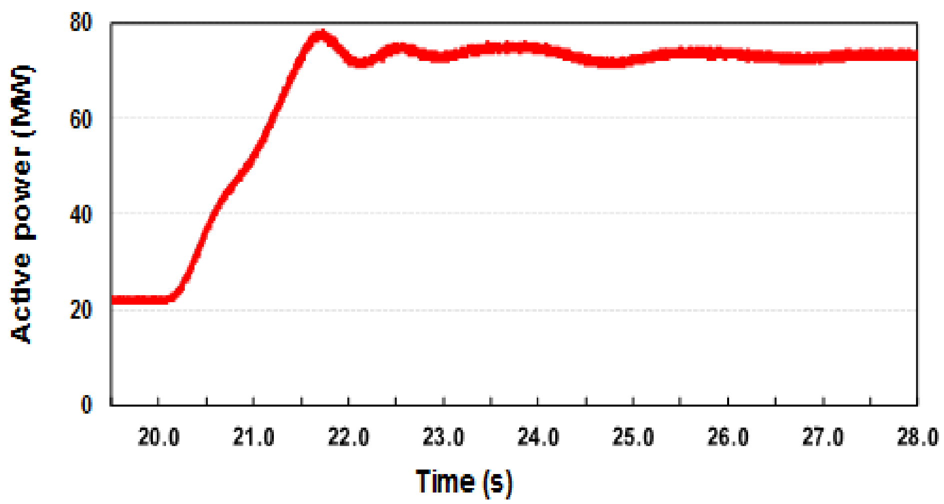


(c) Wind farm, grid, and STATCOM reactive power

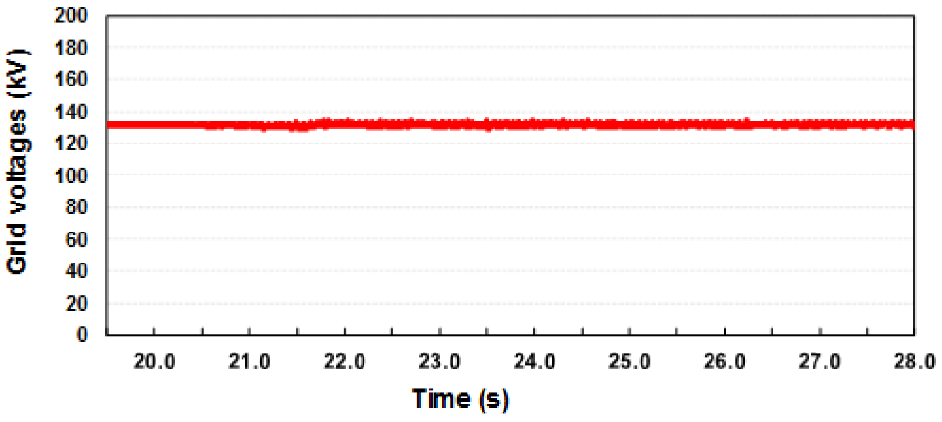
Figure 4- 22: Simulation results of STATCOM with AC voltage control

(ii) STATCOM in droop control mode

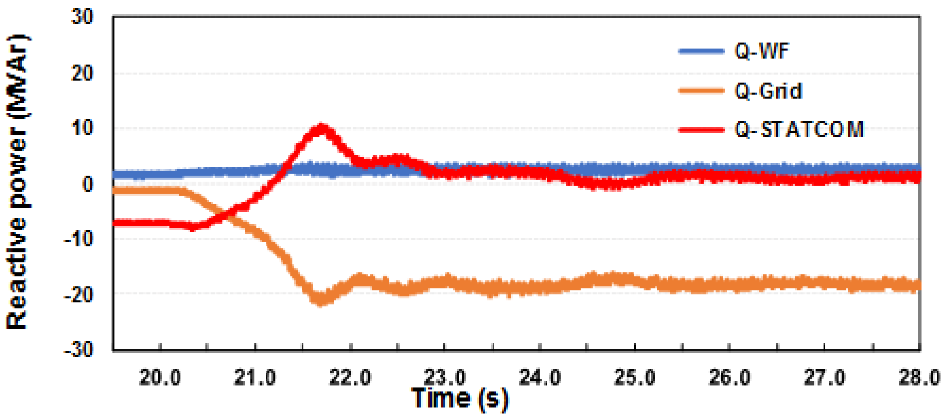
The capability of the STATCOM to improve the steady-state stability limits of the weak AC grids, and to prevent a risk of voltage collapse as a result of the increase in wind generation is shown in Figure 4-23. It can be seen that by applying a STATCOM with droop (K_{vQ} = 24.32) continuous voltage control, it is possible to increase the wind farm output up to 70 MW, as shown in Figure 4-23(a). The voltage of the weak AC grid is regulated within acceptable limits through the increase in wind generation, as shown in Figure 4-23(b). However, the controllers were used to maintain the weak AC grid voltage under high wind generation. The capability of the wind farm converters to meet the requirement of the weak grids is very limited, as shown in Figure 4-23(c). Voltage regulation using droop control leads to an increase in the reactive power contribution of the STATCOM (see Fig. 4-23(c)) and enhances the ability of wind farm to transfer more active power to weak grids. Thus, the increase in wind farm output with STATCOM droop control makes the system stable and enhances the capability of the wind farm to transfer more power to the weak AC grid.



(a) Wind farm active power



(b) AC grid voltage



(c) Wind farm, grid, and STATCOM reactive power

Figure 4- 23: Simulation results of STATCOM with droop control

4.6 Summary

The steady-state characteristics of the connection a wind farm into AC grids were studied. The wind farm comprises of variable-speed wind turbines with a full power converter. The limitations of wind power transmission were clarified, which include AC grid and power converter limitations. The voltage and angle stability limits of the AC grid were discussed analytically. The thermal limits and specification of the power converters were also explained.

The control of the full power converter was presented under different control modes. The main categories of reactive power compensation technologies were highlighted. A static and a dynamic simulation model of the test system were described. Comparison of strong and weak AC grid have done to transfer more wind power to the AC grids. Strong AC grids can accommodate more wind power without negative consequences on voltage stability, the voltage can be quickly re-established without reinforcement. Weak grids cannot accept the increase of wind power, there was a risk of voltage instability. The ac grid has to be supported. Different voltage controllers were investigated by using the full power converter and reactive power compensators to support weak AC grid voltage through increase active power of the wind farm. The dynamic reactive power compensators such as STATCOM and SVC with a local voltage control are acceptable solutions to regulate AC grid voltage and exclude the main concern of weak AC grids.

However, STATCOM has advantages over SVC such as large operating area. STATCOM control was selected and examined with the AC voltage control and the droop control to maximize the wind farm output to the weak AC grid. The AC grid was modelled with two methods, namely, as the voltage source behind a Thevenin impedance and a hydro-synchronous generator. The simulation results prove that the local control of the STATCOM offers a promising method to tackle the challenges in the active power transmission from wind farms connected weak AC grids.

Chapter 5

Transient voltage Stability of Wind Farms Connected to Weak AC Grids

5.1 Introduction

The strength of AC grids has a significant impact on the stability of the integration of wind farms into the AC grids. A transient stability has to be considered for wind farms connected to weak AC grids. Therefore, a transient stability analysis is necessary to determine whether the weak AC grid and wind farm can withstand sudden or large disturbances, such as faults. Much research has already been done in analysing the behaviour of wind farms with strong AC grids during faults and in presenting fault ride-through (FRT) solutions. However, research of the integration of wind farms with weak AC grids is limited [163], [31]. Voltage instability problems and system collapse can possibly occur, since wind farm and the weak AC grid are unable to meet the reactive power demand, or the system controllers cannot resist the sudden change in operating conditions. For these reasons, when wind farms are connected to weak AC grids, accurate power control is required to keep the integrated system stable during and after the fault clearing.

Conventional tools that could model transient stability alone are not suitable to perform wind integration studies under weak AC grid configurations [42]. The transient stability analysis usually needs to be supplemented with the modelling of fast acting power electronic controllers and assessment of the stability of their operation, using a suitable simulation platform, such as an electromagnetic transient simulation tool [42]. Therefore, the transient stability analysis of a wind farm connected to an AC grid has been analysed by a simulation method. Thus, a suitable simulation tool, such as an electromagnetic transient simulation tool, is necessary to implement the analysis. PSCAD/EMTDC is the professional simulation tool for analysing the transient behaviour of power systems.

In this chapter, the transient stability of the connection of the wind farm to a weak AC grid is studied. The challenges of wind farms connection into weak AC grids in a three-phase to a ground fault are highlighted. The FRT and voltage control capability of the wind farm are presented. Technical factors that limit the wind farm’s capability to deliver reactive power and recover normal operation after fault clearing are also discussed.

The impacts of the strength of the AC grid on the transient stability of a wind farm with an AC grid are investigated. AC grids with different SCR values are analysed at the severe faults. Low SCR of very weak AC grid is the main technical factor to make the voltage recovery difficult after clearing the fault. In order to enhance the fault ride-through capability of the wind farm with the very weak AC grid, the vector current control strategy of the GSCs has been enhanced by the supplementary control. The scheme and function of the supplementary control are demonstrated under different control modes. The DC chopper is used to dissipate extra power and limit over-voltage across DC capacitor of full power converter during the fault. The application of the supplementary control with DC chopper control have improved the system performance and have prevented the transient voltage instability post to fault clearance, but there is a high oscillation in the AC grid voltage and power. In addition, a STATCOM with proposed control is used along with wind farms (involving a DC chopper) for stabilising the weak AC grid voltage during fault clearance. In addition, the sensitivity of STATCOM rating is considered for improving the voltage stability of the system. The performance of STATCOM control has compared with the performance of GSC control, the STATCOM offers a better performance to weak AC grids in transient conditions.

5.2 Transient stability of wind farms connected to weak AC grids

Transient voltage stability indicates the ability of an AC power system to control voltages following large disturbances or a sudden change in operating conditions [85]. A large change in load, generation, or AC grid configuration is the main cause of transient instability in electrical power systems. An imbalance between the generated and demand powers occurs in those conditions.

Regarding the wind farm connections to the AC grids, the strength of the AC grid plays an important role in transient stability research. If wind farms are connected to strong AC grids, which are close to a stiff source, like an infinite bus bar, voltage and frequency can quickly recover to their nominal values after a disturbance with the support of the AC power grid itself. In the case of weak AC grids, the recovery to the nominal values of voltage and frequency after a disturbance may be slow [83], [77], [163]. Moreover, the recovery may be not reliable, and there is a risk of voltage and frequency instability and of system collapse [56], [130], [96]. The SCR values of the AC grid and the position and the type of disturbance can significantly affect the connection and restoration of normal operation. Therefore, the most severe disturbance was selected to determine the transient stability in this work. A three-phase to ground fault was applied to test the transient response of the system. The highest fault current will lead to disconnection of the wind farm during the fault [89], and make the recovery difficult. The clearing faults at a weak AC grid bus results in a further decrease in the SCR, which might enhance the severe effect of the fault and have unstable consequences for the voltage recovery [34]. In addition, there is a large oscillation in powers and voltages after the fault clearing [164].

Some measures should be taken when wind farms are connected to weak AC grids in order to improve the transient stability. Some of these measures are mentioned in Chapter 2.

5.3 Grid codes

Grid codes are technical requirements that are usually designed for wind farms connected to AC grids [165]. System operators specify grid codes. The fault ride-through capability and reactive power and voltage control capability of the wind farm are important services in the transient stability of wind farms with weak AC grids.

5.3.1 Fault ride-through capability

In the past, wind farms were disconnected from the AC grids at the faults, and have to reconnect again when the faults were cleared thus the AC grids voltage recovered to the normal value. Therefore, the requirement of maintaining the connection of wind farms to the AC grids during faults is an important issue to avoid active power generation losses and power disturbances as a consequence of these faults. The range of voltage conditions for a wind farm to remain connected to the AC grid is specified in the transmission system grid codes and is known as a FRT capability. The FRT requirement specified in GB grid codes is shown in Figure 5-1 [103]. The grid code of the FRT capability requires that wind farm should be kept in operation during severe AC grid faults, and guarantee quick restoration of active power to the normal value as soon as the fault is removed, if needed, wind farm generates a reactive power to support it and AC grid voltages during the faults. The FRT capability also explains how the control of the wind farms can prevent the disconnection of wind generators from the AC grid during a transient voltage dip [103]. The FRT capability required in the GB defines the minimum time duration of each voltage level required for the wind farm to stay transiently stable and connect to the AC grids for a fault with a clearance time of up to 140 ms with a zero voltage dip [163].

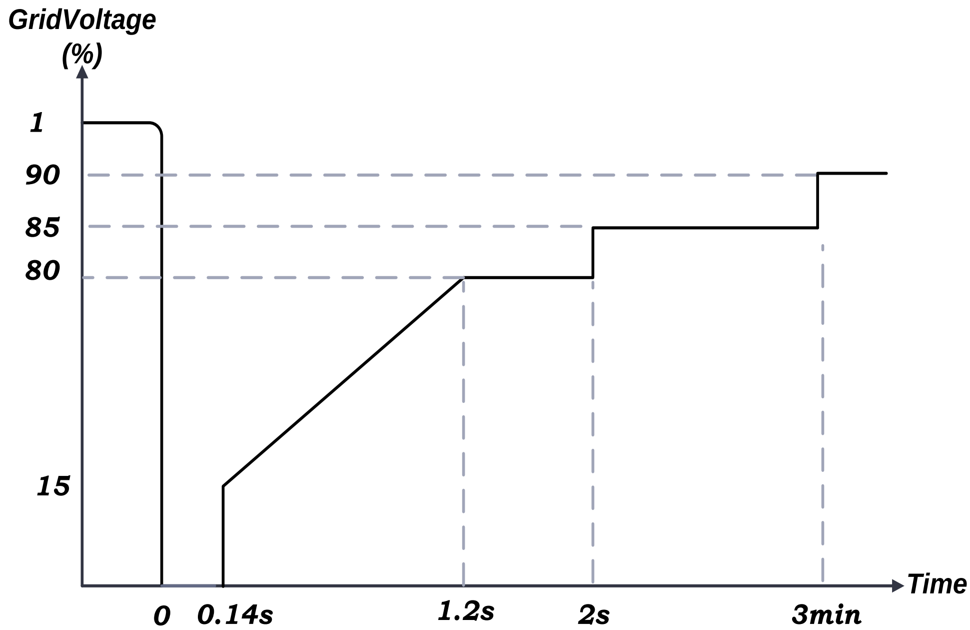


Figure 5- 1: Fault ride-through capability required in GB

Figure 5-1 shows the range of the operating points over which the system should remain stable to recover 85% of the nominal voltage and the minimum duration time is 3 minutes, while it takes 1.2 s to recover 80% of the nominal voltage. In the GB, a zero FRT requirement has to be met upon the occurrence of a symmetrical three phase or unsymmetrical earthed fault [163].

Due to the existence of different wind turbines such as fixed speed and variable-speed wind turbines, they behave differently in fault events. In addition, different control strategies were utilised with those turbines, and thus different techniques to enhance the FRT capability have been developed in the literature as discusses in Chapter 2. In this work, the FRT capability of variable-speed wind turbines with a full power converter will be highlighted.

5.3.1.1 Full-power converter wind turbines

In AC grid faults, variable-speed wind turbines with a full power converter have better performance compared to the partial-power converter with DFIGs or fixed speed wind turbines in wind farms [166], [120]. The AC grid fault does not directly affect the generator dynamics of the wind turbines as a result of total decoupling between the generators and the AC grid [100]. Wind turbines with a full power converter also have a larger capability of reactive power supply compared to partial power converters with DFIG [14].

Wind turbines with a full power converter can limit the current fed into the fault to the nominal current rating of the converter. In severe grid faults, the switching of the converter may also be stopped during the fault period [167]. When a fault occurring at the AC grid results in a drop in the AC grid voltage, and the wind farm active power cannot be fully transferred to the AC grid. In the meantime, the wind generators continue to generate active power that is provided to the DC-link of the full power converter during the AC grid fault. The capacitor of the DC-link will be overcharged, which will cause an overvoltage across the DC-link, and block or damage the converters. In addition, the controllers of the converter are designed to be activated in a certain range of operating points. When the AC voltage declines much more than the nominal level during the fault, the operating point may move out of the designed range, leading to an unreliable response of the controllers, which makes the system unstable. Hence, wind farms are required to have FRT capability for the reliable operation and protect the wind farm converters. A DC chopper is one of FRT requirements to enhance FRT capability of wind farm contains power converters, which is used to dissipate the additional power in the DC link, preventing a DC link over-voltage. Power converter control can be considered as a FRT requirement, expected to help keep the connection during and after the fault and maintain the voltage in the strong AC grids, but in weak AC grids, the FRT capability of power converter control may be limited and inadequate to support the grid voltage within acceptable limits during and after the fault [42], [168].

5.3.2 Reactive power and voltage control capability

Besides the FRT capability, the reactive power and voltage control capability are also important to get a fast active and reactive power restoration to pre-fault values in the transient conditions. The wind farm should provide a sufficient reactive power to re-establish the AC grid voltage during a voltage drop [142]. The active and reactive power can be regulated by GSCs independently in the operation of wind generators. This feature is very beneficial for the FRT and the AC grid support. Under normal conditions, the GSC usually operates with a unity power factor by regulating the reactive power to zero [169]. Occasionally, a unity power factor control strategy is not useful in a transient condition, especially following a fault, when there is a large reactive power which needs to be transmitted by the GSC. The GSC is incapable of transferring sufficient reactive power to the AC grid. To overcome this deficiency, a fast control method with a strong ability to decouple the GSC control variables should be implemented. The GSC controllers are used generally to regulate the DC voltage and control the reactive power flow between the wind farm and the AC grid. Hence, the capability of power converters to deliver reactive power to the AC grid and the recovery ability to establish normal operation are strongly dependent on the following technical factors.

5.3.2.1 Wind farm output

The amount of active power that is transmitted from wind farms into AC grid plays an important role in the voltage control capability of the wind farms. In a low power output of a wind farm, the wind farm and AC grid voltages can recover quickly after clearing a fault [170], [89], [64]. However, at the rated output power, the recovery voltage fails completely to restore the nominal values of the voltages after clearing the faults [170], [17].

5.3.2.2 Converter capacity

A high capacity of the power converters that are connected to the AC grid is more flexible for the voltage control capability during transient conditions. The limiters of the current controller are set according to the capacity of the converter. A large limit of the reference reactive current value is required to restore the normal voltages of the wind farm and the AC grid after clearing a fault as well as recover the normal operation of the system. The limit of the reference active current should be considered too. The GSC with a large capacity can provide a larger maximum value of the reference reactive current. In other words, the high reactive power supplied to the AC grid during a voltage dip period, and consequently, the wind farm voltage can be recovered quickly [61], [119]. The voltage recovery capability can be improved significantly by the increase in the capacity converter [171] but at the expense of increasing the cost [133].

5.3.2.3 SCR of the AC grid

The SCR is an indicator of the strength of the AC grid that is connected to the wind farm [166]. When the AC grid has a high SCR, the amount of AC grid short circuit current is high and can contribute to recovering the AC voltage quickly after fault clearing. Moreover, the high SCR values make it easy for the wind farm and AC grid voltages to recover and meet the grid code requirements. On the other hand, AC grids that have a low SCR, the AC voltages of the wind farm and the AC grid cannot be restored rapidly. In the case of a very low SCR, it is more difficult to restore the voltage recovery and this fails to satisfy the grid code requirement. Adjustments of the wind farm control are required to enhance the system stability after a fault has been removed. Thus, the low SCR values of the AC grids affect the voltage restoration capability of the wind farm [124], [166], [172].

When the wind farm cannot provide sufficient reactive power compensation with an appropriately rapid response, the typical solution is to use a dynamic reactive power compensation, such as a STATCOM, with a fast AC voltage control capability for the voltage stability problems [135].

5.4 FRT Techniques and simulation results

5.4.1 Test system and FRT techniques

The test system comprises an 85MVA wind farm consisting of seventeen 5 MVA wind turbines each with a PMSG, equipped with full power converters, were considered [173]. The control system of the full power converter was used to regulate the operation of the wind generators and AC grid as shown in Figure 5-2. The wind farm is connected to a 33 kV collection system that exports power to a 132 kV AC grid through the length of 10 km. The AC grid is modelled by the Thevenin equivalent circuit, consisting of an ideal voltage source in series with an AC grid impedance. When the AC grid was very weak, the STATCOM was connected to the AC grid bus. Figure 5-3 shows the test system that was studied. The simulation of the test system was done using the PSCAD tool. The test system for this chapter is similar to the one used in Chapter 4. The only difference is the control structure of the GSCs when the AC grid is very weak; this will be highlighted in this Chapter.

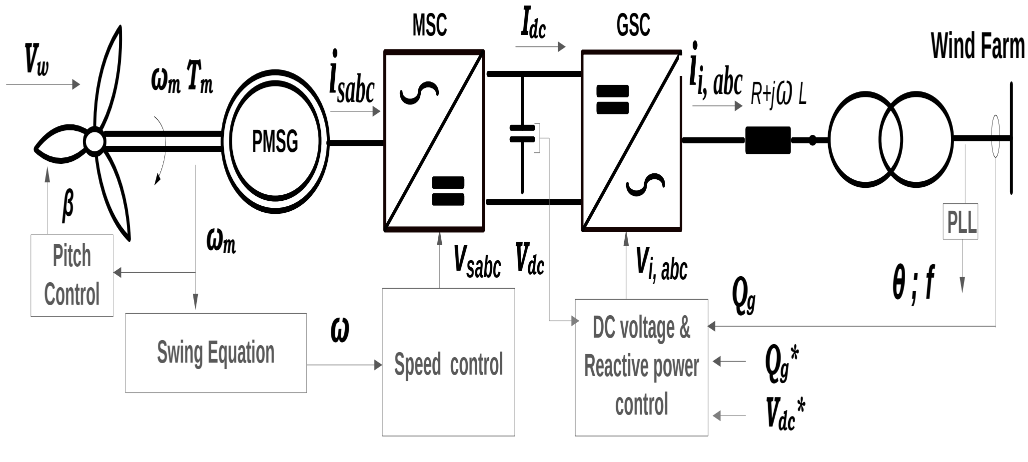


Figure 5- 2: Wind Farm Diagram

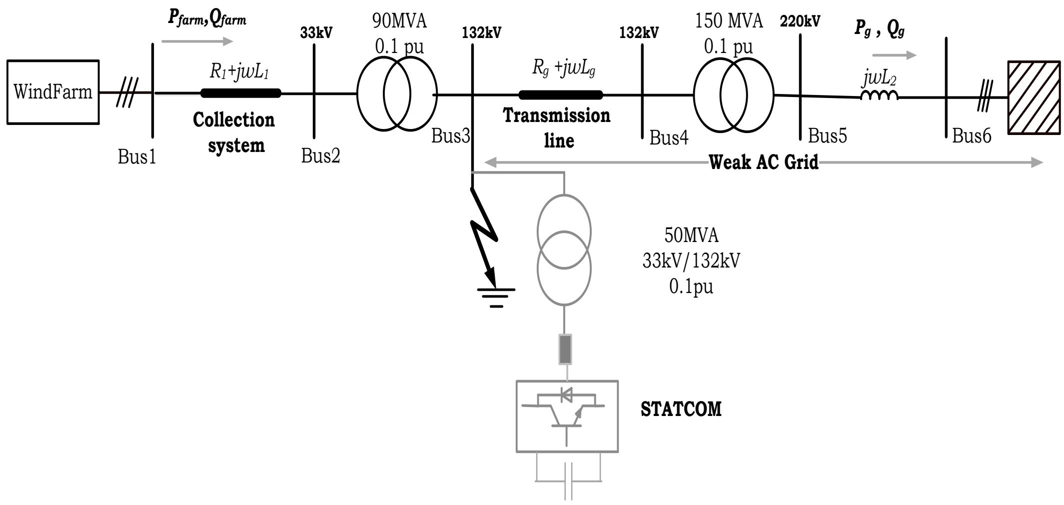


Figure 5- 3: Test System

5.4.1.1 GSC controllers

Recently, the majority of power electrical systems have been used variable-speed wind turbines with a full power converter [174]. In these wind turbines as there is a decoupling between wind generator and the AC grid, the performance of the GSC is more influenced by AC grid disturbance. For that reason, the focus will be on GSC control and on how the control responds to AC grid disturbances, especially if the AC grid is very weak. Figure 5-4 shows the structure of the GSC control including the DC chopper in parallel with the DC link capacitor. The standard vector current control strategy was used to design the control of GSC as explained in section 4.4.2.4 of the GSC’s controllers. Regarding the control of the reactive power flow into the AC grid, this control can be implemented in different control modes. However, converters with that control strategy are often unable to provide appropriate reactive power and voltage support to very weak AC grids due to their limited capacity and an unreliable response by their controllers to the transient conditions, and thus, there is a risk of voltage collapse. The reactive power control of the GSC will be investigated in different control modes when the AC grid is very weak.

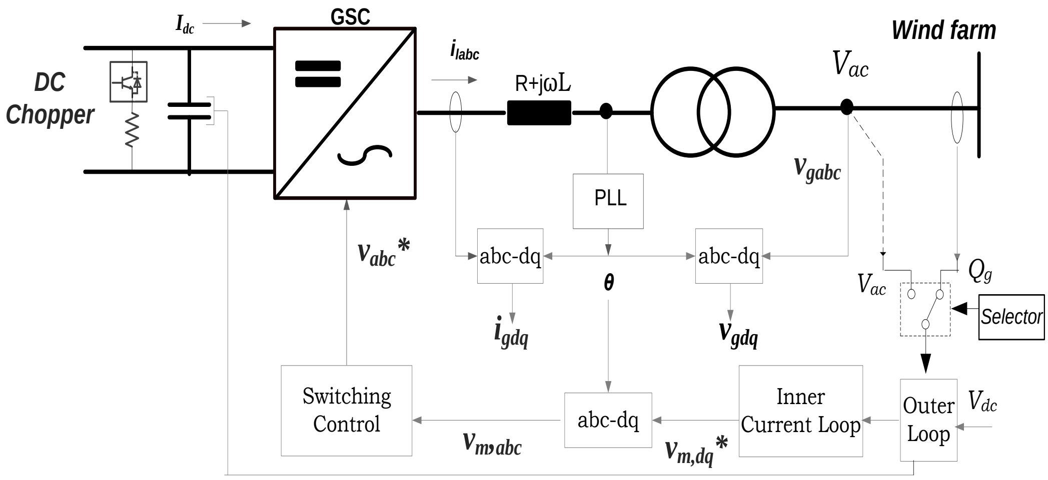


Figure 5- 4: Grid side converter structure

1. DC Chopper

In wind power application, power converters use a braking resistor, which is also known as a DC chopper to improve the FRT capability of wind farms [101], through the dissipation of surplus power injected from the wind generator into the DC link capacitor during an AC grid fault. The DC chopper is modelled as an electronic switch, typically IGBTs in series with a braking resistor. DC chopper connects in parallel with the DC link in order to increase the energy dissipation capacity [101]. The DC chopper is switched on or off by the IGBT switch, which is triggered by a simple threshold controller. The threshold controller works within the duty ratio d , which is described in Equation (5.1) [175].

$$d = \frac{V_{dc} - V_{start}}{V_{max} - V_{start}} \tag{5.1}$$

where V_{strat} is the threshold to start the threshold controller, V_{max} is the allowed maximum DC voltage, and V_{dc} is the measured DC voltage [176].

When $V_{dc} \geq V_{max}$ then $d = 1$. Thus,

$$d = \begin{cases} 0 & if\ V_{dc} < V_{start} \\ \dfrac{V_{dc} - V_{start}}{V_{max} - V_{start}} & if\ V_{start} \leq\ V_{dc} \leq V_{max} \\ 1 & if\ V_{max} \leq\ V_{dc} \end{cases} \tag{5.2}$$

The power dissipated through the braking resistor is

$$P_{Chopper} = \frac{(d.V_{dc})^2}{R_{\text{braking}}} \tag{5.3}$$

When the DC voltage goes beyond a threshold level and burns the surplus power in the braking resistor, it discharges the capacitor of DC link and reduces the DC voltage below the threshold value. This sequence is repeated with the switching frequency of the chopper [177]. The DC chopper generally needs to have the same power rating as the VSC to maintain a stable DC-link voltage during grid faults [178], and so might not be cost-effective [175]. The parameters of the chopper are explained in Appendix D [179].

A DC chopper can help to damp the DC overvoltage rapidly and protect the power converters. Hence, the DC chopper enhances the fault ride-through capability of wind farms [180] and allows them to maintain a reliable operation during the AC grid fault [181]. The DC chopper is being used for the power converter systems with the advantages of low-cost and the simple control performance to consume surplus power [182].

2. Control modes of the GSC

➢ Unity power factor control mode

For unity power factor operation, the reactive power flow between the AC grid and the wind farm is zero under steady-state operation [183], [184]. In very weak AC grids, the vector current control strategy is inadequate to keep the system stable in transient conditions [170], [35]. Therefore, the performance of the vector current control has been improved by using a supplementary control. The function of the supplementary control is changing the reference reactive power to a high value depending on the magnitude of the AC grid voltage as shown in Figure 5-5.

The principle of operation is that if the AC grid voltage is greater than 0.9 p.u, the output of the comparator will be 1 and the AND gate output is also 1. The selected switch will set the reactive power reference to zero. In the case of the AC grid voltage being less than 0.9 pu, the outputs of the comparator and AND gate will be zero and the selector switch will set the high reactive power reference. Thus, the performance of the controller will improve the return to normal operating conditions when the fault is removed by changing the reactive power reference to a higher value while the AC grid voltage is less than the minimum allowable value. The supplementary control is introduced for a few milliseconds just after the fault and then the system returns to the unity power factor control. Thus, the supplementary control helps to keep the operation of the system with the unity power factor control during the steady-state stage, which keeps the reactive power request to the minimum. While during the transient stage, the supplementary control can be inserted to improve the voltage restoration of the wind farm and AC grid.

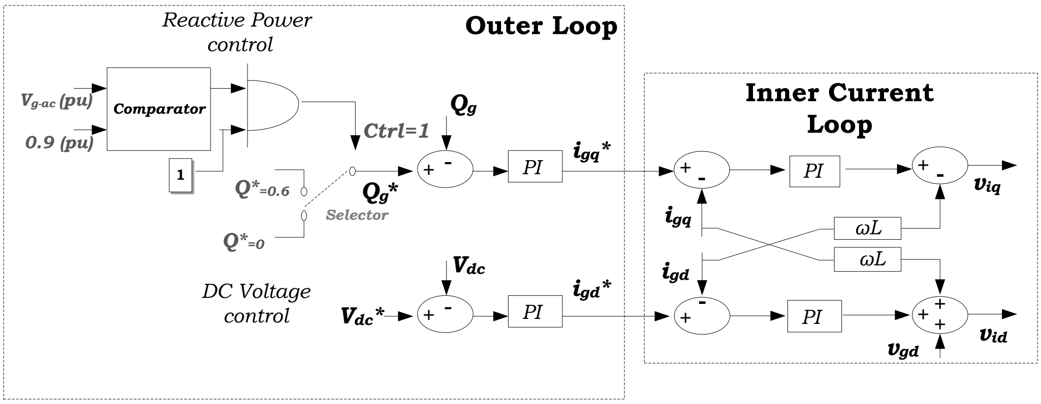


Figure 5- 5: A supplementary control in unity power factor control mode

- **AC voltage control mode**

The AC voltage controller is used to regulate the AC voltage of the converter terminal to reference value 1 pu; consequently, it regulates the wind farm voltage to maintain that value [171]. The amount of reactive power that is delivered to the AC grid depends on the value of the wind farm voltage deviation from the reference value. In the case of an AC grid that has a very low SCR, some problems will arise in relation to the transient operating conditions. One of these problems is that an overvoltage trip could happen after fault clearing as a result of the high reactive power supplied by the GSC during the fault. Thus, AC voltage control is unable to reduce the reactive power immediately after the fault clearing, and if the AC grid is considered very weak to absorb the reactive power injected, the result will be overvoltage at the AC grid and wind farm buses [185].

In order to support the AC voltage recovery of the wind farm, current limiters were used to decrease the fault currents to desired values after the fault had been detected [186]. The AC voltage control with a supplementary control as shown in Figure 5-6. The main idea of the supplementary control is to change the limiters of the current converter during the fault depending on the magnitude of the AC grid voltage. Typically, current limiters can be inserted in the control of the converter to protect the converter from over-currents [187]. The current limiters were added at the output of the outer controllers in order to limit the current references (i_d^*, i_q^*). A maximum converter current (i_{max}) limiter is specified, and fixed the reactive current (i_{q-max}) limiters. The *d*-axis current (i_{d-max}) limiters will be dynamic limiters and these are calculated according to Equation (5.4) [33], [172].

$$\sqrt{i_{d-max}^2 + i_{q-max}^2} \leq i_{max} \tag{5.4}$$

Typically, the maximum converter current output is 1 per unit. After detecting the AC fault by comparing AC grid voltage with a set point voltage, the reactive current limiter makes a reduction from the maximum limit to the minimum limit in order to improve recovery from the severe three-phase AC-system faults applied at the AC grid bus.

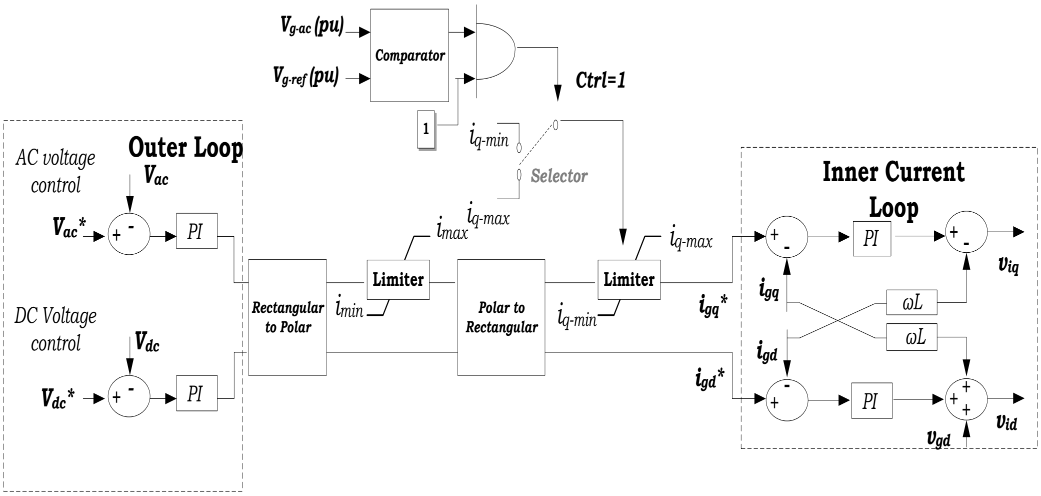


Figure 5- 6: A supplementary control in AC voltage control mode

5.4.1.2 STATCOM

STATCOMs are connected to support AC grids that have a poor voltage regulation and often poor power factor, and they are most commonly utilized to stabilize the voltages [146]. Using STATCOM controllers together with the DC chopper is a reliable solution to support the FRT of the wind farm and maintain the connection of the wind farm to the AC grid during grid faults [188], [189]. A STATCOM can inject reactive power to regulate the AC grid voltage locally [137], [91]; hence, the transient condition of the AC grid, particularly a very weak AC grid is improved significantly [190], [191].

The model of a STATCOM with the proposed reactive power versus AC voltage droop control mode was used, as shown in Figure 5-7. The structure and specifications are approximately similar to the one in Chapter 4, except for the droop gain value, which is 1.52. The other specifications are described in Appendix B.

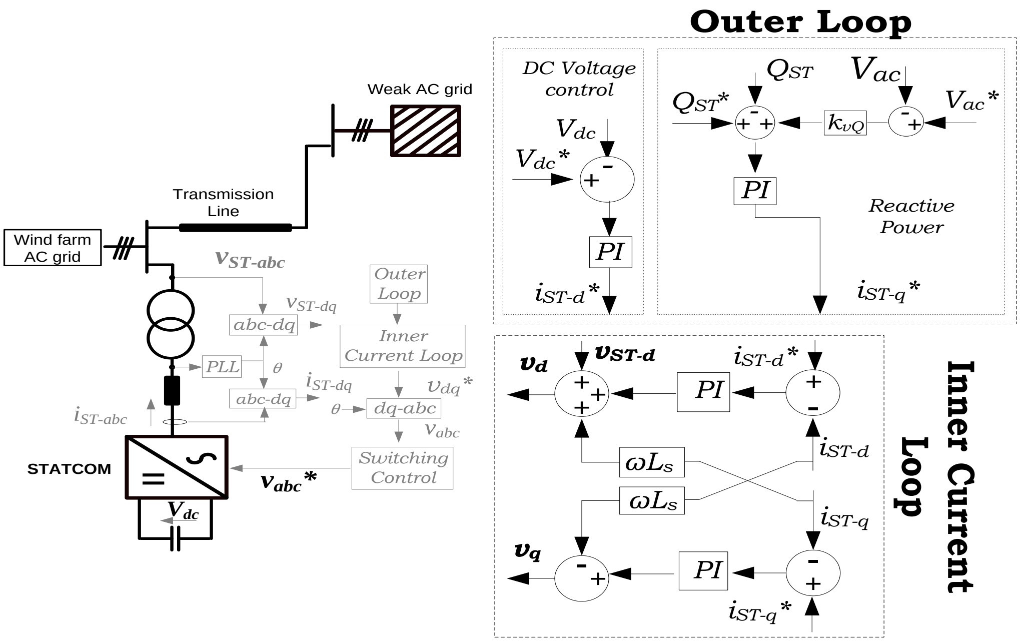


Figure 5- 7: STATCOM Control

5.4.2 Simulation results and discussions

In order to verify the transient stability conditions of the integration of wind farms into weak AC grids, and to identify the technical factors of weak AC grid which make the voltage recovery difficult, the simulation was carried out to analyse transient stability for that integration under three-phase to a ground fault. Variable-speed wind turbines with a full power converter were used in a wind farm. The performance of the wind farm was assessed over a range of SCR values, from a strong AC grid, where SCR is 3.0, to a very weak AC grid, where the SCR is 1.1. Assessment of the performance has focused on various enabling techniques that may be used to extend the reliable connection of a wind farm to weak or even very weak AC grids.

5.4.2.1 **Three phase to ground fault under different SCR values**.

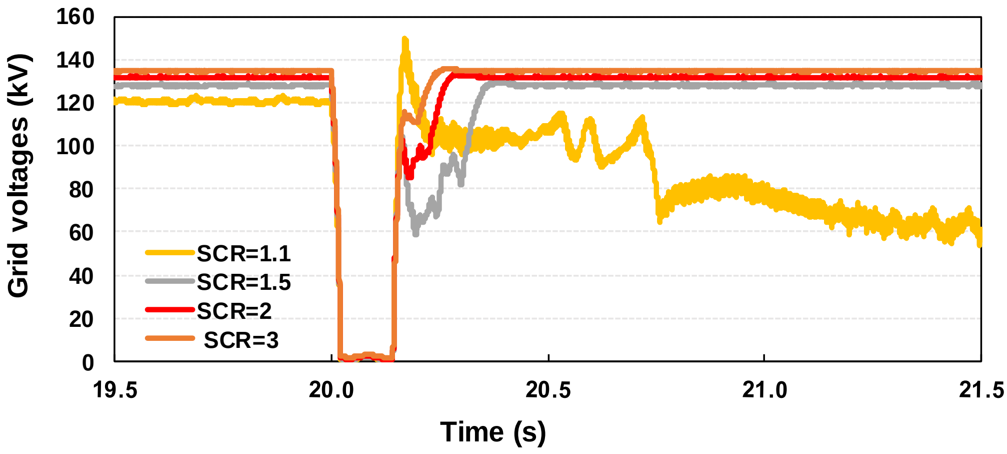
The transient response of a wind farm was tested by applying a three-phase to ground fault at the AC grid bus, and the wind speed was kept constant during the simulation. A three-phase to ground fault is applied only in this thesis because it is the most severe from a stability viewpoint. The fault occurred at 20 s and lasted for 140 ms, according to the fault ride-through requirements in the GB. The fault impedance was selected to be relatively small, as it would result in a more severe effect on the system, and the value was set to 1 Ω resistive. The GSCs performance was tested under different SCR values of the AC grids, and two configurations of the GSC were studied: The first configuration is without a DC chopper, and the other includes the DC chopper with ratings equal to the wind turbine rating of 5 MW.

- **AC grid fault: results without the DC chopper**

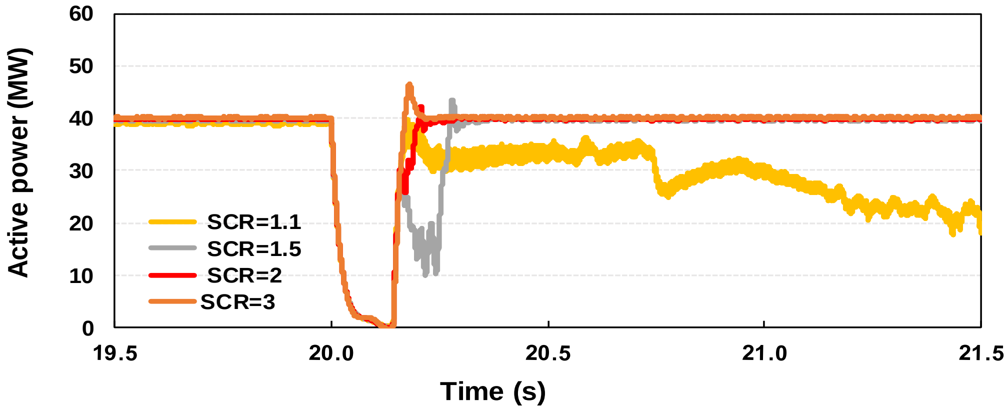
Figure 5-8 shows the simulation results of applying three-phase to ground fault at the AC grid bus under different values of SCR. Figure 5-8 (a) shows the transient response of the AC grid voltage. It can be seen that the voltage can restore its steady-state value after the fault clearing for the AC grid, which has SCR 3, 2 and 1.5 in different time periods, depending on the magnitude of the SCR. An AC grid that has a high SCR can restore the normal operating condition faster than those that have a lower SCR. Slow voltage recovery is as a result of the reactive power compensation not being large enough to compensate completely after the fault clearing. However, with an extremely weak AC grid with an SCR of 1.1, the voltage restoration is lost, and the system becomes unstable after a fault. The transferred wind farm output was decreased in proportion to the reduction of the AC grid voltage and reached approximately zero, while the AC voltage of the grid is closed to zero during the fault, as shown in Figure 5-8(b). Meanwhile, the DC capacitor is charged quickly as a result of extra power from wind generators, and overvoltage is generated across DC link, which may lead to damage to the converter as shown in Figure 5-8(c). The power imbalance created in the system affects the normal operation of the converter and the system stability. The GSC provides much more reactive power than a normal operation to support wind farm voltage and AC grid voltage restoration, as shown in Figure 5-8(d). At fault clearing, it can be seen that a wind farm cannot restore its output to pre-fault levels immediately, but the restoration can be achieved in different periods depending on the value of the SCR. Otherwise, when the AC grid has an SCR of 1.1, the wind farm is unable to restore normal operation as a result of a large voltage deviation and the inability of the wind farm and the AC grid to inject more reactive power to support grid voltage in the case of a wind farm operating with unity power factor, as shown in Figure 5-8(e).

Regarding the AC grid that has an SCR of 3, 2, and 1.5, during the fault, the grid reactive power is reduced to zero whereas the wind farm generates more reactive power to support and faster restore the AC grid voltage. After that, the AC grid delivers enough reactive power to restore normal operating conditions at fault clearing, thus strong AC grid is able to recover normal operations faster than the weak AC grid.

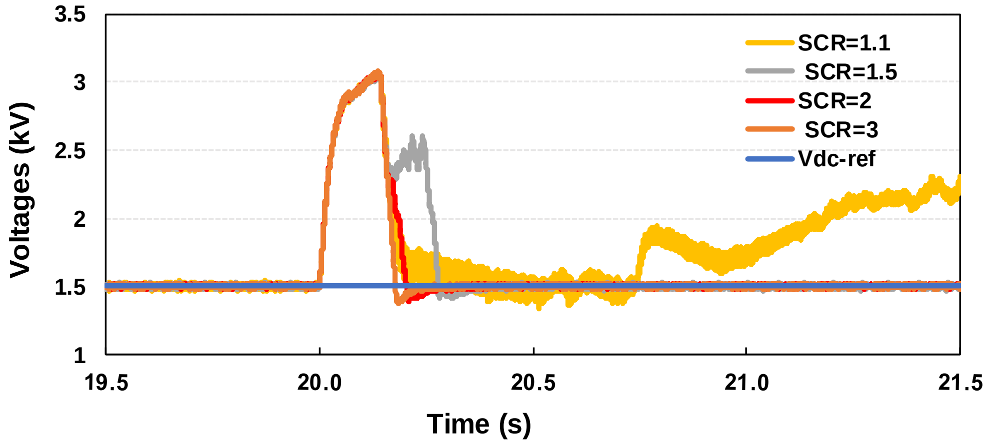
However, in a real wind farm, which has variable-speed wind turbines with a full power converter, the over-voltage in DC link can likely block the converters and force the wind turbines to disconnect from the AC grids during the fault. Therefore, DC chopper control is suggested to eliminate the over-voltage across the DC link and keep wind turbines in operation through fault period.



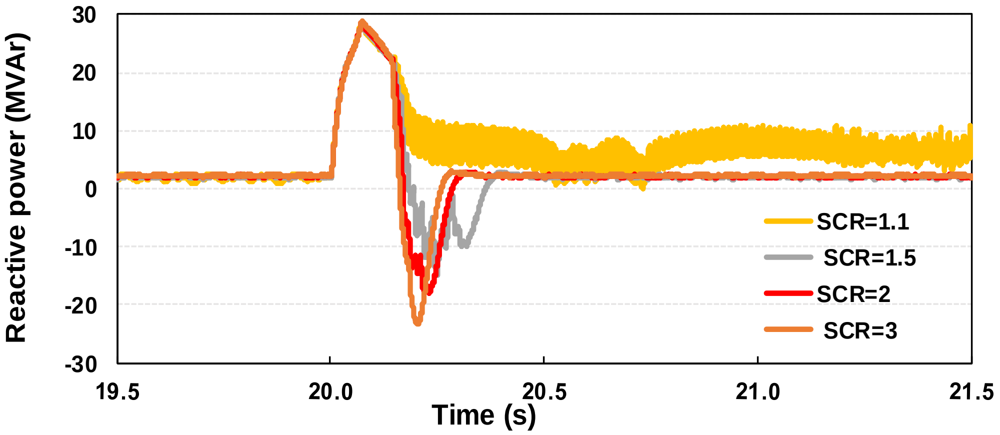
(a) AC grid voltage



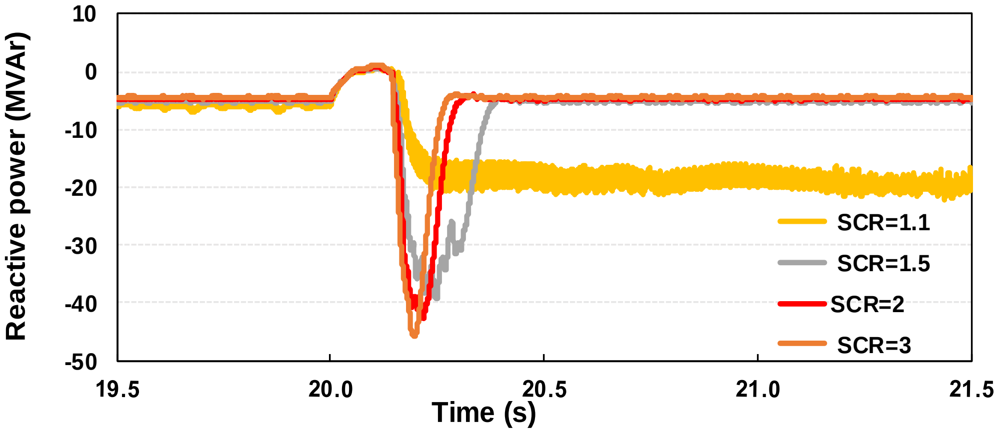
(b) Wind farm output



(c) DC voltage



(d) Wind farm reactive power



(e) Grid reactive power

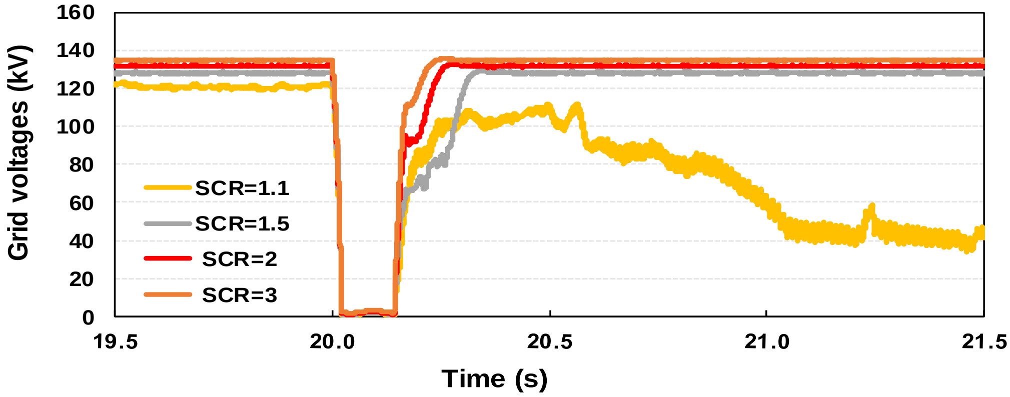
Figure 5- 8: Simulation results of a wind farm with AC grid under different SCR at fault without DC chopper

- **AC grid fault: results with the DC chopper**

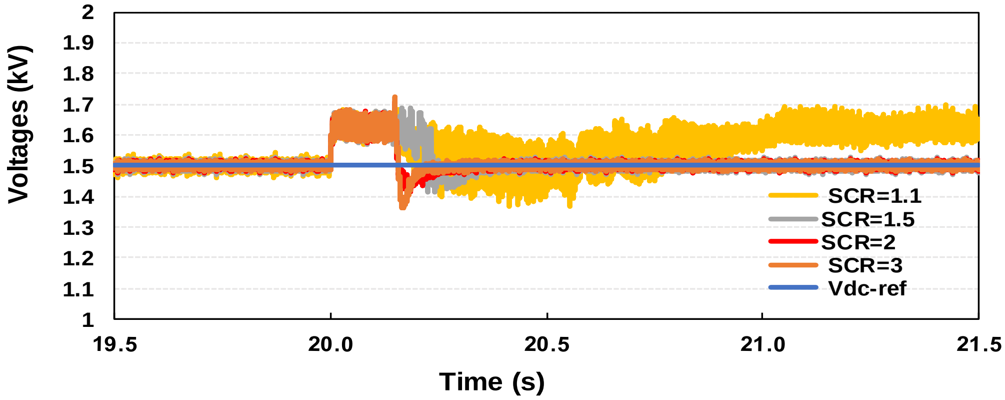
Simulation results show the effectiveness of the DC chopper control at the occurrence of a three phase to ground fault at the AC grid bus for different SCR values as shown in Figure 5-9. Figure 5-9 (a) shows the voltage of the AC grid under different values of SCR; it can be noticed that the longest time taken for the voltage recovery is when the AC grid has an SCR of 1.5 while the shortest one is when the AC grid has an SCR of 3. The transient performance of the AC grid has been improved significantly compared to the results without the DC chopper: the AC grid voltage returned to its steady-state limits much more quickly.

Furthermore, the DC voltage is kept within acceptable limits, and the converter is protected from the overvoltage of the DC link during the AC grid fault, as shown in Figure 5-9 (b). Additionally, the transferred wind power to the AC grid is limited to about zero MW at the same time that the reactive power is generated by the wind farm to support its and AC grid voltages and faster the voltage recovery after clearing the fault, and the AC grid is stopped to deliver reactive power when the AC grid voltage dips to zero; see Figures 5-9 (c), (d) and (e). Then, the DC voltage is backed by a steady state value after clearing the fault. The wind farm is able to recover its pre-fault value as soon as the fault is cleared; when the AC grid has an SCR of 3 and 2, the AC grid is quite immune to the AC grid fault. When the AC grid has an SCR of 1.5, the results demonstrate that a satisfactory performance is possible, but the restoration to the pre-fault value is slow. If the AC grid has an SCR of 1.1, the restoration is not reasonable and does not have a stable steady state operation after clearing the fault since the AC grid cannot generate sufficient reactive power to support its voltage, and the wind farm is unable to return its output to operating with the unity power factor control, as shown in Figures 5-9 (d) and (e).

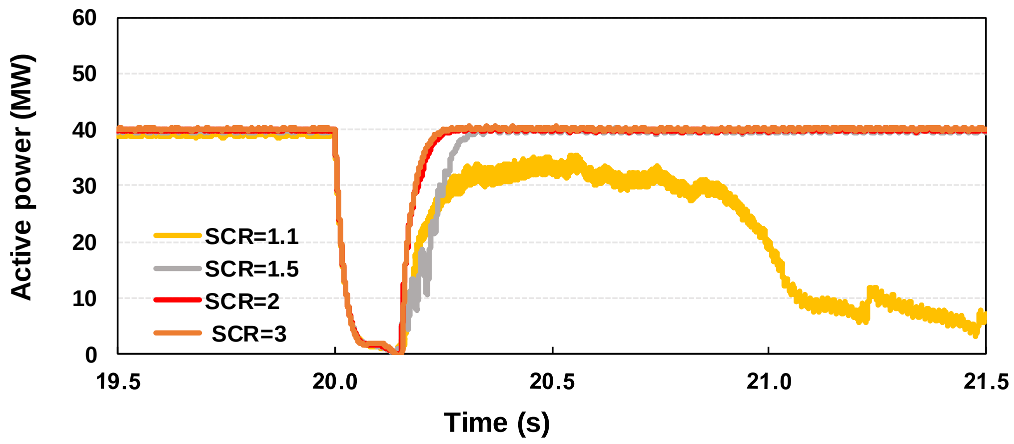
As is clear from the simulation results in Figure 5-9, the full power converter which is equipped with the DC chopper control helps to stay wind farm in operation, when the AC grid has an SCR value equal to 3, 2, and 1.5 without any additional measures. Using the DC chopper improves the FRT capability of the wind farm by mitigating the overvoltage of the DC link to keep the connection with the AC grid. Additionally, wind farm generates a reactive power, which can improve the time of recovery to the normal operation of the system. Thus, the wind farm that operates at unity power factor control and is appropriate to control the connection of the wind farm to the AC grid has these SCR values. The wind farm will have a capability to withstand severe AC grid faults for 140 ms without disconnecting from the grid when the fault has removed. Thus, the compatibility with grid code requirements can be satisfied. However, using the DC chopper control is not sufficient to improve the FRT of the wind farm that is connected to the AC grid with an SCR of 1.1, despite the extra power dissipated in the DC chopper during the fault. The transient response of the wind farm for injecting/ consuming reactive power is related to the reaction of the controllers of the GSC that regulates the reactive power to the AC grids. Therefore, it is necessary to investigate different control modes to regulate the reactive power exchange between the wind farm and the AC grid. In order to improve the performance of the GSCs. External reactive power compensation may be considered as an alternative solution to enhance the restoration of the wind farm after fault clearing. This will be verified in the next part of this Chapter.



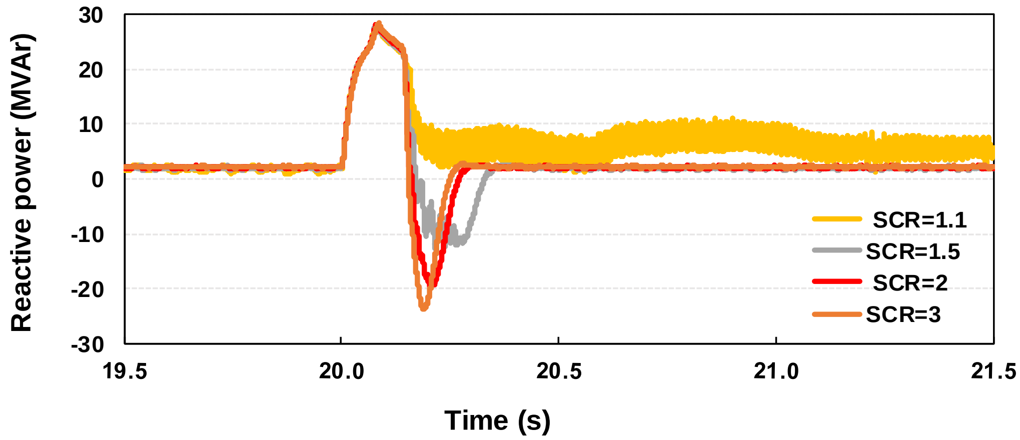
(a) AC grid voltage



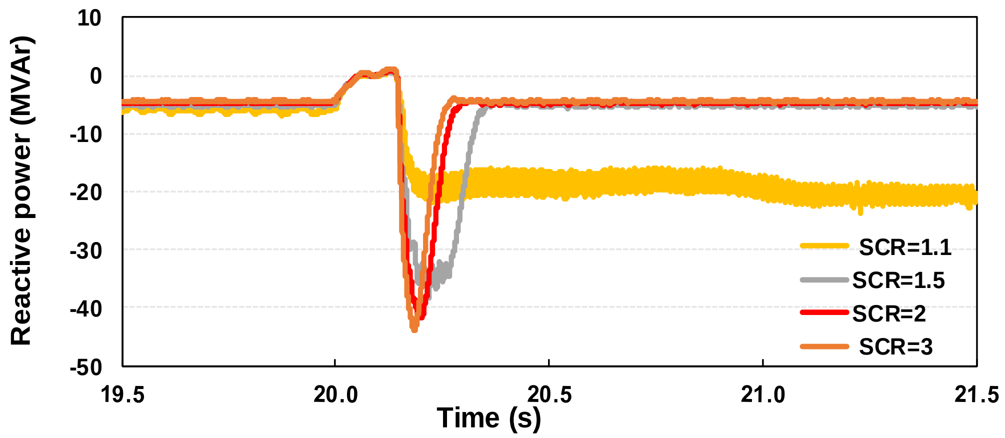
(b) DC voltage



(c) Wind farm output



(d) Wind farm reactive power



(e) Grid reactive power

Figure 5- 9: Simulation results of a wind farm with an AC grid under different SCR values at the fault with a DC chopper

5.4.2.2 AC grid fault: results with a supplementary Control at SCR=1.1

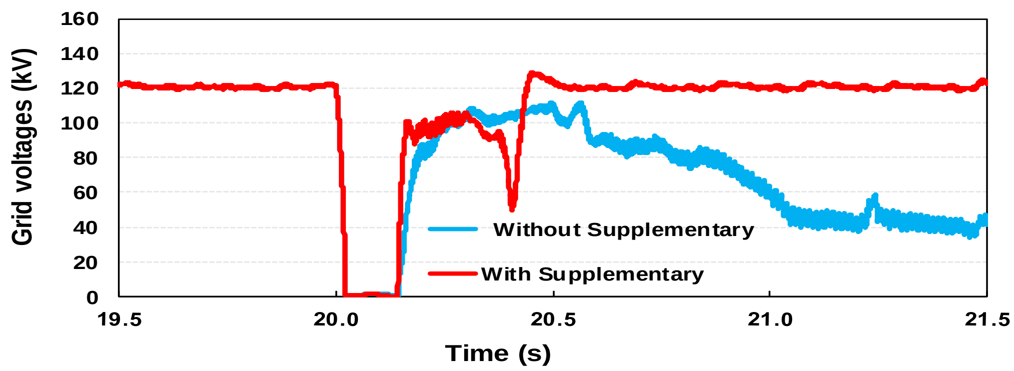
From the above results, the worst case was when the AC grid had an SCR of 1.1. It can be seen that there are several challenges, such as troubled restoration and an undesirable disconnection occurred after clearing the fault, and a large oscillation in powers and voltages. This is against the grid code requirements, which encourages the continuous connection of wind farms to the AC grid during a fault and after clearing the fault. It is expected that the wind farm will provide a sufficient reactive power support to assist in the AC grid voltage recovery. However, what happened was that the wind farm operating at unity power factor was unable to support the AC grid with the SCR of 1.1. During the fault, the wind farm's link to the AC grid will be weaker, and this makes restoring normal conditions very difficult. Furthermore, during the fault recovery, the increase in the wind farm's active power leads to an increase in the reactive losses in the AC grid because those losses are proportional to the square current; thus, a less reactive power will be available to support the AC grid voltage from the grid. Therefore, the reactive power control in the GSCs has been improved by using a supplementary control to help wind farm to resume normal operating conditions when the fault is removed. In this section, the DC chopper was presented in the DC link of the full power converter to dissipate extra power during the fault period. Furthermore, the supplementary control is introduced for a few milliseconds, and then the system operation is returned to the steady state control scheme.

- **Unity power factor control mode**

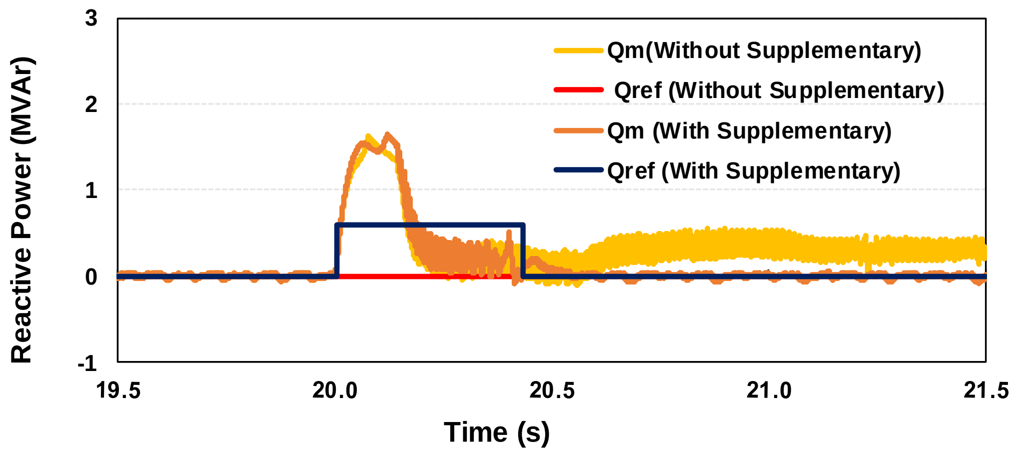
When the wind farm operated at unity power factor (reference reactive power is zero), the AC grid voltage dipped close to zero during the fault, and thus all the power output of the wind farm was trapped. When this happens, the AC grid voltage cannot be restored after the fault clearing, and then the system collapses, as shown in Figure 5-10(a). In order to restore the normal operation when the fault is removed, unity power factor control with the supplementary control was used, the reactive power reference changed from 0 to 0.6 MVAr for each wind turbines when the AC grid voltage exceeds the allowable minimum of 0.9 pu, as shown in Figure 5-10(b). Figure 5-10(c) shows the transferred wind farm output drops to about zero MW during the fault and the GSC generates much more reactive power to support the wind farm voltage and help maintain the connection between the wind farm and the AC grid in both cases, whether the unity power factor control only or with the supplementary control.

When the fault is cleared, the system cannot return to normal operating conditions in the case of only unity power factor control. However, if the supplementary control is used, the normal operating conditions can be restored. At the moment of clearing the fault, the generated reactive power of the wind farm decreases, as in Figure 5-10(d). In the meantime, the generated reactive power of the AC grid increases in order to re-establish its voltages, as shown in Figure 5-10(e). In the case of unity power factor control, the reactive power of the wind farm is reduced, but it cannot be returned to the pre-fault value whereas by applying the supplementary control, the reactive power will be forced to be zero (reactive power reference = 0) when the AC grid voltage is less than 0.9 pu, and to return to the pre-fault value. At the same time, the AC grid is allowed to generate enough reactive power to re-establish the voltage a few milliseconds after the fault has been cleared and normal operation is restored; see Figures 5-10(d & e).

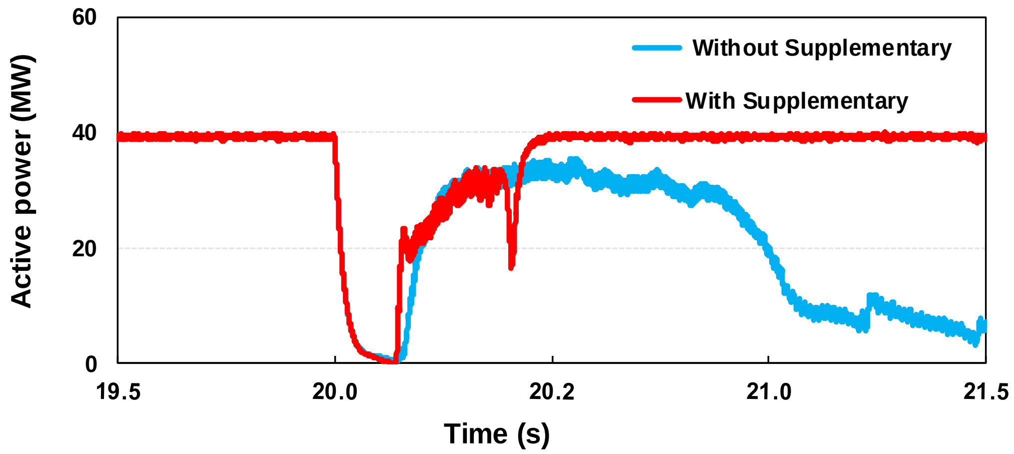
It can be concluded from the results in Figure 5-10 that the AC grid voltage restored the normal operating value by using the supplementary control. When the wind farm output drops, the reactive power of the wind farm increases, and the wind farm returns to pre-fault values within 4 ms. Hence, the cooperation between the wind farm and the AC grid in maintaining their connection during and after the faults with the presence of the DC chopper has been improved by using the supplementary control.



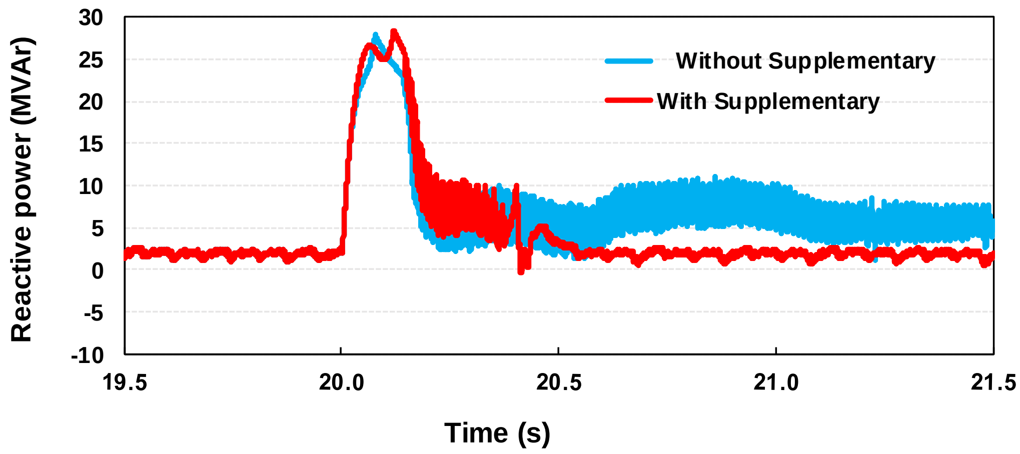
(a) AC grid voltage



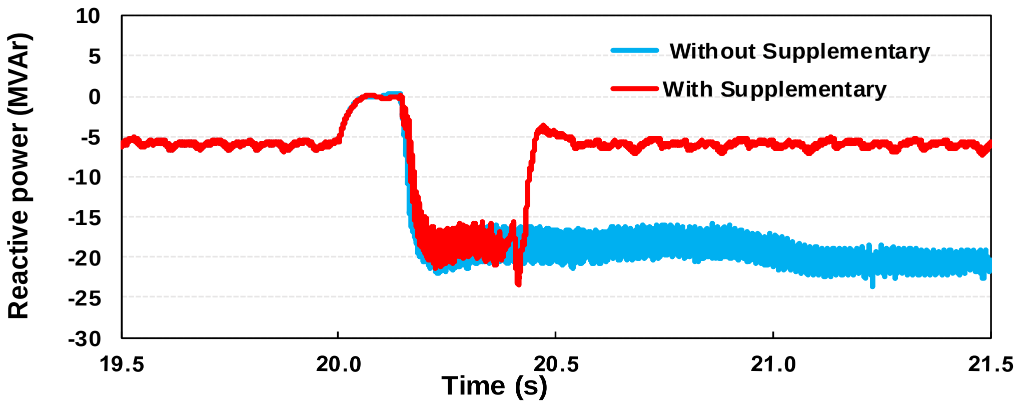
(b) Reference and measured the reactive power of grid side converter



(c) Wind farm output



(d) Wind farm reactive power



(e) Grid reactive power

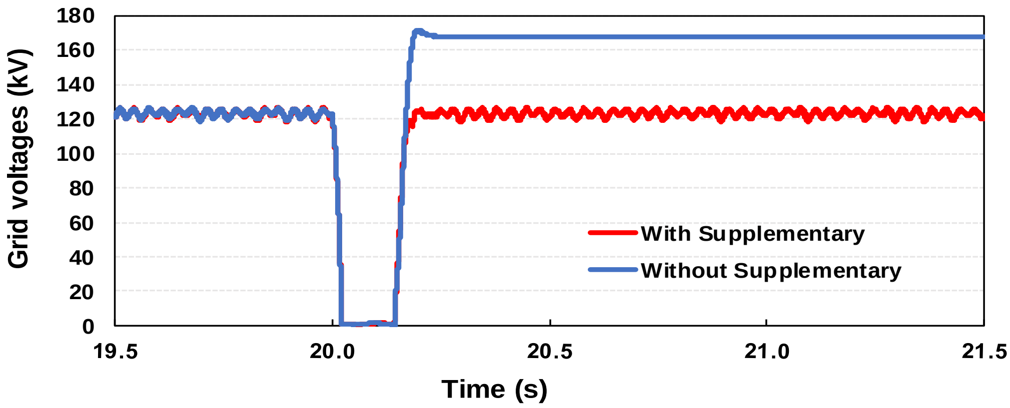
Figure 5- 10: Simulation results of a wind farm with SCR=1.1 in power factor control mode

- **AC voltage control mode**

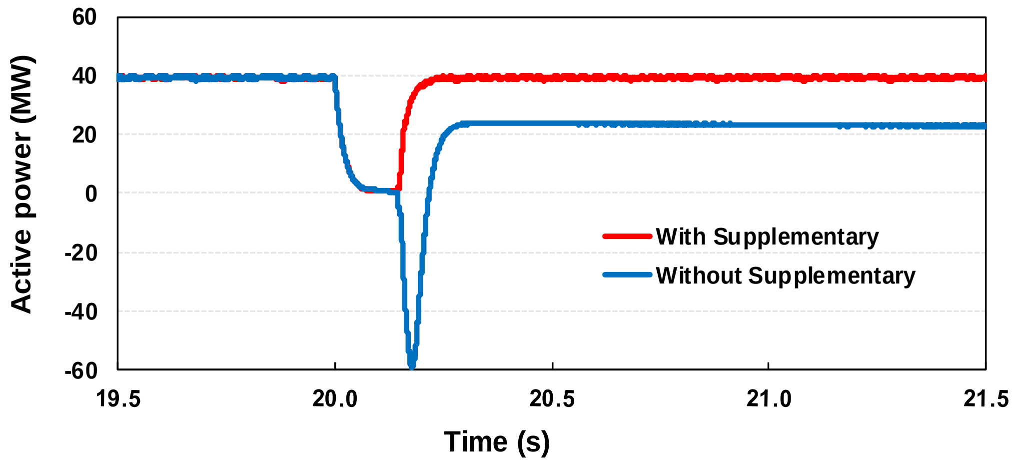
Another possibility would be to implement the AC voltage control mode instead of unity power control mode, which could give a constant regulation of the reactive power. The AC voltage control used to regulate a terminal voltage of the GSC to the set-point is 1 pu; in turn, it regulates the wind farm voltage to the same point, that is, 1 pu. This part will focus on the current limiters of the GSCs because of its importance in supplementary control to improve the recovery to the normal operating conditions after the removal of a fault. In steady state, the current limit for the reactive current reference is assumed to be 0.3 pu, and according to Equation (5.4), the limit of the active current reference will be 0.9 pu to achieve a maximum current of the converter equal to 1 pu in steady state conditions. The reactive current limiters will be changed depending on the value of the AC grid voltages in transient conditions.

Figure 5-11 (a) shows the AC grid voltage. It can be seen that the AC voltage dips to the value close to zero during the fault period in both cases, that is when the AC voltage without and with supplementary control. However, the situation is different in the recovery condition. Regarding the AC voltage control without supplementary control, an overvoltage trip of the wind farm occurred after fault clearing. Due to overvoltage, the system was unstable. The direction of the wind farm active power was reversed, and the wind farm stopped delivering active power to the AC grid at fault clearing, as shown in Figure 5-11(b). AC voltage control contributes to keeping a high voltage due to the full rating (80 MVAr) of the GSC, which is utilized to supply reactive power at the moment of fault clearing, as shown in Figure 5-11(c). The reactive current of around 1.4 pu exceeded the high current limits, as shown in Figure 5-11(d). The AC grid absorbs the reactive power generated by the wind farm, as shown in Figure 5-11(e). In the meantime, the wind farm converters are unable to reduce the reactive power and so return to normal operation after the fault has been cleared.

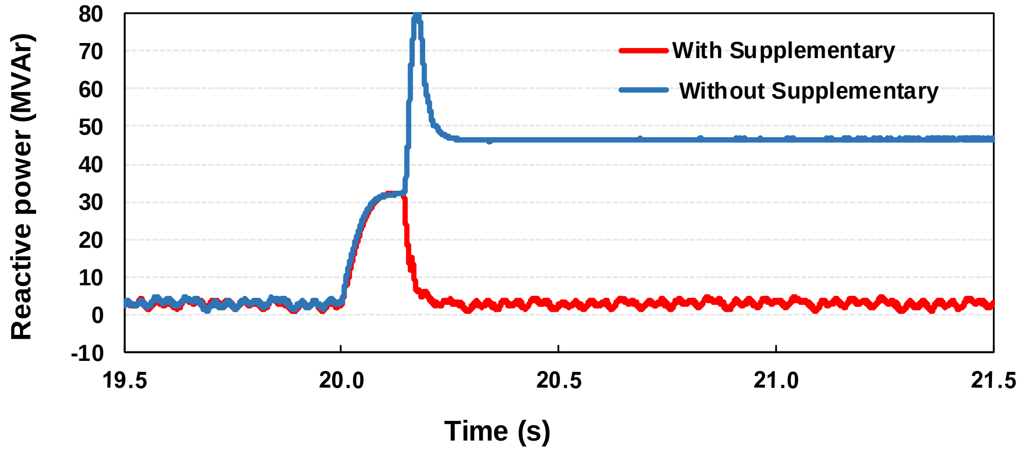
In the case of using supplementary control, it can be seen that upon the occurrence of the voltage dip, as shown in Figure 5-11(a), the transferred power from the wind farm to the AC grid drops to about zero MW. After the fault is cleared, the AC grid voltage is restored to the normal operating value, within the continuous operating voltage. Furthermore, wind farm active power is recovered, as shown in Figure 5-11(b).The wind farm generates reactive power to support the AC grid voltage, and the system returns to the stable state at fault clearing, as shown in Figure 5-11(c). The reactive current limiter reduced to – 0.9 pu assisted significantly in reducing the additional reactive current that causes the overvoltage and in returning the system to stability after the removal of the fault, as shown in Figure 5-11(d). The AC grid generates a sufficient amount of reactive power, as shown in Figure 5-11(e) to maintain the connection between the wind farm and the AC grid at the fault, and to recover stability status after the fault clearing. The disadvantage of this method is an oscillation in the active power, reactive power, and AC voltage.



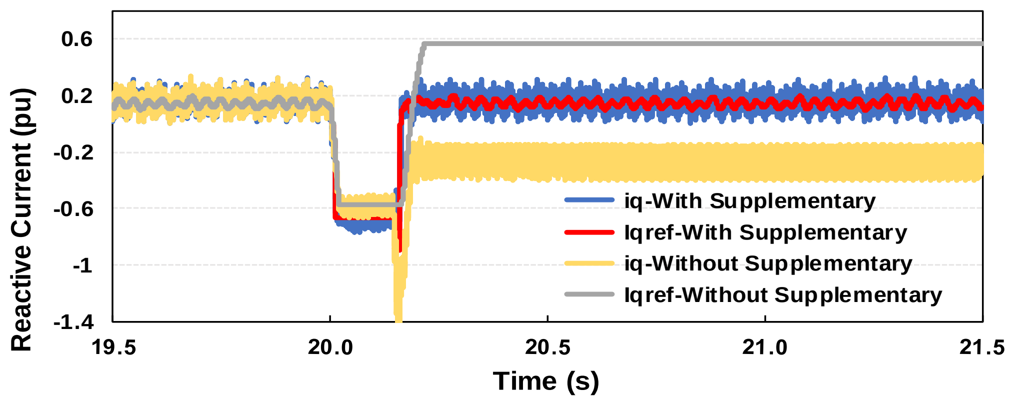
(a) AC grid voltage



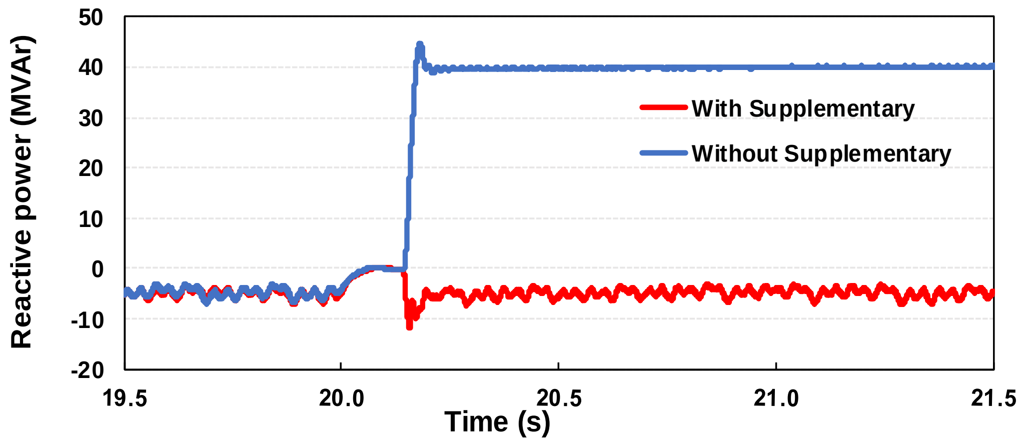
(b) Wind farm output



(c) Wind farm reactive power



(d) Reference and measured reactive current



(e) Grid reactive power

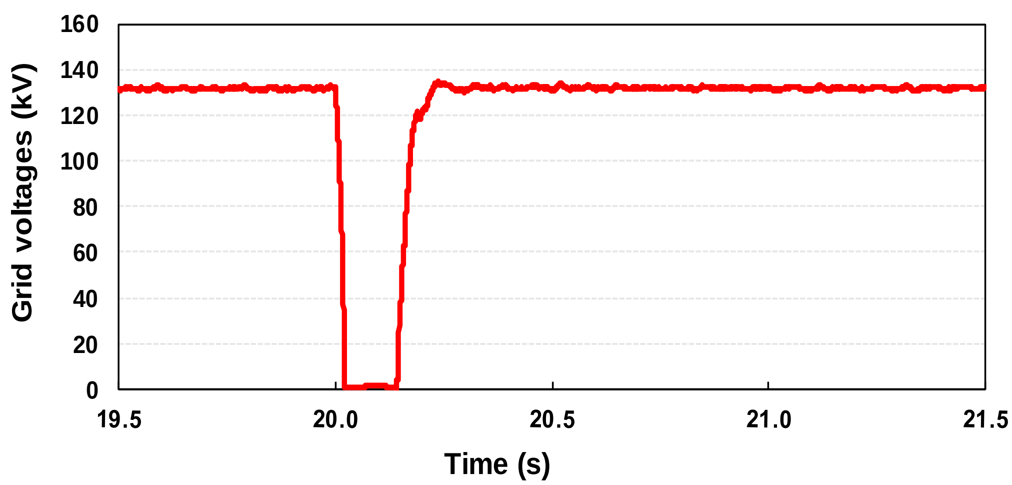
Figure 5- 11: Simulation results of a wind farm with SCR=1.1 in AC voltage control mode

5.4.2.3 AC grid fault: results with the 50 MVA STATCOM at SCR=1.1

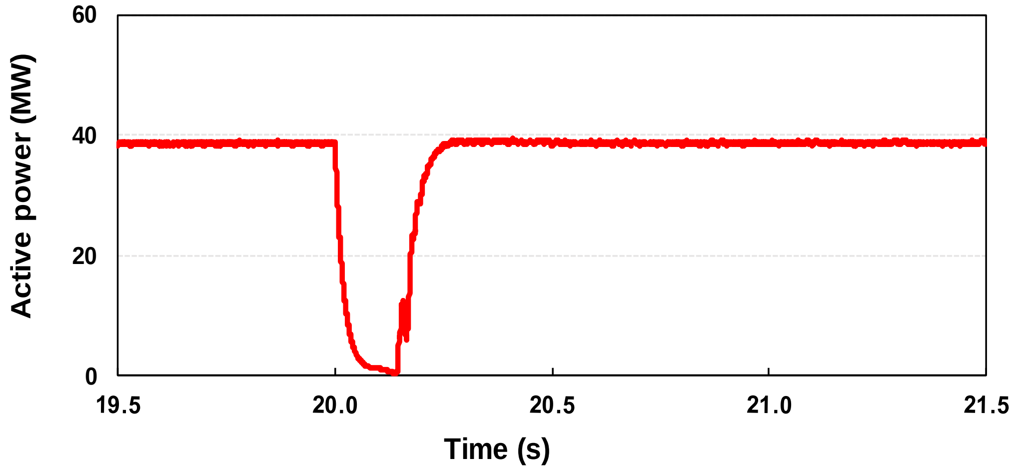
The main purpose of this part is to investigate the use of the STATCOM control and the DC chopper control to support a wind farm in order to achieve the requirement of FRT in the case of severe AC grid faults. In addition, the aim is to demonstrate the effectiveness and sensitivity of the proposed droop control scheme for the STATCOM. The wind farm operates with unity power factor control. The capacity of the STATCOM is designed based only on power flow calculation results in Chapter 4. The STATCOM with a rating of 50 MVA and the droop gain value is 1.52 was used and connected to the AC grid bus to provide a local voltage support to the very weak AC grids. Figures 5-12(a)-(d) show the simulation results of the AC grid voltage, wind farm active power, reactive power curves, and reference and measurement of the reactive power of the GSC.

Figure 5-12(a) shows the AC grid voltage; it can be clearly seen that the AC grid voltage dips to almost zero during the fault. The transferred active power is reduced by around zero MW, as shown in Figure 5-12(b); the wind farm reactive power injected during dip is around 28MVAr to maintain the connection of the wind farm with the AC grids (see Figure 5-12(c)). Thereafter, the AC grid voltage recovers quickly to the pre-fault value at the fault clearing. It seems that the AC grid voltage profile is much improved due to the reactive power and local voltage support that is provided by the STATCOM, as shown in Figure 5-12(c). The STATCOM control responds quickly and injects reactive power to support the AC grid voltage due to the cooperation with the AC grid reactive power. Thus, the reactive power contribution of the STATCOM enhances the ability of the wind farm to recover the normal operation of the system. Moreover, the wind farm power recovers the pre-fault value in less than 2 ms. Thus, the capability of the wind farm's FRT improves significantly, and the wind farm continues to operate during and after the fault clearing. In addition, the reaction of the STATCOM control that regulates the AC grid voltage enables the unity power factor control of the GSC to improve its performance as soon as the fault is cleared, as shown in Figure 5-12(d). The converter adjusts its reactive power exchange with the AC grid in order to support the voltages of the wind farm and AC grid during the fault.

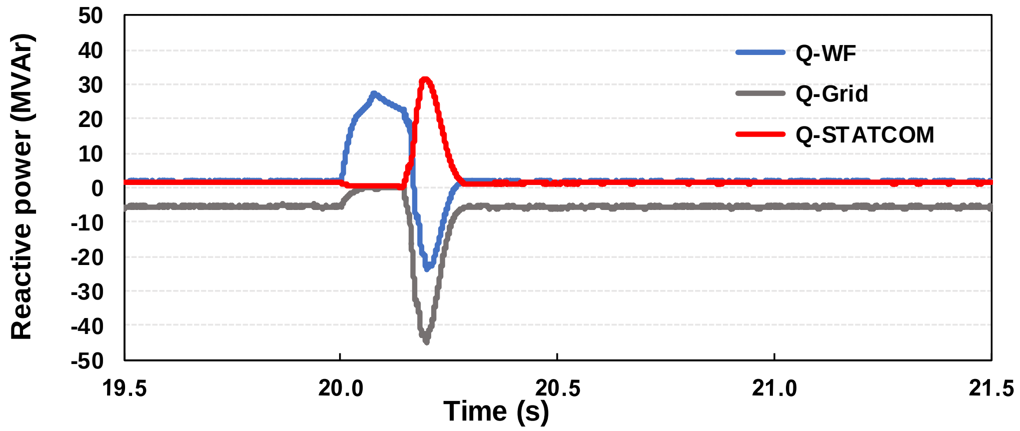
The cooperation of the STATCOM and the DC chopper as FRT technologies are now able to mitigate most concerns of weak AC grids. They prevent a wind farm tripping during faults and allow for the rapid recovery of the wind farm during fault clearing. Their control offer advantages over the GSC control: first, the response is faster to recover normal operation after fault clearing, and second, the oscillation in voltages and powers is less.



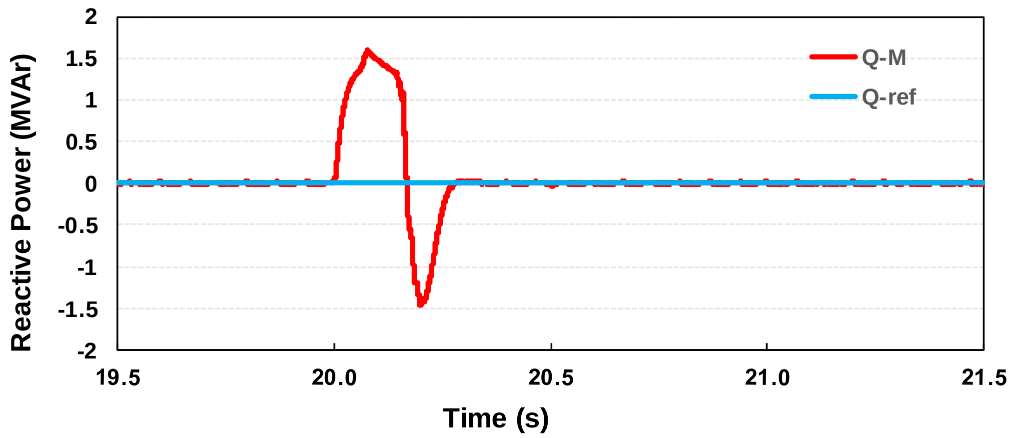
(a) Grid voltage



(b) Wind farm output



(c) Wind farm, grid, and STATCOM reactive power

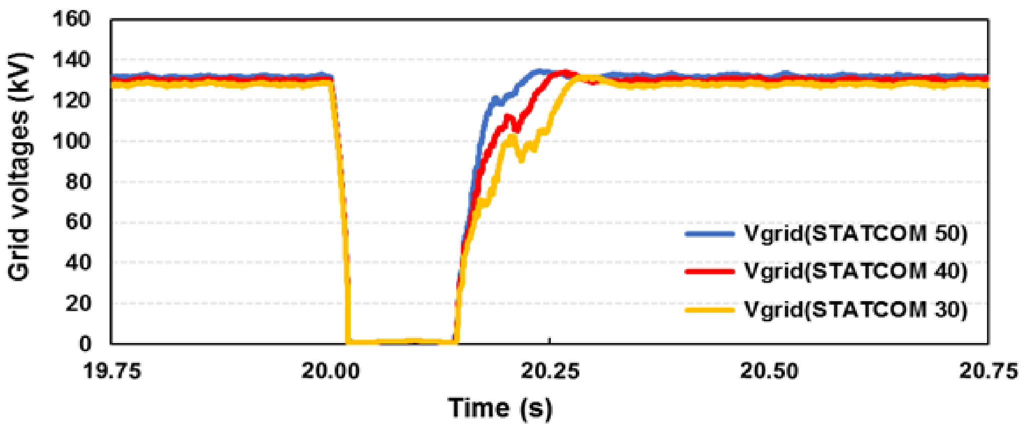


(d) Reference & measured reactive power of grid side converter

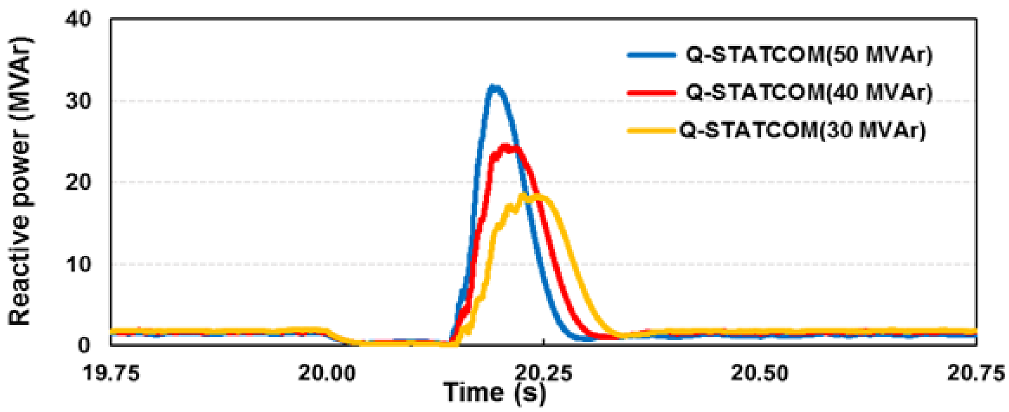
Figure 5- 12: Simulation results of a wind farm with an AC grid that has an SCR =1.1 including a STATCOM

➢ **Different rating of the STATCOM at SCR=1.1**

In order to demonstrate the sensitivity of STATCOM rating, three values are chosen are 50, 40 and 30 MVAr. AC grid voltage does not change considerably during the fault period in three values of STATCOM rating, but the response time to the voltage recovery is reduced as the value of the STATCOM rating is increased as shown in Figure 5-13(a). It means the transient stability margin for three-phase to ground fault is increased. Therefore the connection of the wind farms to the weak AC grid with a high rated STATCOM is able to withstand the fault for a long time. When the reactive power compensation is not large enough to complete compensating after the fault clearing leads to a slow voltage recovery as shown in Figure 5-13(b).



(a) Grid Voltage



(b) STATCOM reactive power

Figure 5- 13: Simulation results of a wind farm with an AC grid that has an SCR =1.1 under different rating of a STATCOM

5.5 Summary

The transient stability of wind farms connection to weak AC grids was studied, and the challenges of that connection during a severe fault were highlighted. The FRT and voltage control capability of the wind farm were explained. Technical factors that limit the wind farm's capability to deliver reactive power and recover normal operation after fault clearing was also discussed. The test system including; wind farm and STATCOM were described. Wind farm comprises of variable-speed wind turbines using full power converters. Full power converters were equipped with the DC chopper.

The effect of the SCR values of the AC grid was investigated on the behaviour of wind farm when three-phase to ground fault at the AC grid bus. The full power converter equipped with and without the DC chopper control strategy was tested. In the strong AC grids which have a high SCR, the full power converter equipped with the DC chopper is able to ride through AC grid faults and allows for rapid recovery with minimal oscillatory behaviour. In very weak AC grids that have a low SCR, DC chopper control is not enough to enhance the fault ride-through capability of the wind farm and high oscillations may grow with the risk of voltage instability problems and collapse when the fault has removed. The supplementary control was proposed in the GSCs under different control modes to improve recovery of the system. The effectiveness supplementary control in the GSCs with the DC chopper control was tested. Those control could be a satisfactory solution to enhance the FRT of wind farms, but grid voltage recovery is slow and a high oscillation in power and voltages. A fast voltage control capability of the STATCOM was also utilized to support the transient stability of a very weak AC grid. STATCOM with DC chopper control is able to exclude most concerns about tripping wind farm during faults and allows for the rapid and well-behaved recovery of the wind farm and the AC grid when fault clearing. STATCOM with DC chopper offers good advantages over the GSC control: first, the response is faster to recover normal operation after fault clearing second, the oscillation in voltages and powers is less. Thereby, the reliable and secure system can be achieved with those technologies.

Chapter 6

Conclusions & Future Work

6.1 Conclusions

6.1.1 Steady-state characteristics of weak AC grids

In power systems, voltage instability is frequently associated with weak AC grids. The weak AC grids have steady-state characteristics that make the connection unreliable and unstable. The characteristics of weak AC grids were investigated and compared to those of the strong AC grids by using P-V and V-Q curves. AC grids were presented by different short-circuit levels.

The simulation results show that the voltage stability limits of the AC grids vary significantly with the grid short-circuit level. A weak AC grid, which is represented by a low short-circuit level has a low voltage stability limit and is closer to the voltage instability as a result of a high grid impedance. In contrast, a strong AC grid, which is represented by a high short-circuit level has a high voltage stability limit. Moreover, the weak AC grid has the reactive power margin lower than that in the strong AC grid. Thus the capability of reactive power support of weak AC grid is low compared to that in strong AC grids.

6.1.2 Power transfer capability of wind farms

Limitations of the AC grid and the power converter are known as the technical factors which limit wind power transferred to AC grid. The limitations of the AC grids, including angle and voltage stability limits were investigated analytically. From that analysis, it can conclude that the low SCR and a high phase angle impedance of the AC grid can restrict the amount of the transmitted wind power. In addition, weak AC grid that has a low SCR needs more reactive power compared to strong AC grid that has a high SCR to support its voltage and accommodate more active power from the wind farms.

The amount of the power transferred from a wind farm was compared for strong and weak AC grids. Simulation results show that strong AC grids can accommodate more wind power without adverse effects on voltage stability and the grid voltage can be quickly re-established. Whereas it was found that power transferred from a wind farm is limited in a weak AC grids and voltage instability has happened. It was found that the reactive power support is required to regulate the AC grid voltage within acceptable limits and to help weak AC grids to accommodate more power from the wind farm.

In wind farm, full power converter control under different control modes (constant reactive power control, power factor control, and AC grid voltage control) was considered to increase the transferred wind power and to support weak AC grid voltage. The use of constant reactive power control and power factor control is allowed to increase the transferred power, but the AC voltage of the weak grid and wind farm exceeded the upper allowable limit at a low amount of the wind power. However, within the acceptable voltage limits for a wind farm and weak AC grid, the highest wind power is transferred when the power converter operates in the AC voltage control mode.

The capability of static and dynamic reactive power compensators was also examined to increase the power transferred from a wind farm and to support weak AC grids. A fixed capacitor was used as a static reactive power compensator. The use of the fixed capacitor has a benefit in increasing the power transferred to the weak grid, but the operation of the fixed capacitor is not very sensitive to the AC grid voltage change, hence the grid voltage considerably exceeds the safe margins with the high size capacitor. The dynamic reactive power compensators such as SVC and STATCOM were also investigated. The simulation results show that local control by the STATCOM and SVC greatly helps to increase the power transfer from a wind farm and to support the weak AC grid. However, the STATCOM shows advantages over SVC and full power converter control. The advantage of the STATCOM over SVC is that the compensating current is not influenced by the AC grid voltage level; thus the compensating current does not drop as the AC grid voltage drops. The main advantage of the STATCOM over full power converter of wind turbines is STATCOM provides much higher capacity that the full power converters. As the main duty of the wind farms' converter is to inject active power into the AC grid, there is only a limited capacity to deliver reactive power. Furthermore, the local STATCOM control is able to support the weak AC grid to accommodate more wind power compared to full power converter control. The use of the STATCOM control helps the power converter rating to be utilised only for the active power transfer in a wind farm.

6.1.3 Application of STATCOM for increased power transfer of wind farms to weak AC grids

Different control modes are implemented for the STATCOM to regulate the reactive power support to weak AC grids. The AC voltage, the reactive power and AC voltage droop control modes have been investigated. The AC grid was modelled as a voltage source behind the Thevenin impedance and as a synchronous generator. The simulation results show that the STATCOM control responds quickly when it detects the AC grid voltage reduction. The STATCOM injects reactive power and compensates the voltage reduction whether the weak AC grid is modelled by the voltage source or by the synchronous generator. The effectiveness of the STATCOM control is demonstrated by its ability to improve the grid voltage regulation, enabling the weak AC grid to accommodate more transferred power, and thus preventing voltage instability and system collapse.

6.1.4 Transient recovery of wind farms connected to weak AC grids

The transient stability of wind farms connected to AC grids was studied. A large amount of wind farm output, the low converter size, and the low SCR values of the AC grids are the main technical factors that limit a wind farm converter's capability to deliver reactive power to the AC grid and restore stable operation after fault clearing. Different SCR values of the AC grid were investigated to identify their effect on the behaviour of a wind farm during a three-phase to ground fault at AC grid bus.

When a fault occurs at the AC grid bus bar, it results in a drop in the AC grid voltage, and the wind farm active power cannot be fully transferred to the AC grid under different SCR values. In the meantime, the wind generators continue to generate active power that is provided to the DC-link of the full power converter. The capacitor of the DC-link will be overcharged, which will cause an overvoltage across the DC-link, and likely block the converters and force the wind generators to disconnect from the AC grids during the fault.

When the full power converter is equipped with DC chopper control, the simulation results show that standard vector current control strategy with the participation of the DC chopper control is an appropriate technique to connect a wind farm to the strong AC grid when the wind farm operates with unity power factor. The wind farm stays connected to the AC grid during and after fault clearing and with the acceptable restoration of the stable operation. However, in weak AC grids, particularly very weak ones, voltage instability and system collapse occurred as a result of a difficult voltage recovery after fault clearing. The voltage recovery was difficult as a result of the AC grid and wind farm are unable to meet the reactive power required to build AC grid voltage when the fault has removed. Furthermore, the high oscillations in the voltages and powers are observed as a consequence of the high grid impedance. Therefore, the use of DC chopper control is not adequate to improve the FRT of the wind farm that is connected to a weak AC grid, despite the extra power dissipated in the DC chopper during the fault.

A supplementary control incorporated to the standard vector current control strategy in GSC has proposed to aid the recovery process, and to continue operation for the wind farm after fault clearing. In addition, the overvoltage of the DC link of full power converters was addressed by the DC chopper control. The supplementary control in GSCs is satisfactory solutions to improve the restoration of the stable operation. However, the restoration is slow compared to that in strong grids. The voltage and power oscillations have not been mitigated significantly.

A STATCOM with the AC voltage droop control was tested to improve recovery operation in a very weak AC grid. The effectiveness of STATCOM control compared to that in the GSC offers advantages such as recovery to normal operation is faster as the reactive power compensation quickly produces a large amount of reactive power after fault clearing, the oscillation is less in voltage and power, and the AC grid voltage profile has improved considerably. In addition, the application of the STATCOM control that regulates the AC grid voltage, enable the unity power factor control of GSC to improve its performance as soon as the fault is cleared. The continuous operation of the STATCOM is not required, resulting in an increase in the lifetime of the devices in STATCOM. STATCOM control with DC chopper control as a FRT technology is able to exclude most problems of weak AC grids and ensure the stability and security of the connection to wind farms.

6.1.5 Recommendation

Existing Grid Codes and Connection Agreements cover only strong power grids, and there are few regarding weak power grids. Grid Codes and Connection Agreements should adopt the technical constraints, which are related to the AC grid strength, and specify the minimum (critical) SCR that is valid depending on the characteristics of wind generation technologies.

6.2 Contribution of the Thesis

The main contributions of the thesis are listed as follows:

- ❖ The main technical characteristics of the weak AC grids were investigated that make the voltage stability for those grids difficult.
- ❖ A static model for a wind farm connected to an AC grid through reactive power compensators was developed in IPSA simulation tools, to investigate the capability of the wind farm control and the reactive power compensators to increase the transferred wind power and support weak AC grid voltage.
- ❖ The relationships of the voltage deviation, transmitted wind power, and required reactive power were derived to analyse steady-state voltage stability of the AC grid.
- ❖ A dynamic model for the wind farm connected to the AC grid and a STATCOM were developed. A reactive power versus AC voltage control was designed in a STATCOM to help a weak AC grid to accommodate more wind power generation. The AC grid was modelled using two methods: as an ideal voltage source behind a Thevenin impedance and as a synchronous generator. The effectiveness of STATCOM control was tested to support and increase the transferred wind power to weak AC grid by simulation results.

- A new supplementary control was proposed in GSCs to enhance a restoration of the stable operation after the fault clearing and improve voltage profile for very weak AC grids. The effectiveness of supplementary control in GSCs and the STATCOM control were tested to recover the stable operation and improve the voltage for weak AC grid by simulation in PSCAD.

6.2.1 Achievements of the research

The outcomes of this research were written up in conference

- M. Nawir, O.D. Adeuyi, G. Wu and J. Liang (2017), "Voltage stability analysis and control of wind farms connected to weak AC grids". The 13TH IET international conference on AC and DC power transmission in Manchester, UK.

In addition, this work was presented at HVDC Colloquium, Cardiff University, UK in September, 2017 under the title of "Integration of wind farms into weak AC grids"

6.3 Future Work

Several topics possible for future work are outlined below.

- An experimental test rig may be designed to further investigate the performance of the connection of wind farms to weak AC grids and with the STATCOM, and to verify and support the effectiveness of the GSCs and STATCOM control in steady-state and transient stability analysis.
- Controllers are often designed to operate in a particular range of operation points. When an abnormal condition occurs, the operating points may go out of the designed range for the controllers, leading to an unpredicted response. Gains of the PI controller in vector current control strategy have reflected the operating range of the controllers. An AC grid that has a low SCR is more sensitive to the change in operating conditions. Therefore, the automatic regulation of control gains is a useful method to ensure stable operation over a wide range of operation points. The proposed future controllers are based on the mathematical relationships between the control gain and operation variables in the design the controllers such as the AC grid voltage or frequency.

The controllers can operate automatically to determine the control gain such as the gains of PLL, AC voltage control and reactive power control.

- Further analysis can be carried out with the aim of increasing the transferred power into a weak AC grid, where the angle of the AC grid voltage is taken into account. That angle is detected by the PLL, which is used to create synchronization between the wind farm converter voltages and the AC grid voltages. The performance of the PLL should be considered in the detection of the grid voltage angle during the increase wind power generation to weak AC grids. In addition, PLL stability can be taken into account under transient conditions when the wind farm is connected to weak AC grids.

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Appendix A

Wind farm connected to AC grid by the transmission line

A.1. Voltage deviation at AC grid bus

A possible explanation for the difference in critical load active power and critical voltage for different short circuit levels is described here. Comparison between the grid active power and reactive power for 150 and 500 MVA short circuit levels were carried out by increasing the load active power and shown in Figure A-1.

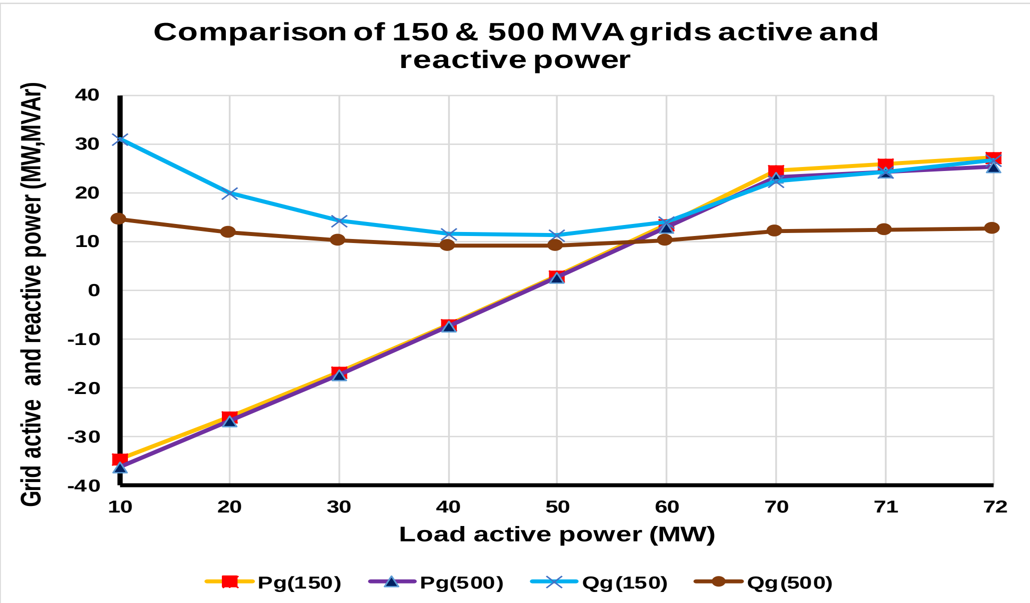

Figure A- 1: Comparison of 150 and 500 MVA grid active and reactive power

It can be seen that the reactive power flow has a significant difference when the short circuit level changes from 150 to 500 MVA; whereas the active power flow is approximately the same.

Figure A-2 illustrates a wind farm is connected to AC grid with transmission impedance $(R_g + jX_g)$. The voltage of the connection point is Vg (load bus bar). The voltage at a remote point can be taken as constant Vs (slack bus) and Vs = |Vs| . The output power and reactive power of the energy source such as wind farm are P and Q.

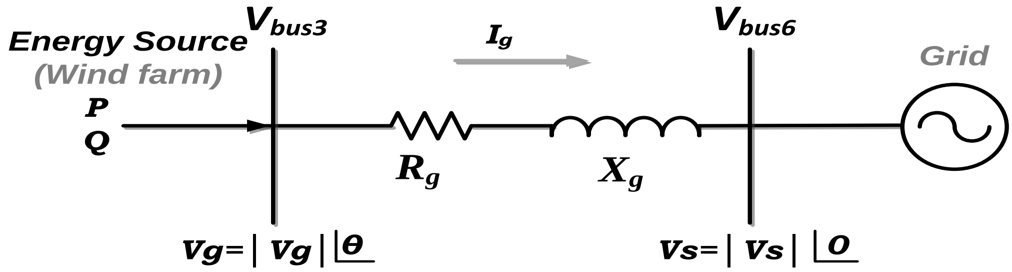

Figure A- 2: The equivalent diagram of the system between bus bars 3 and 6

In the diagram, R_g and X_g are the equivalent resistance and reactance between grid bus3 and slack bus 6 respectively. X_g is 0.34 pu at 500 MVA and 0.9301 pu at 150 MVA while R_g is 0.102 pu in both cases.

The short circuit power level S_{sc} in MVA is defined in equation (A.1) as

$$S_{sc} = \frac{V_s^2}{Z_g} \tag{A.1}$$

The grid current Ig is given in equation (A.2)

$$I_g = (\frac{S}{V_g})^* = \frac{P - jQ}{(V_g)^*} \tag{A.2}$$

The phasor diagram of the equivalent system in Figure A-2 is shown in Figure A-3

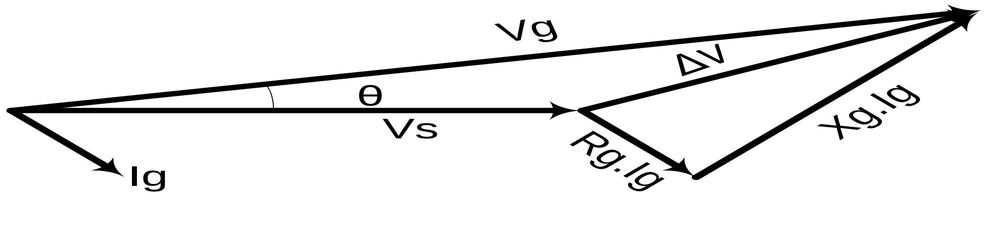

Figure A- 3: The phasor diagram of equivalent system between two bus bars

The voltage deviation, ΔV, between the AC grid bus and the system is given by (A.3)

$$V_g - V_s = \Delta V \tag{A.3}$$

ΔV is also given by (A.4)

$$\Delta V = Z_g I_g = (R_g + jX_g)(\frac{P - jQ}{(V_g)^*}) = \frac{R_g P + X_g Q}{(V_g)^*} + j\frac{X_g P - R_g Q}{(V_g)^*} \tag{A.4}$$

Substituting (A.4) in (A.3), yields

$$V_g = V_s + \frac{R_g P + X_g Q}{(V_g)^*} + j\frac{X_g P - R_g Q}{(V_g)^*} \tag{A.5}$$

Multiplying both sides of the equation (A.5) by $(V_g)^*$ yields

$$V_g.(V_g)^* = V_s.(V_g)^* + R_g P + X_g Q + j(X_g P - R_g Q) \tag{A.6}$$

It is clear from the equation (A.4) ΔV is related to the grid impedance and the real and reactive power output of the energy source. High transmission impedance Z_g cause large voltage variations compared to small impedance.

The grid voltage can be determined according to following equations.

$$V_g = |V_g|.e^{j\theta} = |V_g|cos\theta + j|V_g|sin\theta \tag{A.7}$$

where θ is the angle of AC grid voltage.

Substituting (A.7) and Vs = |Vs| in (A.6), yields

$$|V_g|^2 = |V_s|.|V_g|cos\theta + R_g P + X_g Q + j(X_g P - R_g Q - |V_s|.|V_g|sin\theta) \tag{A.8}$$

Equating the real and imaginary parts of both sides of equation (A.8) yields,

$$|V_g|^2 = |V_s|.|V_g|cos\theta + R_g P + X_g Q \tag{A.9}$$

And

$$0 = X_g P - R_g Q - |V_s|.|V_g|sin\theta \tag{A.10}$$

From equations (A.9) and (A.10)

$$|V_g|^4 - |V_g|^2.\left(2\left(R_g P + X_g Q\right) + |V_s|^2\right) + \left(R_g P + X_g Q\right)^2 + (X_g P - R_g Q)^2 = 0 \tag{A.11}$$

Solving equation (A.11)

$$|V_g| = \sqrt{\frac{|V_s|^2 + 2.\left(R_g.P + Q.X_g\right) + \sqrt{|V_s|^4 + 4.\left(R_g.P + Q.X_g\right).|V_s|^2 - 4.(X_g.P - R_gQ)^2}}{2}} \quad \text{(A.12)}$$

Equation (A.12), describes the grid voltage in terms of the delivered active and reactive power and the impedance of AC grids.

$$\Delta V = \sqrt{\frac{|V_s|^2 + 2.\left(R_g.P + Q.X_g\right) + \sqrt{|V_s|^4 + 4.\left(R_g.P + Q.X_g\right).|V_s|^2 - 4.(X_g.P - R_gQ)^2}}{2}} - |V_s| \quad \text{(A.13)}$$

In order to show why there is a difference in grid voltage in different short circuit level, the voltage at each bus was obtained by carrying out a power flow study. For instance, if the load active power is 56 MW, according to Equation A.12 the grid bus bar voltages are 0.9149 pu for short circuit level of 150 MVA and 0.9788 pu for the grid which has 500 MVA. Thus the voltage deviation according to Equation A.13 is 0.1051 for 150MVA and 0.0412 for 500 MVA grid. As a result of the reduction in reactive power flow and the low equivalent reactance make ΔV is much smaller in the case of short circuit level equal to 500 MVA.

The voltage deviation of the buses voltage buses in the system is given in Table A-1 for short circuit levels of 150 and 500 MVA.

Table A- 1: Comparison the voltage deviation of AC grids have short circuit levels of 150 and 500 MVA.

Name	S=150MVA	S=500MVA	ΔV(150 MVA)	ΔV(500 MVA)
Busbar6	1.02	1.02	-0.0658	-0.009
Busbar5	0.9542	1.011	-0.0768	-0.018
Busbar4	0.9432	1.002	-0.1051	-0.0412
Busbar3	0.9149	0.9788	-0.1111	-0.0461
Busbar2	0.9089	0.9739	-0.0723	-0.0081
Busbar1	0.9477	1.0119		

The reason why grid bus voltage increases with load growth when the short circuit level is 150 MVA in Figure 3-7 is the ΔV is positive when the load increase from 10 to 35 MW since the 150 MVA grid absorbs the real power from the wind farm. Whereas when the load increases more the 35 MW, the low short circuit grid generates a real power to meet the demand of the system thus ΔV will be negative and the grid bus voltage reduces.

A.2. Angle Stability Limit

Base on Equations (A.9) and (A.10) in section A.1 as written below

$$|V_g|^2 = |V_s|.|V_g|cos\theta + R_g P + X_g Q \qquad \text{(A.9)}$$

And

$$0 = X_g P - R_g Q - |V_s|.|V_g|sin\theta \qquad \text{(A.10)}$$

Solve Equation (A.10) to obtain Q, as shown in Equation (A.14)

$$Q = \frac{X_g P - |V_s|.|V_g|sin\theta}{R_g} \qquad \text{(A.14)}$$

Substituting Equation (A.14) in Equation (A.9) and extracting P from the resulting equation, P is given by

$$P = \frac{|V_g|}{{R_g}^2 + {X_g}^2}[R_g|V_g| - |V_s|.R_g cos\theta + |V_s|.X_g sin\theta] \qquad \text{(A.15)}$$

Equation (A.15) shows that the amount of active power transfer that can be delivered into the AC grid is limited by the AC grid impedance. Furthermore, the active power delivered to the grid depends on the angle of the AC grid voltage.

A.3. Voltage Stability Limit

From Equation (A.12) in section A.1, the magnitude of grid voltage as a function of power flows and grid impedance. The reactive power can be extracted from Equation (A.12) to obtain the required reactive power to set AC grid voltages within a certain level, regardless of reactive power source whether from the wind farm, the AC grid or any an external reactive power compensation.

$$Q = \frac{1}{{R_g}^2 + {X_g}^2}\left(|V_g|^2.X_g - \sqrt{|V_g|^2(2R_g P + |V_s|^2)({R_g}^2 + {X_g}^2) - |V_g|^4.{R_g}^2 - P^2({R_g}^2 + {X_g}^2)^2}\right) \qquad \text{(A.16)}$$

Appendix B

Parameters of PSCAD simulation

Table B- 1: Parameters of the PMSG

Generator Type	PMSG, 5 MVA, 690 V, 50 Hz
Number of Pole Pairs	100
Stator Winding Resistance, reactance	0.001 pu, 0.064 pu
d axis Synchronous reactance	0.15 pu
q axis Synchronous reactance	0.1 pu
Angular moment of inertia	0.7267 s

Table B- 2: Back to back converter parameters

Machine side converter		Grid side converter	
Inner loops		Inner loops	
id current	k_p =3,k_i=300	id current	k_p =3,k_i=300
iq current	k_p =3,k_i=300	iq current	k_p =3,k_i=300
Outer loop		Outer loop	
Speed control	k_p =0.5,k_i=25	DC voltage control	k_p =5,k_i=100
Reactive power control	k_p =0.5,k_i=25	Reactive power control	k_p =0.5,k_i=25
Capacitance	$20000\ \mu F$		
L; R	105 mH,0.001Ω		
Switching frequency	1650Hz		

Table B- 3: STATCOM parameters

Rating	50 MVA	Outer loop	
Inner loops		DC voltage control	k_p =10,k_i=200
i_d current	k_p =3,k_i=300	AC voltage control	k_p =1,k_i=50
i_q current	k_p =3,k_i=300	Reactive power control	k_p =0.5,k_i=25
L; R	105 mH, 0.001Ω	Switching frequency	1650Hz

Table B- 4: Parameters of hydro-synchronous generator

Generator Data Format	
Rated voltage, rated frequency	20 kV, 50 Hz
Inertia constant	3.117 s
Armature Resistance, Ra	0.0025 pu
Portier Reactance, X_P	0.163 pu
D: Unsaturated Reactance,X_d	1.8 pu
D: Unsaturated Transient Reactance,X'_d	0.3 pu
D: Unsat. Transient Time (Open),T'_{dO}	8 s
D: Unsat. Sub-Transient Reactance,X''_d	0.25 pu

D: Unsat. Sub-Transient Time (Open),$T_{dO}^{''}$	0.03 s
Q: Unsaturated Reactance,X_q	1.7 pu
Q: Unsat. Sub-Transient Reactance,$X_q^{''}$	0.25 pu
Q: Unsat. Sub-Transient Time (Open),$T_{qO}^{''}$	0.05 s
Air Gap Factor	1

Table B- 5: Parameters of excitation system

AC1A Alternator Supplied Rectifier: Forward Path Parameters	
Regular Gain, K_A	400.0 pu
Regular Time Constant, T_A	0.02 s
Maximum Regular internal voltage, V_{AMAX}	14.5 pu
Minimum Regular internal voltage, V_{AMIN}	-14.5 pu
Maximum Regular Output, V_{RMAX}	6.03 pu
Minimum Regular Output, V_{RMIN}	-5.43 pu
AC1A Exciter parameters	
Rate Feedback Gain, K_F	0.03 pu
Rate Feedback Time Constant, T_F	1.0 s
Exciter Time Constant, T_E	0.8 s
Exciter Constant Related to Field, K_E	1.0 pu
Field Circuit Commutating Reactance, K_C	0.2 pu
Demagnitizing Factor, K_D	0.38 pu
Saturation at V_{E1}, $S_E[V_{E1}]$	0.10 pu
Exciter voltage for $S_E[V_{E1}]$	4.18 pu
Saturation at V_{E2}, $S_E[V_{E2}]$	0.03 pu
Exciter voltage for $S_E[V_{E2}]$	3.14 pu

Table B- 6: Water turbine model parameter

Tur1: Non-Elastic Water Column & No Surge Tank	
Water Starting Time, $\boldsymbol{T_W}$	2.0 s
Penstock Head Loss Coefficient, $\boldsymbol{f_P}$	0.02 pu
Turbine Damping Constant, D	0.5 pu

Table B- 7: Governor model parameter

Gov1: Mechanical-Hydraulic Governor	
Pilot Valve-Servomotor Time Constant, $\boldsymbol{T_P}$	0.05 s
Servo Gain, $\boldsymbol{Q}$	5.0 pu
Main Servo Time Constant, $\boldsymbol{T_a}$	0.02 s
Temporary Droop, $\boldsymbol{R_t}$	0.5 pu
Reset or Dashpot Time Constant, $\boldsymbol{T_R}$	6.0 s

Appendix C

Transfer functions of some parts in the test system

- **Wind Governor Transfer Function**

The block diagram of the wind governor is shown in Figure C-1

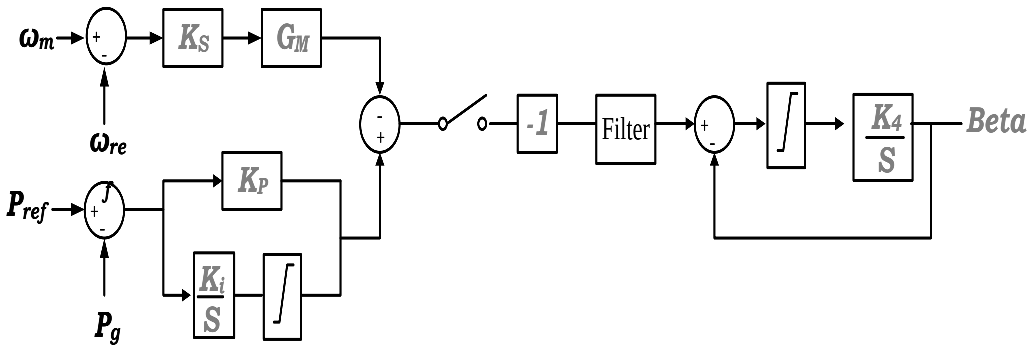

Figure C- 1: Wind Governor Transfer Function

ω_m	Mechanical speed of the machine rad/s	K_P	Proportional gain
ω_{ref}	Reference speed rad/s	K_i	Integral gain
P_{ref}	Power demand MW	G_M	Gain multiplier
P_g	Power output of the machine based on the rating	K_S	Gain
K_4	Blade actuator integral gain [s]		

- **Mechanical –Hydraulic Control (GOV1)**

The block diagram of GOV1 as shown in Figure C-2

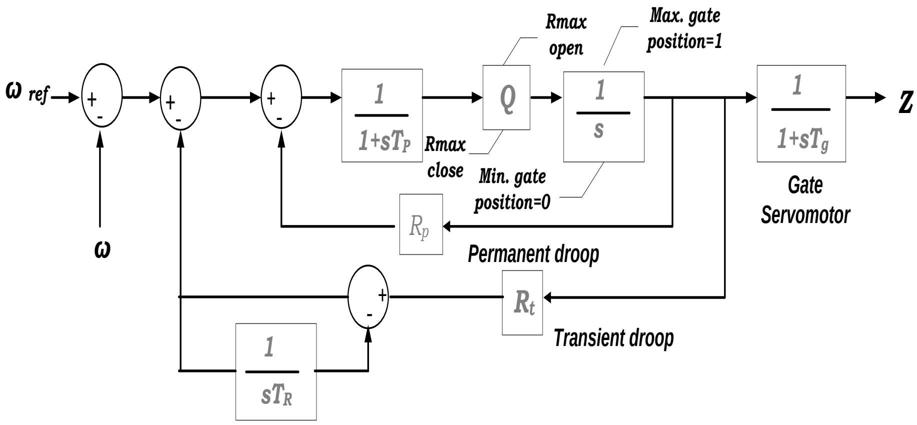

Figure C- 2: Mechanical –Hydraulic Control (GOV1)

T_g	Main Servo Time Constant [s]	T_P	Pilot valve and servo motor time constant [s]
R_P	Permanent Droop [pu]	T_R	Reset or Dashpot Time Constant [s]
R_t	Temporary Droop [pu]	$R_{MAX}open$	Max. Gate Opening Rate
Q	Servo gain [pu]	$R_{MAX}close$	Max. Gate Closing Rate

- **Non –Elastic Water Column without Surge Tank (TUR1)**

The block diagram of TUR1 as shown in Figure C-3

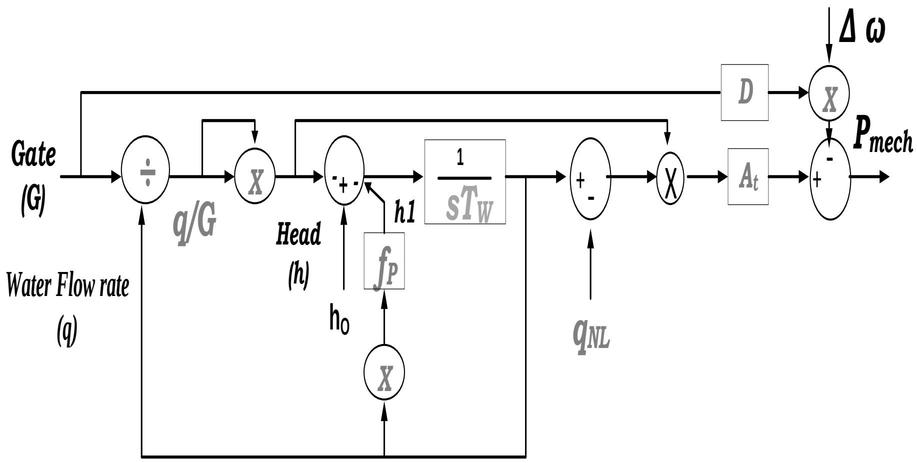

Figure C- 3: Non –Elastic Water Column without Surge Tank (TUR1)

A_t	Turbine Gain Factor Flow	q_{NL}	No load water flow [pu]
f_P	Penstock Head Loss Coefficient [pu]	T_W	Water Starting Time [s]
G	Gate Position [pu]	D	Turbine Damping Constant

q	Turbine Flow Before reduction by Deflector and Relief valves [pu]	h	Hydraulic Head at Gate
h_o	Initial Steady – State Value of h		

- **IEEE Alternator Supplied Rectifier Excitation System (AC1A)**

The block diagram of the AC1A as shown in Figure C-4

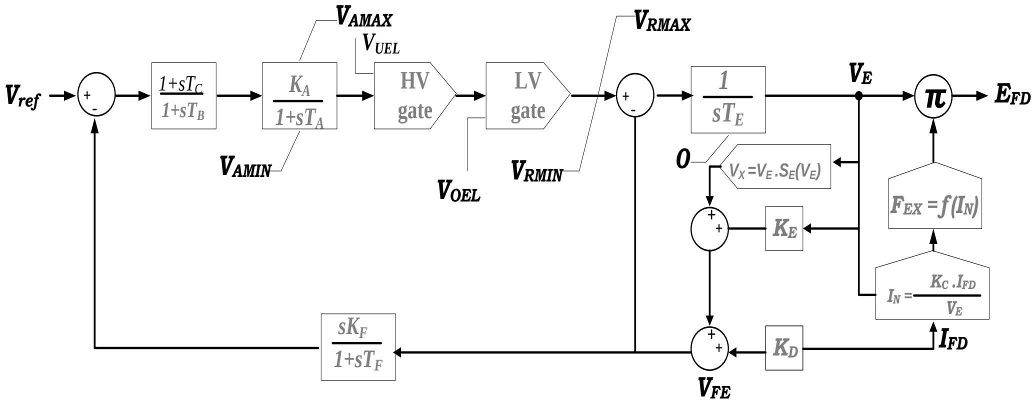

Figure C- 4: IEEE Alternator Supplied Rectifier Excitation System

E_{FD}	Exciter output voltage [pu]	T_E	Exciter time constant [s]
E_{EX}	Rectifier loading factor, a function of IN [pu]	T_F	Rate feedback time constant [s]
I_{ED}	Synchronous machine field current [pu]	V_{AMAX}, V_{AMIN}	Maximum and minimum regulator internal voltages [pu]
I_N	Normalized exciter load current [pu]	V_{E1}	Exciter voltage for SE1 [pu]
K_A	Regulator gain [pu]	V_{E2}	Exciter voltage for SE2 [pu]
K_C	Field circuit commutating reactance [pu]	V_F	Excitation system stabilizer output [pu]
K_D	Exciter constant related to field [pu]	V_{FE}	Signal proportional to exciter field current [pu]
K_E	Exciter Constant Related to Field	V_{OEL}	Over-excitation limiter input [pu]
K_F	Rate feedback gain [pu]	V_R	Voltage regulator output [pu]
$S_E[V_{E1}]$	Saturation at VE1 [pu]	$S_E[V_{E2}]$	Saturation at VE2 [pu]
V_{REF}	Voltage regulator reference (determined to satisfy initial conditions) [pu]	V_{RMAX}, V_{RMIN}	Maximum and minimum regulator outputs [pu]
V_X	Signal proportional to exciter saturation [pu]	V_T	Synchronous machine terminal voltage [pu]
T_B	Lag time constant [s]	V_{UEL}	Under-excitation limiter input [pu]
T_C	Lead time constant [s]	T_A	Regulator time constant [s]

Appendix D

Parameters of PSCAD simulation IN CHAPTER Five

Table D- 1: Grid side converter parameters

Grid side converter	
Inner loops	
i_d current	k_p =3,k_i=300
i_q current	k_p =3,k_i=300
Outer loop	
DC voltage control	k_p =5,k_i=100
Reactive power control	k_p =0.5,k_i=25
AC voltage control	k_p =1, k_i=50
c	$20000\ \mu F$
L; *R*	105 mH, 0.001Ω
Switching frequency	1650Hz

Table D- 2: DC chopper parameters

V_{start}	1.05 pu
V_{max}	1.15 pu
$P_{Chopper}$	5 MW
R_{braking}	0.5 Ω
Switching frequency	450 Hz