“Impact of Integration of FACTs Devices on Wind Farm Connected to Medium Voltage Grid under Healthy and Faulty Conditions”

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By

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Abstract

Wind energy is attracting more attention from researchers and even utilities due to its benefits as a clean and abundant source of energy. In this thesis a comprehensive and intensive study of a wind farm connected to the grid has been proposed. The aim of this thesis is to investigate the system stability of a wind farm connected to medium voltage grid in different operating conditions and to investigate the behavior of the system when using a Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) for wind farm integration. A wind farm of 12 MW consisting of four wind turbines connected to medium voltage grid has been proposed. Wind turbines, transmission systems, transformers and grid models as well as SVC and STATCOM models are all developed in SimPowerSystem library in MATLAB / SIMULINK. It was observed that STATCOM and SVC support the system voltage and reactive power in case of healthy conditions. However, it was noticed that they considerably improve the system stability during and especially after short circuits. STATCOM has approved a better voltage recovery time and reactive power support than SVC. But, in case of rotor speed stability, both of them have the same performance in recovering the system back to a stable operation.

Keywords: Wind energy, Integration of Wind farm, fixed speed induction generator, Medium voltage grid, Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), System Stability, Double line to ground (DLG) fault, Three phase to ground fault.

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List of Abbreviations

DC	Direct current
AC	Alternating current
FACTS	Flexible AC transmission systems
SVC	Static var compensator
STATCOM	Static synchronous compensator
RES	Renewable energy sources
DG	Distributed generation
CHP	Combined heat and power
WECS	Wind energy conversion system
AWEA	American wind energy association
WWEA	World wind energy association
HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
SCIG	Squirrel cage induction generator
WRIG	Wound rotor induction generator
DFIG	Doubly fed induction generator
PMSG	Permanent magnet synchronous generator
IG	Induction generator
WTIG	Wind turbine induction generator
PE	Power electronic
BDFIG	Brushless doubly fed induction generator
Mph	meter per hour
TSC	Thyristor switched capacitor
TCR	Thyristor controlled reactor
PI	Proportional integral
VSC	Voltage source converter
FSWTs	Fixed speed wind turbines
PWM	Pulse width modulation
FSIG	Fixed speed induction generator

PCC	point of common coupling
WPGS	Wind power generation system
TSO	Transmission system operation
WPP	Wind power plant
HVDC	High Voltage DC
DVR	Dynamic voltage restorer
SSTS	Solid state transfer switch
UPFC	Unified power flow controller
WTGS	Wind turbine generation system
VSWT	Variable speed wind turbine
LVRT	Low voltage ride through
P.U	Per unit
DLG	Double line to ground

List of Symbols

Symbol	Description
P_T	Mechanical power extracted from the turbine rotor
T_T	Mechanical torque extracted from the turbine rotor
A_r	Area covered by the rotor which is equal to πR^2
R	Turbine rotor radius in [m]
V_w	Wind velocity in [m/s]
C_p	Power coefficient or Performance coefficient
ρ	Air density in [kg/m^3]
λ	Tip speed ratio (TSR)
β	Rotor blade pitch angle in [rad]
W_T	Angular speed of the turbine shaft in [rad/s]
f_{TP}	The periodic torque frequency
N	Number of blades
f_r	Rotor angular speed in Hz
J_T	Wind turbine inertia in kg.m^2
J_G	Generator inertia in kg.m^2
K_S	Stiffness coefficient in N.m/rad
B	Damper coefficient in N.m/rad
T_e	Generator electromechanical torque in N.m
w_T	Wind turbine shaft speed in rad/s
w_G	Generator shaft speed in rad/s
θ_T	Wind turbine shaft angle in rad
θ_G	Generator shaft angle in rad
W_s	Synchronous speed in rad/sec
W_e	Stator angular electrical frequency in rad/sec
P	the number of poles
W_r	the mechanical shaft speed of the machine in rad/sec

S	the slip
rs	Stator resistance
Lls	Stator inductance
LM	Magnetizing inductance
Llr	Rotor inductance
rr	Rotor resistance
Ir	Rotor current
i_d	Direct axis
i_q	Quadrature axis
SB	Base power
VB	Base voltage
$P_{t\,max}$	Maximum power at base wind speed
P_e	Electrical power
P_m	Mechanical power
$E^{`}$	Generator terminal voltage
E_B	Infinite bus voltage
X_T	Total system reactance
δ	Power angle
P_{max}	Maximum power
R_1, R_2	Stator resistance and rotor resistance
$\mathrm{I}_1, \mathrm{I}_2$	Stator current and rotor current
X_{l1},X_{l2}	Stator and rotor leakage reactance’s
X_m, I_m	Magnetizing reactance and magnetizing current
V	Terminal voltage
$\Delta\mathrm{P}$, $\Delta\mathrm{Q}$	Vectors of incremental changes in real and reactive power
$\Delta\mathrm{P}_{\mathrm{mis}}$	Mismatch equation
$\Delta\delta, \Delta V$	Vectors of incremental changes in voltage magnitudes and angles

Δs	Vector of incremental changes in induction machine’s slip
i	Iteration number
$\lvert V \rvert$	Voltage magnitude
Ng	Generator bus
$N1$	Load bus
Nw	Wind farm bus

Chapter 1

1. Introduction

1.1 Overview

The increasing demand of electrical energy cannot be achieved by the conventional energy sources only because the fossil fuels amounts are bounded. On the other hand, conventional energy sources utilization causes the environmental retrogression like global warming. Therefore, the transition from conventional energy sources to developed energy sources became substantial.

Renewable energy is a massive source of energy and in rural areas it is deemed as an effective and economical source of energy. Wind energy is considered as one of the top growing renewable energy technologies in the world. Wind energy has confirmed to be abundant, a clean, and purely renewable source of power. It is frugal to use in producing power in rural areas [1].

In sustainable energy system, the key paradigm is attained by energy conservation and the utilization of renewable source. The appeal to consolidate the renewable energy such as wind energy into power system is to make it possible to depress the environmental effect on conventional effect [2]. Technical challenges and consideration of stability, voltage regulation power quality problems are presented in many works related to integration of wind energy into existing power system. The quality of power is a fundamental customer focused measure and is extremely influenced by the operation of a distribution and transmission network. The affair of power quality is of major significance to the wind turbine [3].

Wind energy system converts the obtainable kinetic energy in the wind into mechanical energy that can spur an electrical generator. Predominantly, wind power generators are self excited induction generators. Induction generators characteristics are mainly the massive reactive power absorbed during their normal operating conditions. This reactive power trouble may create dynamic voltage instability in the system. Wind generators are classified into two major types, which are used in wind farms to a large degree, the first one is the squirrel cage induction generator while the second is doubly fed induction generator. Low cost and low maintenance rate and possible utilization under wind gusting conditions are the major reasons of using squirrel cage induction generators.

The needed reactive power of induction generator can be provided either by the grid or self capacitor bank in parallel with the generator stator terminals. Reactive power consumption also depends on active power production. Traditionally, reactive power consumption is compensated by connecting shunt capacitor banks at the generator terminals. In some schemes, feedback signal from generator reactive power could be used to switch on/off shunt capacitor banks automatically.

Dynamic reactive power compensators are evermore required to settle down the voltage and to supply desired reactive power at wind generator interface bus under normal operation, disturbances of load and wind divagations. FACTs (Flexible AC Transmission Systems) devices can be very profitable to simultaneously deliver reactive power and advocate bus voltage at wind generator interface [4].

1.2 Motivation and Objective of Research

Several researchers and huge development in the area of wind turbine technology has been done from decades to investigate the optimal design for wind turbine operation. The main aim was the altitude of energy production from the wind and cost reduction. New power quality issues and improvement of grid stability by utilities and researchers has a great interest due to increasing number of wind turbines connected to grid. Majority of wind turbine manufacturers are developing new larger wind turbines. These wind turbines are all based on variable speed operation with pitch control. Three main types of variable speed wind turbine are illustrated as follows:

- Wind turbines equipped with squirrel cage induction generator, connected to the grid through a stator converter cascade.
- Wind turbines equipped with doubly fed induction generator, connected to the grid through a rotor converter cascade.
- Wind turbines equipped with synchronous generator and a stator DC-link cascade for network connection.

Wind turbines have been used widely in recent years. The motives behind this widespread use of wind turbines can be the low cost and its being environment friendly. However, when wind turbines are produced with large power, some problems arise in connecting it to power systems. One of the reasons for this is that the changes in load demand of the system make the system unstable. This instability in the power system brings about the voltage and reactive power problem of the system.

In power systems, voltage and reactive power control problems are important for continuous case stability. These problems have been solved through power electronics drivers included in Flexible AC Transmission Systems (FACTS). Parallel facts drivers such as SVC & STATCOM have been used widely in transient voltage control due to their high performance.

The objective of the research is:

- Designing of a wind farm consisting of four wind turbines connected to medium voltage grid and modeling of architecture of that system.
- Studying the impact of wind farm on the grid during normal and abnormal case.
- Studying the impact of integration of two kinds of FACTS devices (STATCOM, SVC) on the proposed system during normal case and during abnormal case.
- Analyzing the transient stability at point of common coupling of the proposed system taking into consideration the following parameters reaction (Voltage, Reactive power, Rotor Speed).

1.3 Thesis Structure

This thesis consists of this introductory chapter and five other chapters arranged as follows:

- **Chapter 2:** The relevant principles related to this research, some general definitions are covered in this chapter. Furthermore, it consists of detailed sequence about Renewable Energy Sources (RES) and Distributed Generation (DG) as well as induction generator based wind turbine. This chapter also depicts the overall dynamic operation of the wind turbine, modeling and structure of FACTS devices.
- **Chapter 3:** This chapter discusses the basic concepts, definition, classifications of power systems stability. It also talks about the transient stability of power systems, power flow analysis and the impacts of system stability and security.
- **Chapter 4:** the literature review including the research papers and reports related to this study has been also covered in this chapter.

- **Chapter 5:** The simulation results and the various MATLAB plots of the proposed system model without FACTS devices during normal case and abnormal case are described in this chapter. On the other hand, the integration of facts devices into the proposed scheme will be noticed and analyzed during normal and abnormal conditions. Discussion and analysis will be described on the basis of simulation results.
- **Chapter 6:** The conclusion, future work and recommendations which can be developed over this research study are included in this chapter.

Chapter 2

2. Theoretical Study

2.1 Distributed Generation and Renewable Energy Sources Background

Distributed generation (DG) and Renewable energy sources (RES) have occupied a lot of concern in recent years. Both are considered to be paramount issues in advancing the energy supplies security by minimizing the subordinate on imported fossil fuels and in reducing greenhouse gases emissions. Distributed Generation relates to the generation of electricity locally. There are many factors where the economics of DG and RES depend on. Initial investments, fuel costs, energy prices, electricity and heat, and the cost of connecting to the grid are the essential cost provisions of such factors. In general biomass gives the lowest cost electricity of all RES based options, onshore wind and hydro capacity occupies the second ranking while solar cells being the most expensive [5].

2.2 Distributed Generation Definition

Distributed generation is an incoming technique in the electricity industry. Analysis of the relevant literature has shown that there is no generally accepted definition of distributed generation yet. In the literature, a massive number of expressions and definitions are used concerning distributed generation. For example, "*Anglo-American countries often use the term 'embedded generation', North American countries use the term 'dispersed generation', and in Europe and parts of Asia, the term 'decentralized generation' is applied for the same type of generation*" [6].

2.3 Advantages, Disadvantages, Benefits of DG & RES

Renewable energy systems primary advantage is that it has no contribution to the exhaust of greenhouse gases where there are no fossil fuels involved. Another advantage is the independency to fuel prices. This in turn decreases the operational cost of RES and reduces operational hazards. Initial investment in RES constitutes the major drawback, which is often more considerable than for non-RES. Other disadvantages of RES are the nominated demands of the site and the unpredictability of the generated power. The feasibility of a renewable energy system depends upon the availability of renewable energy (sun, wind, water) and this may enhance environmental issues. The unpredictability of RES as well means a cost boost for equalizing the electricity grid and maintaining reserve capacity like for example, when the wind decreases or increases above the wind turbines operating area. This problem is already confronted in areas with a high penetration of wind turbines, such as Germany and Denmark [7].

Benefits of distributed generation include two parts of benefits, the first one is additional energy related benefits which include (improved security of supply, avoidance of overcapacity, peak load reduction, reduction of grid losses) and the second one is network related benefits which include (power quality support, reliability improvement). Connection costs, metering and balancing is another disadvantages of DG beyond those mentioned earlier [8]. Figure 1 illustrates the effect of the degree of penetration of distributed generation on grid losses.

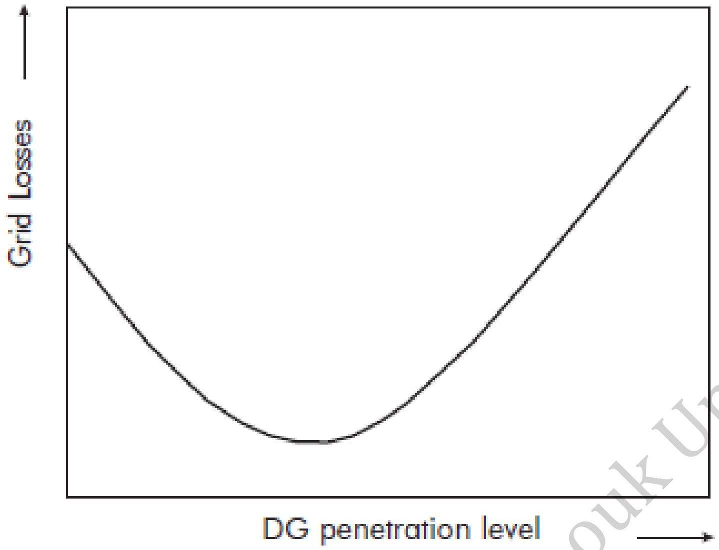


Fig. 1. Grid losses related to the penetration of DG [5]

2.4 Distributed Generation Applications and Technologies

Applications of DG include [9]:

- Uninterrupted power (where there are 6 hours per day in which the DG can operate).
- Combined heat and power loss (CHP) (where DG wasted heat is used for heating and / or cooling applications).
- Higher generated power (where DG is operated between 200-3000 hours per year during periods of high electricity price or high site demand).
- Green and clean power (where DG is operated by a modality so that environmental emissions from the generating supply units are reduced).
- Super power (where a higher level of reliability and power quality is provided by DG).
- Transmission and distribution postponement (where DG is used to delay the purchase of new transmission or distribution systems).

- Favorable service power (where DG is used to provide ancillary service at a transmission or distribution level; includes spinning / non spinning reserves, reactive power, voltage control, and local area security).

Technologies of DG include:

- Reciprocating engines technology.
- Micro-turbines technology.
- Industrial combustion turbines technology.
- Fuel cells technology.
- Photovoltaic technology.
- Wind turbine systems technology.

2.5 Wind Turbine Structure and Modeling

2.5.1 Wind Energy Development

It's worth noting that wind energy history go back to the 19th century, but fossil fuels low prices made the unattractiveness for wind energy at that time [10]. In 1973, the oil recession has increased so the research on new wind energy conversion systems (WECS) was put into action again. Previous research was accordingly on making modern wind turbines with higher power, which require huge electrical generators. At that time, making enormous turbines was restrained, because of electrical problems and a highly manufacturing cost [10] [11]. Therefore, low price wind turbines were preferable from the point of view of several researches, which consists of an induction generator, a small turbine, a gearbox and a mechanical control manner. These turbines can deliver of at least several tens of kilowatts, and it has three fixed blades. In such a system, the turbine rotates at a constant speed by the movement of its shaft. The asynchronous generator is a suitable choice of such kinds of systems. Individuals can even purchase because of the low cost and small size components which made the price reasonable [12].

Consequently, new wind energy generation systems was evolved on a larger level due to successful research on wind energy conversion systems, over the last two decades, wind turbines production has augmented in size and power rating, as the industry gained experience. It implies that the generator rating, rotor diameter and tower height have all raised. During the beginning of 1980s, wind turbines were installed with rotor spans of about 10 to 15 meters, and generators rated at 10 to 65kW. By the mid-to late 1980s, wind turbines with rotor diameters of about 15 to 25 meters and generators rated up to 200kW began manifesting. Nowadays, turbines rated at 200kW to 2MW with rotor spans of about 47 to 80 meters were developed. As the American Wind Energy Association (AWEA) reclaimed, wind turbines at these days produce as much as 120 times more electricity than former turbines, with little operation and maintenance costs, thus largely reducing Operation and Maintenance (O&M) costs per kWh. In comparison to small wind turbines, large turbines produce less noise and do not turn as fast [13]. New types of generators in wind systems have been developed. Since 1993, synchronous generator has been replaced by the traditional asynchronous generator by several manufacturers, while others have used doubly-fed asynchronous generators. After that, electrical developments in advanced power electronics in the wind generator system design were utilized, thus inserting the new notion which is variable speed. As a result of the fast improvement of power electronics, presenting both lower price/kW and higher power handling capability [14], a rapid increase of power electronics applications in wind turbines is expected more and more. Also, in order to control the speed of the turbine shaft, some control methods were developed for big turbines with the variable-pitch blades.

Comparison of different structures for wind energy systems have been done, as well as their mechanical, electrical and economical aspects. An effective example is the comparison of variable-speed against constant-speed wind turbine systems. If we talk about energy capture, then, all researches and studies resulted in the fact that variable speed turbines will produce more energy than constant speed turbines [15]. Certainly, energy output of about 20% in a typical wind turbine system was increased by the use of variable-speed tactic [16]. The benefits of using pitch angle control have demonstrated in a more stable operation during wind gusts as well as increasing the power captured. Different schemes have been proposed in case the wind turbine operates in a variable speed mode. For example, assessment of the wind speed in order to optimize wind turbine operation is one of the schemes that can be used [17].

Field-oriented control and constant Voltage /frequency (*V/f)* have been used in order to perform speed control of the turbine shaft. Accordingly, maximum power might be achieved [18]. In the last 25 years, several generations of wind turbine systems have been evolved as mentioned before. These various generations are discriminated according to the use of different types of wind turbine rotors, generators, control methods and power electronic converters.

Figure 2 shows the total installed capacity in MW all over the world as the World Wind Energy Association (WWEA) declared [19]. It should be noted from the figure shown below that the capacity of wind energy is increasing year by year.

Fig. 2. Total Capacity of world wind energy [19]

2.5.2 Wind Turbine Components

The major components of the wind turbine can be summarized as follows [20]:

- Blades: wind turbines in general have three blades; nonetheless there are some with two blades. Blades are generally 30 to 50 meters (100 to 165 feet) long, with the most common sizes around 40 meters (130 feet). Blade varies in weights, depending on the design and materials – a 40 meter LM Glass fiber blade for a 1.5 MW turbine weighs 5,780 kg and one for a 2.0 MW turbine weighs 6,290 kg.
- Controller: There are two kinds of controllers one in the nacelle (which is a cover housing that houses all of the generating components in a wind turbine including the generator, gearbox, drive train and brake assembly) and one at the base of the turbine. The controller monitors the state of the turbine and controls the turbine activity.

- Gearbox: The gearbox increases the rotational speed of the shaft. A low-speed shaft feeds into the gearbox and a high-speed shaft feeds from the gearbox into the generator. There are some turbines that use direct drive generators (bigger low speed generators) which can produce electricity at a lower rotational speed. Such kinds of turbines do not require a gearbox. Thus, reducing the operating costs over the long term, this kind of turbines is more profitable for offshore wind farms because the maintenance complexity at sea is more than that on the ground.
- Generators: A single AC generator converts the mechanical energy from the wind turbines rotation into electrical energy.
- Nacelles: The nacelle covers the main components of the wind turbine, such as the controller, gearbox, generator and shafts.
- Rotor: The rotor comprises both the blades and the hub which is the component to which the blades are connected.
- Towers: It is ordinary tabular steel towers 60 to 80 meters (about 195 to 260 feet) high that consist of three sections of varying heights. There are some towers with heights around 100 meters (330 feet)).

Figure 3 shown below depicts the basic components of the wind turbine [20].

2.5.3 Wind Turbine Rotors classification

Direction of the wind determines the orientation of the axis of rotation, as shown in figure 4. Wind turbines are usually classified into two categories [21]:

- Vertical axis wind turbines (VAWT).
- Horizontal axis wind turbines (HAWT).

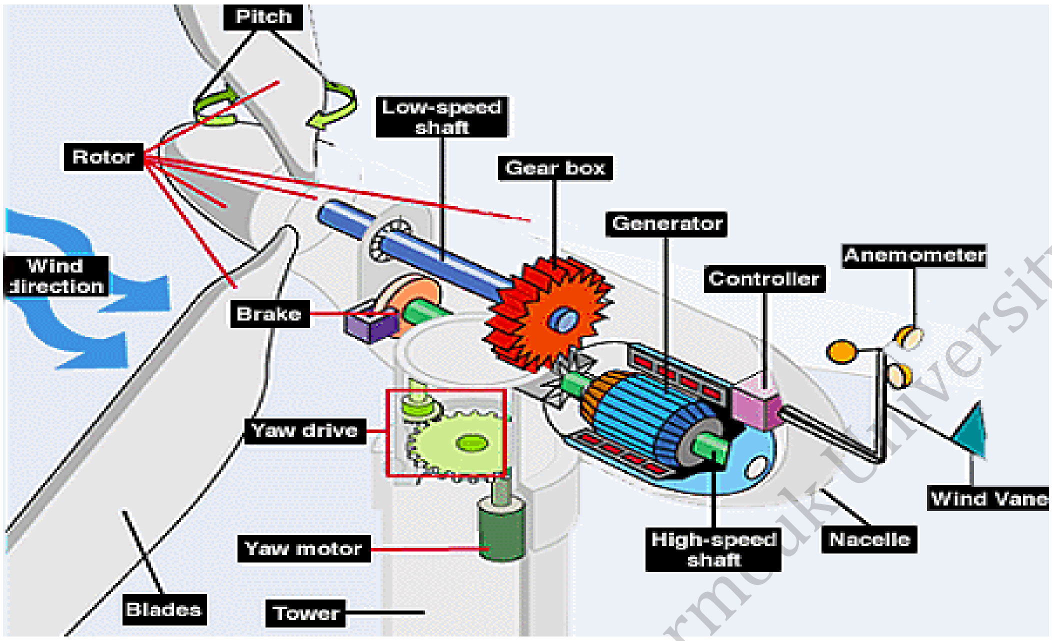
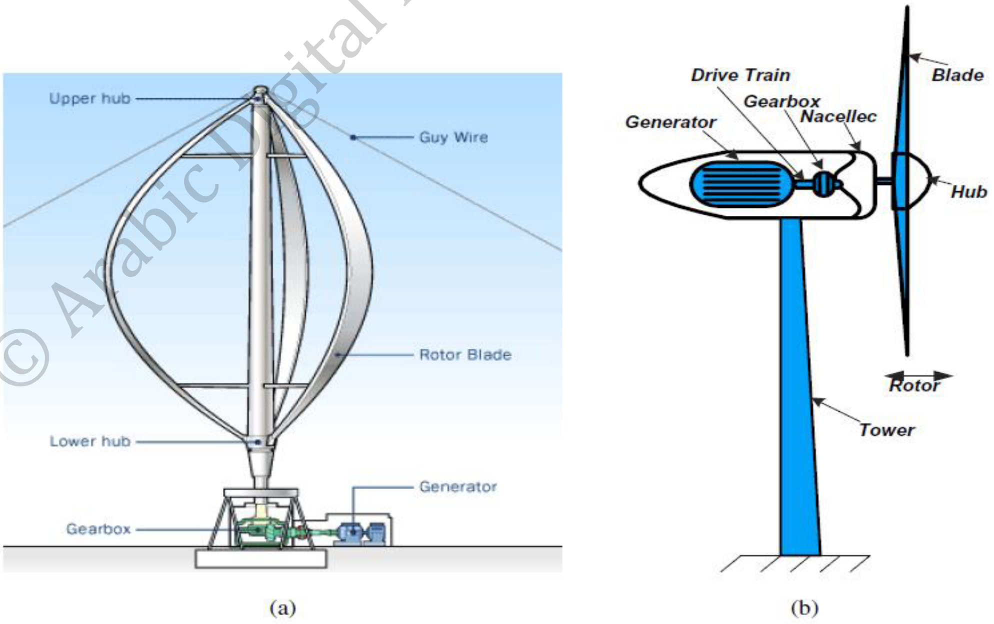


Fig. 3. Basic components of the wind turbine [20]



(a) (b)

Fig. 4. (a) Typical vertical axis turbine, (b) horizontal axis wind turbine [22]

There are many advantages that make the HAWT more preferable and profitable than VAWT which is the efficiency, the capability to turn the blades, the necessity of a generator to work in motor mode at start.

Based on the direction of extraditing the wind, the HAWT can be classified as upwind and down wind turbines, as shown in figure 5 [23] [24]. As shown from the figure the rotor faces the wind directly in the upwind structure, while in downwind structure, the rotor is placed on the lee side of the tower.

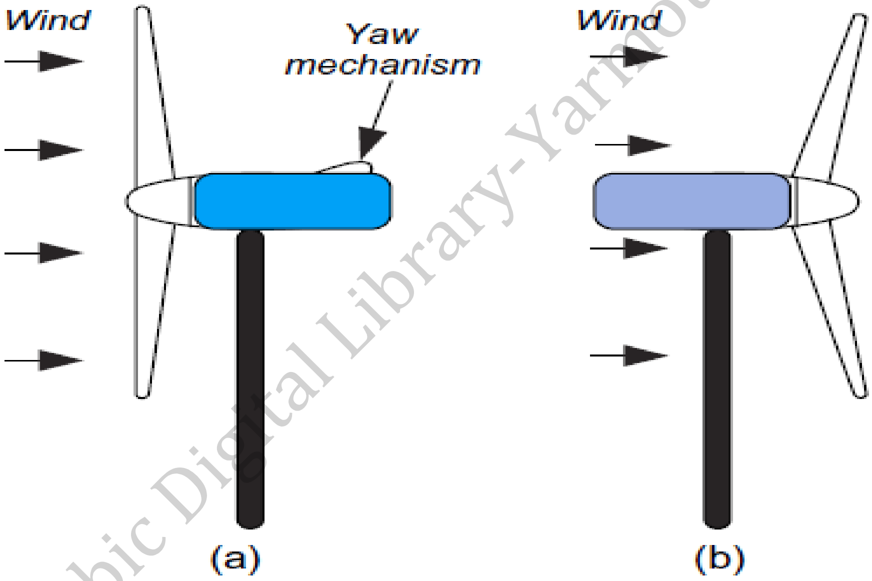


Fig. 5. (a) Upwind Structure, (b) Downwind Structure [23][24]

2.5.4 Types of Generators in Wind Turbines

The electrical generator is an apparatus which provides the local load or the electric grid by the desired power. Wind turbines are equipped with different types of generators. Small wind turbines are equipped with DC generators which has a capacity of a few kilowatts.

Three-phase AC generators are used with modern wind turbine systems [25]. The common types of AC generator that uses modern wind turbine systems can be summarized as follows:

- Squirrel-Cage rotor Induction Generator (SCIG).
- Wound-Rotor Induction Generator (WRIG).
- Doubly-Fed Induction Generator (DFIG).
- Synchronous Generator (with external field excitation).
- Permanent Magnet Synchronous Generator (PMSG).

For estimating the type of generator in wind energy conversion system (WECS), there are some standards that can be used such as, the characteristics of the WECS, active material weight, cost and price, maintenance consequences and the proper type of power electronic converter.

The induction generator (IG) has been widely used in commercial wind turbine systems. Asynchronous operation of such generators is considered as a feature for usage in wind turbine systems, because a flexible operation is provided to some extent when the wind speed is fluctuating. Induction machines have two main types: squirrel-cage (SC), and wound rotor (WR). DFIG is another category of induction generator, which may be based on the squirrel-cage or wound-rotor induction generator.

There are several features such as low price, mechanical simplicity, powerful structure, and resistance against disturbance and vibration that make the induction generator based on SCIG a very popular machine.

For speed control purposes, wound-rotor scheme is a suitable choice. The output of the generator can be controlled and even speed control of the generator can be done by changing of rotor resistance. But it’s worth noting that WRIG is more expensive than a SCIG.

In DFIG the stator windings and the rotor windings are connected to the source. The rotating winding is attached to the fixed supply circuit via power electronic converter. The merit of connecting the converter to the rotor is the variable-speed operation of the turbine. The converter power rating is often about 1/3 the generator rating [26].

The synchronous generator has been proposed for wind turbines in several research papers. The synchronous generator has the ability of direct connection (direct-drive) to wind turbines, with no gearbox. This advantage is appropriate concerning existence and maintenance. These synchronous machines can use either electrically excited or permanent magnet (PM) rotor. The difference between PM and electrically-excited synchronous generators and the induction generator is that the magnetization is provided by a Permanent Magnet pole system or a dc supply on the rotor. High power factors and high efficiencies for the PM synchronous can be achieved by self excitation. Induction generators are likely the most popular types of generators that are used in modern wind turbine systems [27]-[29].

2.5.5 Various schemes of the wind turbine induction generators

Figure 6 shows a squirrel-cage induction generator (SCIG), which is an asynchronous machine and it, is connected directly to the grid because of its simplicity, robust operation and comparatively low-cost system. For an induction generator, it is necessary to use a gearbox in order to join the generator and turbine speed. Reactive power compensation by capacitor bank, and using of soft-starter for facilitate grid connection are also necessary. Power and speed are assigned aerodynamically by stall or pitch control. Slip variation should be in range of 1–2%, but in industry there are some wind turbines based on SCIG which is provided by increased rotor resistance. Increasing of rotor resistance can reduce the torque fluctuations in the shaft of the wind turbine, particularly during wind gusts. For wind gusts, the mechanical torque will increase causing an increase in the mechanical rotor speed, so the electrical torque will increase as will and as a result the stator power will increase. But, increasing the rotor resistance of the induction machine will increase the slip and allow the rotor to speed up during the happening of the wind gust, so this scheme will keep the rotor current constant and consequently a constant stator power. However, this scheme is not proper for a wind turbine in a higher range or for locations with fluctuating wind velocity [30] [31].

Induction generators with the capability of variable speed operation are presented by three forms of wind turbine systems. These wind turbine induction generators are shown in figure 7.

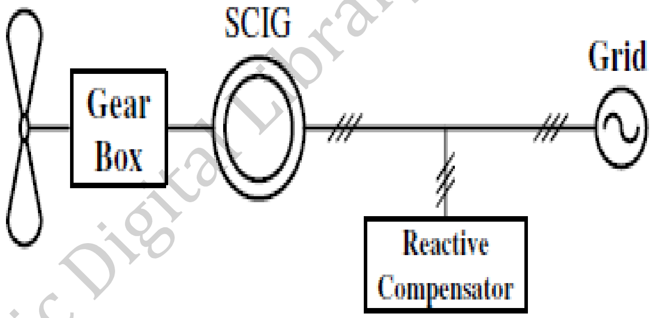


Fig. 6. Wind Turbine system with SCIG [22]

In figure 7 (a) the wind turbine system uses a wound-rotor induction generator (WRIG). In this scheme, using a variable external rotor resistance and a power Electronic (PE) converter rotor resistance can be altered electronically. The slip of the machine will be varied over a 10% range by controlling the rotor resistance. In normal operation, the rotor resistance is low, associated with low slip, but during wind gusts the rotor resistance is increased to allow speeding up.

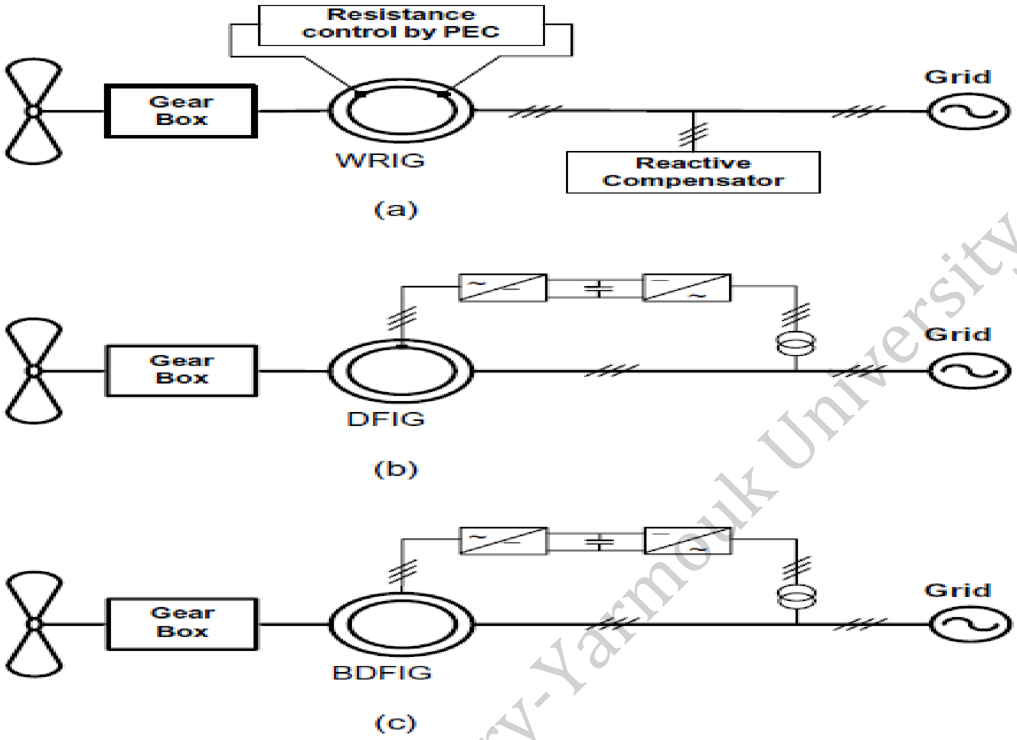


Fig. 7. Wind turbine systems based on the induction generator with the capability of variable speed operation: (a) Wound Rotor, (b) Doubly Fed, and (c) Brushless Doubly Fed induction generators [32]

In Figure 7 (b) the wind turbine system uses a Doubly-Fed Induction Generator (DFIG) and a power electronic converter that connects the rotor winding to the grid directly. Therefore, it is possible to stretch the speed range further without affecting the efficiency. It should be noted that slip power can be fed back to the grid by the converter instead of being wasted in the rotor resistance, as a result of speed control without loss of efficiency.

The entrance to the rotor is possible through the slip rings and brushes as depicted in the configurations shown in Figs 7 (a) and 7 (b), with slip rings and brushes an electrical losses and mechanical problems could be produced. Brushless Doubly-Fed induction generator

(BDFIG), shown in Fig 7 (c) is another choice to solve the problems of using slip rings and brushes.

The main winding is directly connected to the grid in this configuration, while the three-phase auxiliary winding is connected to the electrical grid through a power electronic converter. By using the appropriate control in the auxiliary winding, it is possible to control the induction machine at almost any speed.

2.5.6 Wind turbine operating limits

Wind turbines blades typically start rotating when wind velocities reach approximately 7 miles per hour, and they will start generating electricity when the velocity reaches 9 to 10 mph. Wind turbines in general shut themselves down automatically when wind speeds reach 55 to 65 mph to avoid damage and harm. Voltage fluctuation and transient currents can occur when the wind turbines are connected to or disconnected from the grid [33].

2.6 Overall Dynamic Model of the Wind Turbine System

2.6.1 Dynamic Model of the Wind Turbine System

Dynamic models of the mechanical aerodynamic conversion, drive train, electrical generator, and power electronic converter are presented in this section. A nonlinear dynamic model of WECS connected to grid is developed in quadrature and direct (*qdo)* reference frame. Figure 8 shows the various components of a wind turbine system model and the interactions between them.

Blocks for wind speed, the aerodynamic model, mechanical model, electrical generator, power electronic converter and utility grid are shown in the figure. Some mechanical parts for blades angle control is also might be considered. Accurate discussions of the building blocks of the overall model are presented in the following sections. It is worth noting that the wind turbine system with constant blade angle and without blade angle control is considered in the modeling.

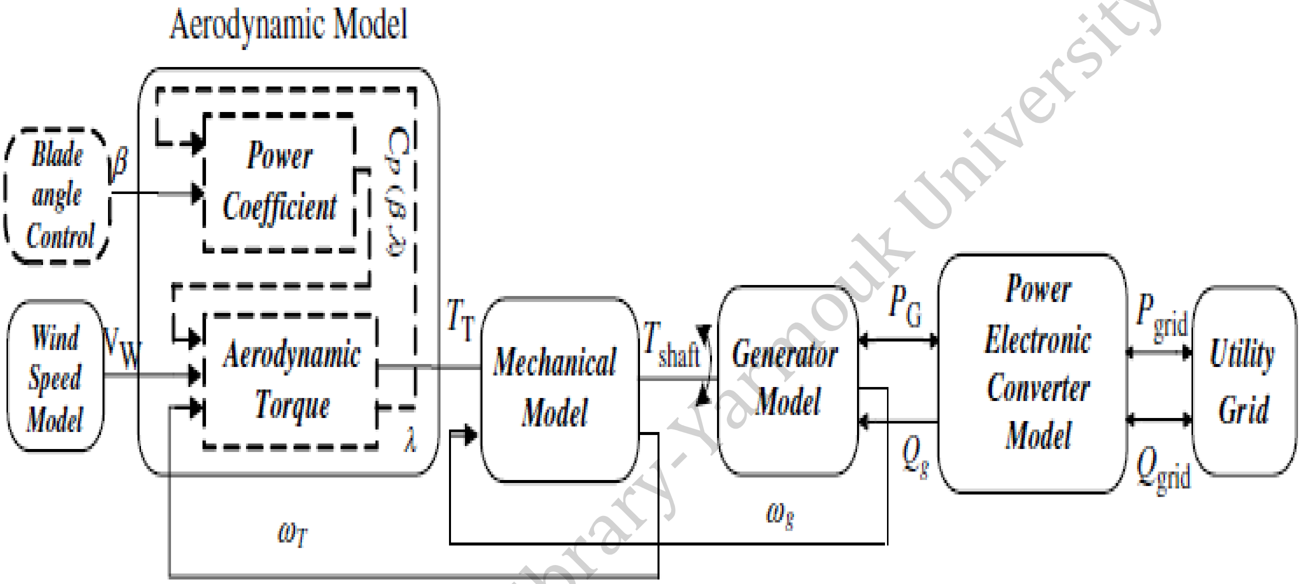


Fig. 8. Block diagram of the overall wind turbine system [22][34]

2.6.2 Aerodynamic Model

The mechanical torque on the wind-turbine shaft is the output of the aerodynamic model block as depicted in Figure 8 that is a function of the wind-turbine characteristics, wind and shaft speed, and the blade angle.

2.6.3 Wind turbine output torque

Wind turbine blades are turned as the wind strikes, and then the generator rotor turns to generate electricity. Wind speed and rotor size are the main parameters that the output power of the wind turbine is related. This power is proportional to the cubic wind speed, assuming all other parameters are constant. Thus, as the wind speed increases the output power of wind turbines will increase significantly. In addition, larger rotors allow turbines to protest more wind, to increase their output power. The rotors sweep a circular surface whose area is a function of the square of the blade length is the reason for that. But, the size of the blades in wind turbines has limitations, for economical and technical reasons.

Eqs. (2.1) and (2.2) respectively depicts the mechanical power and mechanical torque on the wind turbine rotor shaft [35] [36].

$$P_T = \frac{1}{2}\,\rho A_r C_p(\beta,\lambda) V_w^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

$$T_T = \frac{1}{2\,W_T}\,\rho A_r C_p(\beta,\lambda) V_w^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

Where,

P_T : Mechanical power extracted from the turbine rotor.

T_T : Mechanical torque extracted from the turbine rotor.

A_r: Area covered by the rotor which is equal to πR^2, where R is turbine rotor radius in [m].

V_w: Wind velocity in [m/s].

C_p: Power coefficient or Performance coefficient.

ρ: Air density in [kg/m^3].

λ: Tip speed ratio (TSR).

β: Rotor blade pitch angle in [rad].

W_T: Angular speed of the turbine shaft in [rad/s].

The blade tip speed ratio is the ratio of blade tip speed and the actual velocity of the wind. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively if the rotor turns too quickly, the blurring blades will appear like a solid wall to the wind. Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible. TSR can be defined as follows:

$$\lambda = \frac{W_T}{V_w} . R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

Where,

W_T . R is the blade tip speed , V_w is the wind speed.

Tip speed ratio λ and power coefficient C_p are correlated, also rotor blade pitch angle β. A typical C_p versus tip speed ratio curve is shown in figure 9. C_p changes with different values of the pitch angle, but the best efficiency is obtained for $\beta = 0$. In the study it is assumed that the rotor pitch angle is fixed and equal to zero.

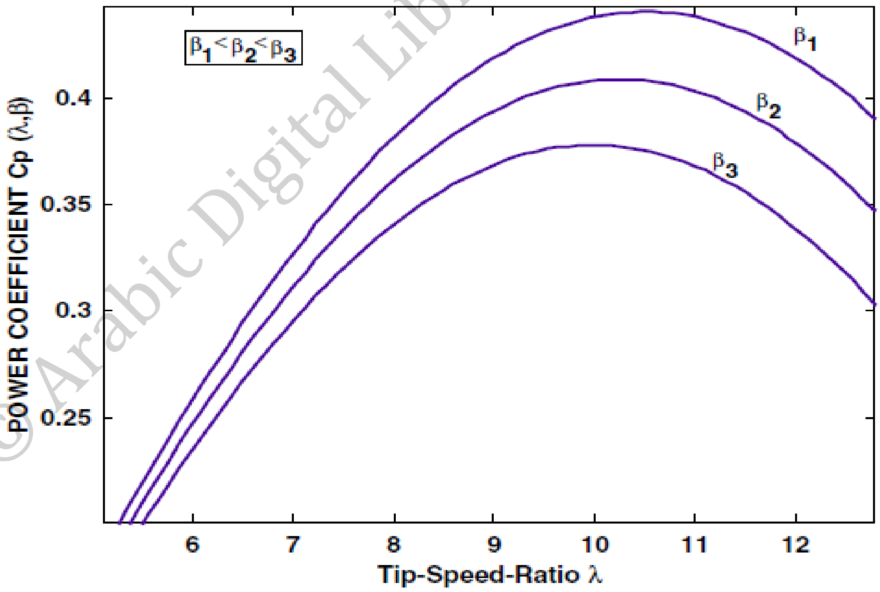


Fig. 9. A typical Cp versus λ curve [22]

Various equations have described the power coefficient in the literature [37] [38]. It can be formulated as approximately: [39] [40]

$$C_p(\beta,\lambda) = (0.44 - 0.0167\beta)\sin\left[\frac{\pi(-3+\lambda)}{15-0.3\beta}\right] - 0.00184(-3+\lambda)\beta \; ….. \; (2.4)$$

According to Betz law, the theoretical upper limit for C_p is 0.59, as well as its practical range of variation is 0.2 - 0.4 [41].

The transfer of wind kinetic energy to mechanical energy on the shaft of wind turbine is illustrated in Equations (2.1) – (2.4) and also in the model of figure 10.

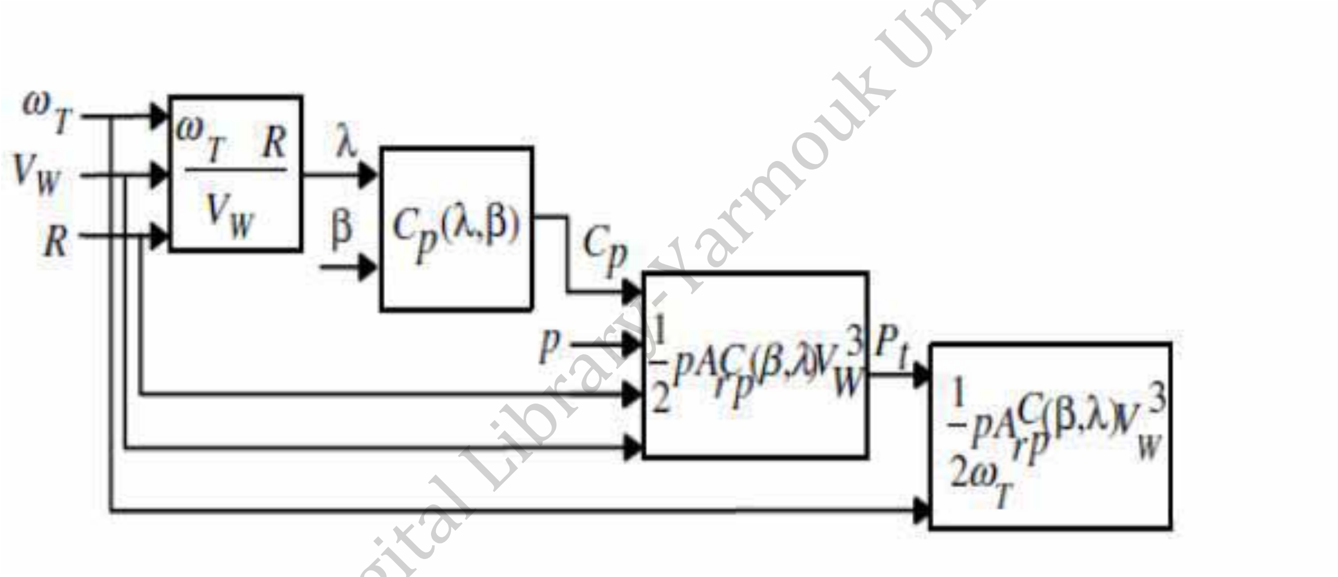


Fig. 10. Block diagram of the aerodynamic wind turbine model [22]

2.6.4 Tower shadow Effect

The distribution of wind is changed by the location of the tower; the wind directly in front of the tower is redirected and thereby reduces the torque at each blade, specifically for upwind rotors [42]. This decline the mechanical torque transferred to the generator shaft and subsequently the output voltage drops. The tower shadow effect has a frequency proportional to the number of blades, for example, three per revolution for a three blade turbines. To represent the tower shadow effect, a periodic torque pulse with frequency FTP is added to the output torque of the aerodynamic model. The periodic torque frequency is [43].

$$f_{TP} = N \, . \, f_r \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.5)$$

Where, N is the number of blades and f_r is the rotor angular speed in HZ. A more significant effect of tower shadow can be appeared in downwind turbines.

2.6.5 Mechanical Model

Based on available data and several studies and researches, the mechanical model has been developed. Corresponding to a large mass for the wind turbine rotor, the model of a wind turbine drive train is fundamentally a three-mass model, a mass for the gearbox and the generator is also denoted. The study has omitted the moments of inertia of the shafts and gearbox because they are small compared with the moments of inertia of the wind turbine and the generator [44]. Therefore, the mechanical model is essentially a two-mass model of rotor dynamics, consisting of a large mass and a small mass, corresponding to the wind turbine rotor inertia JT and generator rotor inertia JG, respectively [45] as shown in figure 11.

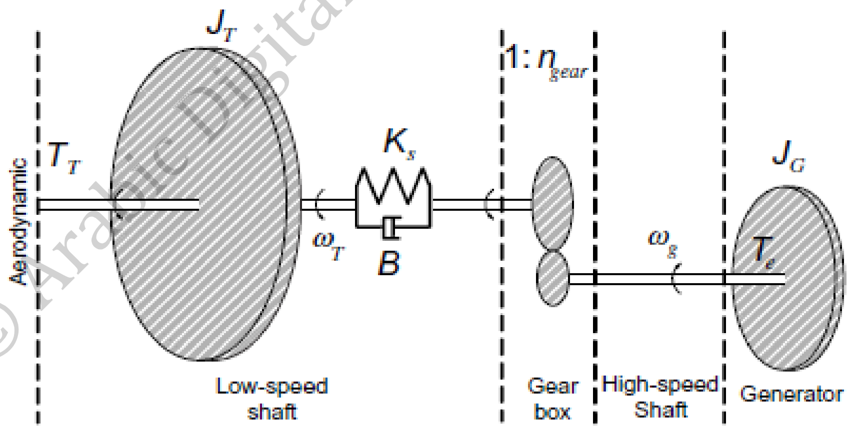


Fig. 11. A complete mechanical model of the wind turbine shaft [22]

Inertia, stiffness coefficient Ks of the spring, and damping coefficient B of the damper all constitute the modeling of low speed shaft. An ideal gear box is included between the low speed and high speed shafts with the gear ratio 1: ngear. Table 1 defines the parameters of the mechanical model.

Table 1. Mechanical model parameters

Parameter	Description
J_T	Wind turbine inertia in kg.m^2
J_G	Generator inertia in kg.m^2
K_S	Stiffness coefficient in N.m/rad
B	Damper coefficient in N.m/rad
T_T	Wind turbine torque in N.m
T_e	Generator electromechanical torque in N.m
w_T	Wind turbine shaft speed in rad/s
w_G	Generator shaft speed in rad/s
θ_T	Wind turbine shaft angle in rad
θ_G	Generator shaft angle in rad
1:ngear	Gear ratio

The aerodynamic torque T_T is converted by the drive train on the low speed shaft to the torque on the high speed shaft T_e. The following three differential equations illustrate the dynamics of the drive train.

$$\frac{d}{dt}(w_T) = \frac{1}{J_T}[T_T - (K_s\delta_\theta + B\delta_w)] \text{ .... } (2.6)$$

$$\frac{d}{dt}(\delta_\theta) = \delta_w \text{ .... } (2.7)$$

$$\frac{d}{dt}(w_g) = \frac{1}{J_T}\left[\frac{1}{n\ gear}(K_s\delta_\theta + B\delta_w) - T_e\right] \text{ .... } (2.8)$$

Where,

$$\delta_\theta = \theta_T - \frac{\theta_g}{n\ gear};$$

$$\delta_w = w_T - \frac{w_g}{n\ gear}.$$

2.6.6 Induction machine model

An idealized three phase induction machine consisting of a stator and a rotor is shown in figure 12. A concentrated coil structure is equipped with each phase in stator and rotor windings. By induction or transformer action, the balanced three-phase ac voltages in the stator induce current in the short-circuited rotor windings. The synchronous speed of the rotating sinusoidal flux density wave that the stator current establishes in the air gap is given by:

$$W_s = \frac{2}{P} W_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.9)}$$

Where, W_s is the synchronous speed in rad/sec, W_e is stator angular electrical frequency in rad/sec, and P is the number of poles. If the mechanical shaft speed of the machine is defined as W_r (in rad/sec), at any speed W_s, the speed difference $W_s - W_r$ creates slip (S). The slip is defined as follows: $S = \frac{W_s - W_r}{W_s}$ ……………………….. (2.10)

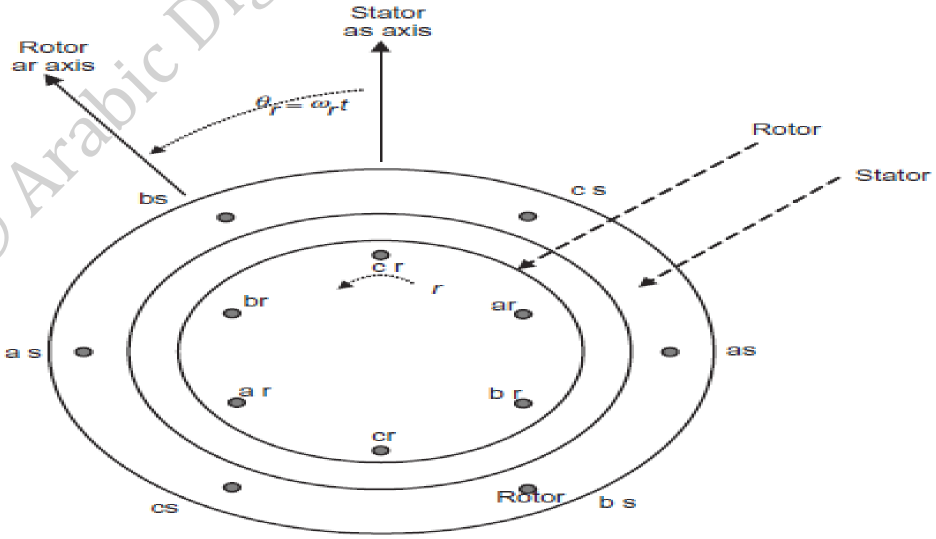


Fig. 12. Equivalent circuit for the induction machine [46] [47]

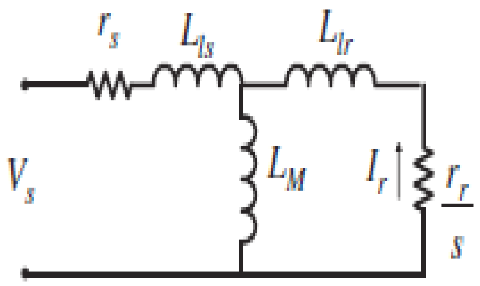


Fig. 13. A per phase equivalent circuit for induction machine [22]

In case of induction generator, a steady state condition $W_r = W_g$ is slightly higher than W_s this mean that S < 0, while in induction motor, W_r is slightly lower than W_s which means that S > 0. A transformer like per phase equivalent circuit for induction machine is shown in figure 13 [22].

Where, rs is the stator resistance, Lls the stator inductance, LM the magnetizing inductance, Llr the rotor inductance (referred to stator circuit) and rr the rotor resistance (referred to stator circuit).

The resistance rr/s has a negative value in the generator mode. This negative resistance indicates the existence of a source so; the direction of power is from the rotor circuit to the stator circuit in the generator mode.

The electromechanical torque on the shaft can be formulated as expressed by Eq. (2.11) which is function of the rotor current, resistance and slip [48].

$$T_e = \frac{3}{W_s} I_r^2 \frac{T_r}{S} \quad \text{......................... (2.11)}$$

T_e can be calculated as a function of slip (S) from Eq (2.11) if the terminal voltage and frequency are constant. Figure 14 shows the torque speed curve of an induction machine, two different zones can be shown from the figure, the first is generating mode ($S < 0$) and the second is the motoring mode ($0 \geq S \geq 1$). Based on the convention that $T_{motor} > 0$ and $T_{generator} < 0$, the sign of the torque in the motoring and generating regions has been specified.

As seen from figure 14, the induction generator absorbs reactive power from its terminals because it has inductive nature. The reactive power affords the rotating magnetic field in the air gap between the cage rotor and the stator winding. This reactive power should be supplied by the grid or by the capacitor-bank that is connected at the stator terminals. Further, inserting a power electronic converter can provide a dynamic reactive power compensation, which result in additional and smoother reactive power control [49].

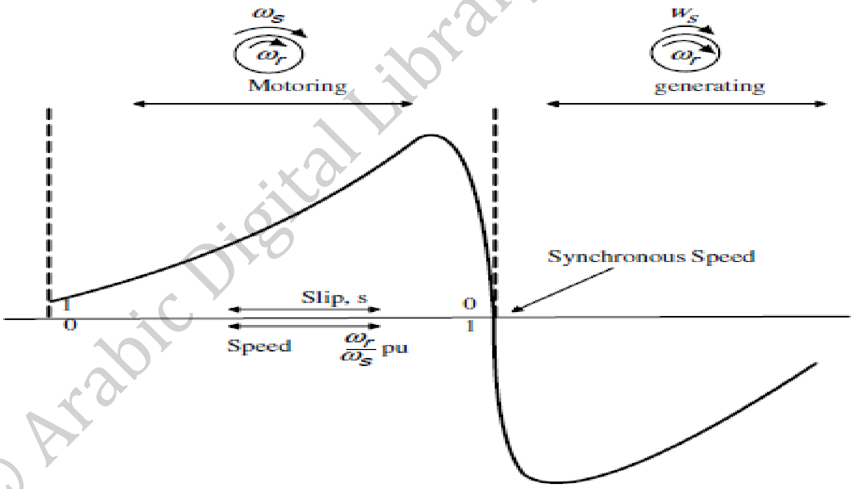


Fig. 14. Torque speed curve of induction machine [22]

In stand-alone operation, the output voltage of the generator can be identified from the intersection point of the magnetization curve of the machine and the impedance line of the capacitor which defines the operating point. In a grid connection, the output frequency is dictated by the grid. However, in standalone operation, it is a function of the excitation capacitance rotor speed and the load [50].

2.6.7 Gearbox Model

Transforming the mechanical power from the slow speed shaft to a fast speed shaft is the function of the mechanical gearbox, which drives the generator. Wind turbines with induction generators at most uses gearbox. This issue comes from the problem that an induction generator cannot be built for very low speeds with good efficiency. Referring to figure 11 in order to model the gearbox, it is only needed to consider that the generator torque can simply be transferred to the low speed shaft by a multiplication. Possible formula might be written as [51]:

$$\frac{T_T}{T_e} = \frac{W_g}{W_T} = n\ gear \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.12)$$

It should be noted that the efficiency of the gearbox should be considered in the model for a non ideal gearbox.

2.6.8 Grid Model

The system frequency and voltage are constant in the grid model, independent of active and reactive power flows. Such a model consists of an infinite bus. This model can be used when the capacity of grid power is appropriately large such that the action of any one user or generator will not affect the operation of the power grid.

2.6.9 Wind Speed Model

Instantaneous wind speed knowledge is required in order to calculate the output power of the wind turbine rotor. The fluctuating behavior of the wind makes it difficult to be modeled.

Wind speed has continual diversities over a long-term scale. But, surface conditions such as buildings, trees, and areas of water affect the short-term behavior of the wind and introduce fluctuations in the flow, i.e., wind speed turbulence.

Literature review detects different wind speed models. Wind speed can be modeled by four kinds: mean wind speed, ramp wind speed, gust wind speed and noise wind speed. However, it is a difficult duty to determine all four components. In this research study, wind speed is modeled with a constant value.

2.7 Integration of FACTS devices to the Power System

2.7.1 General Introduction

Power electronics have witnessed rapid development these days, in power systems Flexible AC Transmission Systems (FACTS) devices have been suggested for utilization. In order to control power flow and enhance power system stability, there is an increasing interest in using FACTS devices. FACTS devices have many forms and may include one or more of the following characteristics [52]:

- Steady state power transfer
- Voltage stability
- Transient stability
- Power system oscillation
- Short circuit power

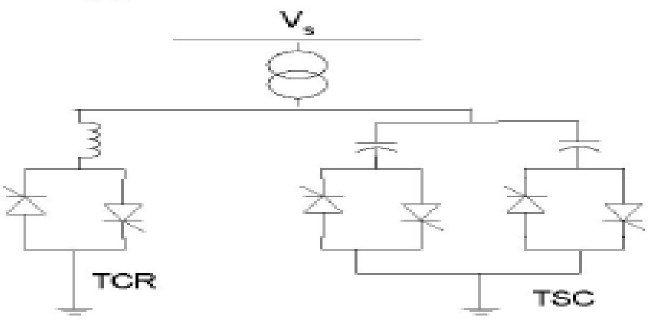
2.7.2 Modeling and Structure of STATCOM & SVC

For wind farm integration, this research study uses both the static var compensator (SVC) and the static synchronous compensator (STATCOM). Providing dynamic reactive power compensation using SVC and STATCOM can possibly raise the network voltage during and after fault. As a result, the electric torque produced by the FSIG will increase. So, generators will over - speed and thus increasing system stability [53].

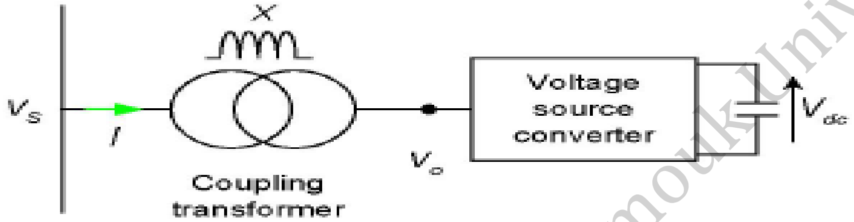
A typical SVC configuration is shown in Figure 16(a). It consists of a number of thyristor switched capacitors (TSC) shunted with a thyristor controlled reactor (TCR). Step change of connected shunt capacitance is provided by the TSC, while continuous control of the equivalent shunt reactance is provided by the TCR. The SVC can be operated to provide reactive power control or closed loop AC voltage control.

In case of closed loop AC voltage control, the line voltage as measured at the point of connection is compared to a reference value and an error signal is produced. Then it is passed to a PI controller to generate the required susceptance value. After that, it is transmitted to the non - linear admittance characteristic so as to generate the firing angle for the TCR and to determine the number of TSC stages need to be turned on. The firing angle is passed to the gate pulse generator, which then generates the firing pulse for the TCR [53].

Figure 16(b) shows a typical STATCOM, which consists of a voltage source converter (VSC) and coupling transformer connected in shunt with the AC system. STATCOM DC voltage is usually controlled to a fixed value so as to operate satisfactorily.



(a) SVC



(b) STATCOM

Fig. 15. Schematic diagram of SVC and STATCOM [53]

Controlling the voltage generated by the converter to control the generated reactive power is the essential operation of STATCOM. The control system of STATCOM is usually defined in the synchronous d – q reference frame with the d – axis fixed to the network voltage. This enables the independent control of active power (DC) voltage and reactive power by controlling the q – axis and d – axis currents respectively. Similar to a SVC, closed loop AC voltage control can be realized by using a AC voltage controller which generates reactive power order for the STATCOM control system [53].

The principle operation and voltage – current (V-I) characteristics of SVC and STATCOM are analyzed as depicted from SimPowerSystem library in Matlab/Simulink. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR). On the other hand, The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive). The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize its voltage from a DC voltage source.

For the SVC, As long as its susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (Bc_{max}) and reactor banks (Bl_{max}), the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output). The V-I characteristic is described by the following three equations:

$$V = V_{ref} + X_s . I \quad \text{if SVC is in regulation range } \left(-\mathrm{B}_{\mathrm{Cmax}} < B < \mathrm{B}_{\mathrm{Imax}}\right) \quad (2.13)$$

$$V = -\frac{I}{B_{Cmax}} \quad \text{if SVC is fully capacitive } (\mathrm{B} = \mathrm{B}_{\mathrm{Cmax}}) \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.14)$$

$$V = \frac{I}{B_{Imax}} \quad \text{if SVC is fully inductive } (\mathrm{B} = \mathrm{B}_{\mathrm{Imax}}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.15)$$

Where,

V is the positive sequence voltage (p.u), I is the Reactive current (pu/Pbase) (I > 0 indicates an inductive current), X_s is the Slope or droop reactance (pu/Pbase), $\mathrm{B}_{\mathrm{Cmax}}$ is the Maximum capacitive susceptance (pu/Pbase) with all TSCs in service, no TSR or TCR, $\mathrm{B}_{\mathrm{Imax}}$ is the Maximum inductive susceptance (pu/Pbase) with all TSRs in service or TCRs at full conduction, no TSC, Pbase is the Three-phase base power.

For the STATCOM, As long as the reactive current stays within the minimum and minimum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output). In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{ref} + X_s . I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.16)$$

Where,

V is the Positive sequence voltage (pu), I is the Reactive current (pu/Pnom) (I > 0 indicates an inductive current), X_s is the Slope or droop reactance (pu/Pnom), Pnom is the Three-phase nominal power.

The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. This is due to the fact that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). This ability to provide more capacitive reactive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the VSC, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for a SVC).

Chapter 3

3. Power System Stability Concerns

3.1 Basic Concepts of Power System Stability

Power system stability is the ability of an electric power system, for a given initial operating conditions to regain a state of operating equilibrium after being subjected to a physical disturbance. The power system operates in a constantly changing manner because it has various nonlinear components. If the power system is subjected to a transient disturbance, then the nature of the disturbance and the initial operating conditions are the main factors in which the stability of the system depend on. The disturbance could be small disturbance in the form of load changes and in this case the system should reset its operating conditions and successfully meets the load demand or it could be large disturbance such as loss of a large generator, short circuits on a transmission line, etc.

Modern power systems have the property of very high order multivariable process. Thereby, its dynamic performance is influenced by several devices with different responses and characteristics. Therefore, instability in a power system may occur in many different ways depending on:

- The form of the disturbance
- The operating mode
- System topology

A power system depends strongly on synchronous machines for electrical power generation. Therefore, maintaining a synchronous operation is a necessary condition for convenient system operation.

Loss of synchronism is not the only reason of instability, unstable condition due to collapse of load voltage may occur if a generator is feeding an induction motor which is an issue of stability and control of voltage not a synchronism problem. In addition, if a power system is not coordinated correctly, frequency of the system may become unstable and blackout could be occurred [54].

3.2 Power System Stability Classification

Power system stability problems have the shape of complexity due to its different forms and wide range of factors.

Figure 16 shows the appropriate classification of power system stability into various categories and subcategories.

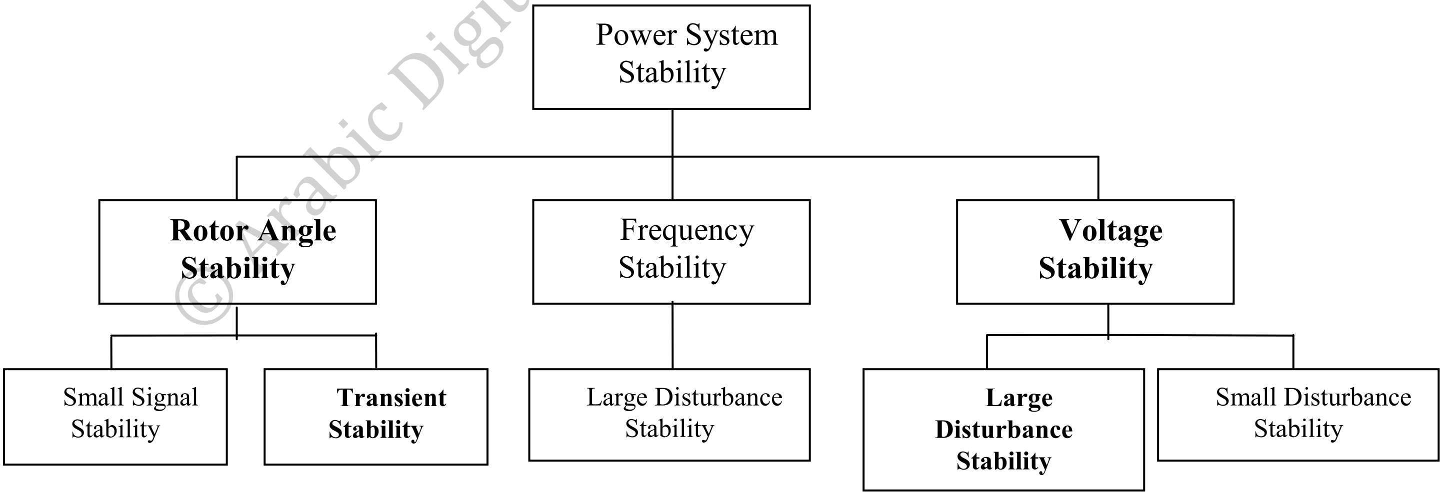


Fig. 16. Power system stability classification [55]

In this research study, voltage stability in terms of large disturbance stability as well as rotor angle stability in terms of transient stability have been analyzed and investigated at point of common coupling of the proposed system.

3.2.1 Rotor angle Stability

Rotor angle stability is the ability of the synchronous machines that are connected together in a power system to remain in synchronism under normal and abnormal operating conditions. Such kind of stability relies on the ability to restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. One form of instability can happen if an increase in angular swings of some generators with others have established. In this problem, an essential factor is the manner in which the power outputs of synchronous machines vary as their rotor angles change. Maintaining of synchronism in this case is achieved by restoring forces which tend to accelerate or decelerate one or more machines with respect to other ones.

Rotor angle stability can be classified into two categories:

- Small signal or steady state stability which is concerned in the ability of the power system to maintain synchronism under small disturbances.
- Large disturbance rotor angle stability or transient stability which is concerned in the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. [56]

3.2.2 Voltage Stability

Maintaining steady voltages at all buses in the power system under normal operating condition and after being subjected to a disturbance is the key paradigm of voltage stability. A cumulative voltage fluctuation at some buses is one of the forms of voltage instability. The major factor participating to voltage instability is commonly the voltage drop that occurs when active and reactive power flow through inductive reactance of the transmission network. In response to a disturbance, the driving force for voltage instability is the loads; power consumed by the loads tends to be restored by the action of distribution voltage regulators, tap changing transformers, and thermostats. Restored loads increase the stress on the high voltage network causing more voltage reduction. A rundown situation causing voltage instability occurs when load dynamics attempts to restore power consumption beyond the capability of the transmission system and the connected generation. [57]

Voltage stability can be classified into two categories:

- Large disturbance voltage stability is concerned with a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.
- Small disturbance voltage stability is concerned with a system's ability to control voltages following small perturbations such as incremental changes in system load.

3.2.3 Frequency Stability

Frequency stability depends on the ability to restore balance between system generation and load. It concerns also with the ability to maintain steady frequency within a nominal range when subjected to an imbalance between generation and load, with minimum loss of load. This kind of stability is usually associated with islanding (which is a phenomenon generally occurs in a network with wind generation in which a portion of the distribution network becomes electrically isolated from utility grid due to transmission system events & after disconnection, wind generator maintains supply to local loads. Islanding can be categorized as intentional island and unintentional island. Islanding is a condition in which local distribution generation systems continue to supply stable real power and reactive power to the local loads at a sustained voltage and frequency while the main Energy system is de-energized). Stability in this case is a question of whether or not each island will reach an acceptable state of operating equilibrium with minimal loss of load. It is determined by the overall response of the island as evidenced by its mean frequency, rather than relative motion of machines. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. [58]

3.3 Theory of Transient Stability

3.3.1 Overview

Remaining of synchronism of synchronous machines during large transient disturbances is the main aspect of transient stability. Faults on transmission lines, loss of generation or load as well as loss of system components such as transformers are the main forms of transient disturbances that could happen in the power system. Analysis of transient stability issues in power systems especially under certain conditions and contingences (disturbances, loss of generation or load) has attracted more attention than other kinds of power system stability.

Plots of generator rotor angle (δ) versus time are shown in figure 17. The generator is supposed to have a particular system disturbance, and as seen from the figure, the generator rotor angle recovers and oscillates around a new equilibrium point as in trace ‘a’ which is in transiently stable case or the generator rotor angle increases randomly as in trace ‘b’ which is in transiently unstable case. [59]

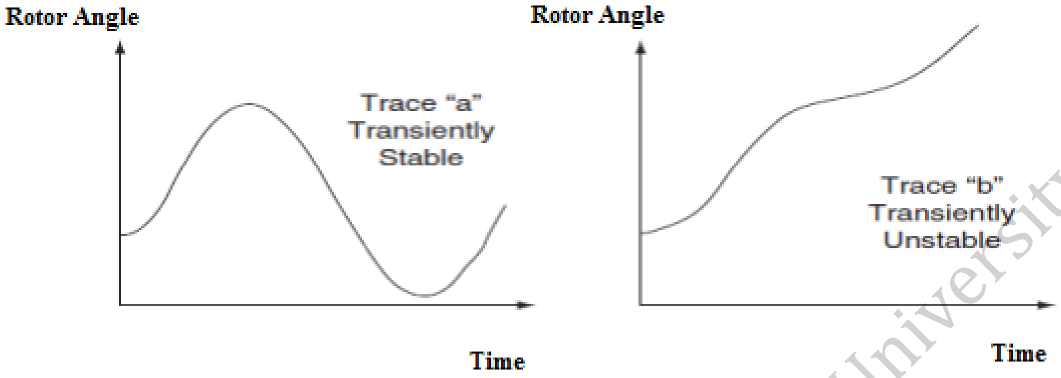


Fig. 17. Generator rotor angle for transient stable and transient unstable cases [59]

3.3.2 Power Angle Relationship and Swing Equation

To clarify the concept of power angle relationship, a single generator is connected to an infinite bus through a transmission line as shown in figure 18.

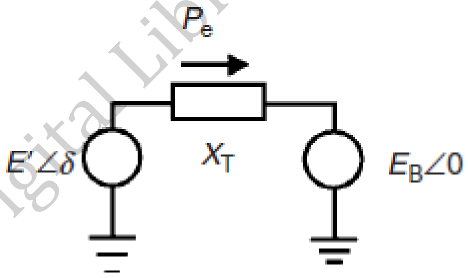


Fig. 18. A model of generator connected to infinite bus [60]

The relationship between the electrical power of the generator (P_e) and the rotor angle of the machine (δ) is given by:

$$P_e = \frac{E^{`} E_B}{X_T}\sin\delta = P_{max}\sin\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

Where, P_e is the electrical power of the generator, $E^{`}$ is the terminal voltage of the generator, E_B is the terminal voltage of the infinite bus, X_T is the reactance of the transmission line, δ is the rotor angle of the generator.

This equation can be shown graphically as shown in figure 19.

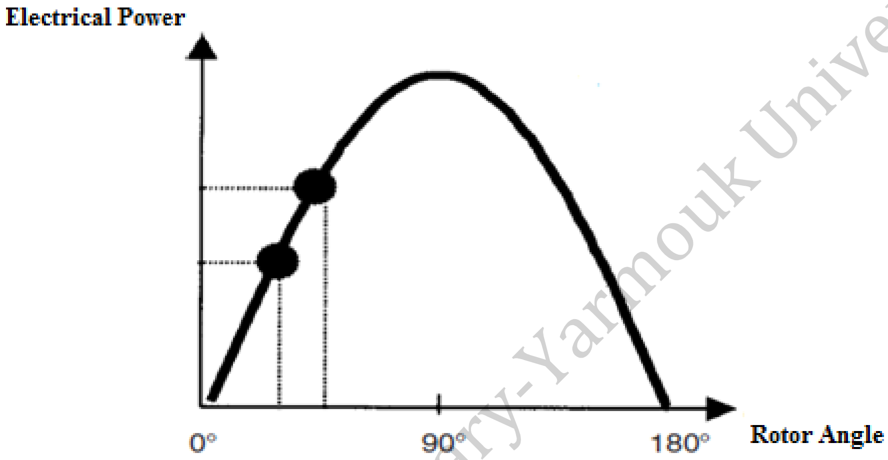


Fig. 19. Power angle relationship [60]

As seen from the figure if the power is initially increased then δ will increase until 90° when P_e reaches its maximum. Taking into account δ being beyond 90°, the power will decrease until δ equals 180°, so the power will decay to zero. This is the concept of power angle relationship and it describes the transmitted power as a function of rotor angle.

Further, to determine the stability of a machine in the power system the swing equation should be used so as to determine the swing curve of each machine in the power system. Swing equation can be identified by the two first order differential equations which are given by:

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_m - P_e \text{ per unit} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

Where, P_m is the shaft power input to the machine, P_e is the electrical power crossing its air gap, H is the inertia constant, ω_s is the synchronous speed of the rotor, ω is the angular velocity of the rotor.

It should be noted that it is not necessary to plot the swing curve of a machine to investigate whether the rotor angle increases or oscillates around an equilibrium point. Equal area criterion which is a combination between the dynamic behaviors of the generator as defined by the swing equation with the power angle relationship can determine the stability using graphical means. [60]

3.4 Power Flow Analysis

Power flow analysis is the best facility for estimating the operation of the system in steady state conditions as well as transient conditions. The buses of wind turbines generating units cannot be treated as voltage specified buses (P-V buses), because none of these units types have enough reactive power capability to hold their terminal voltage at a specified value. These buses can be treated only as P-Q buses with P and Q varying across iterations in contrast to a conventional P-Q bus where they remain constant. [61]

The power flow analysis with wind power plants has a bit more complexity than the power system with conventional sources. There are two reasons related to this problem, the first one is that the power injected into the grid by wind generation depends on the wind velocity which is variable and unpredictable, while the second one is that most wind turbines use induction generators. Therefore, there is a problem of slip convergence which is a slip value that should be attained by iterations to optimize a best solution for the electric output of a wind turbine.

The steady state model of an induction machine can be presented by its equivalent circuit which is shown in figure 20.

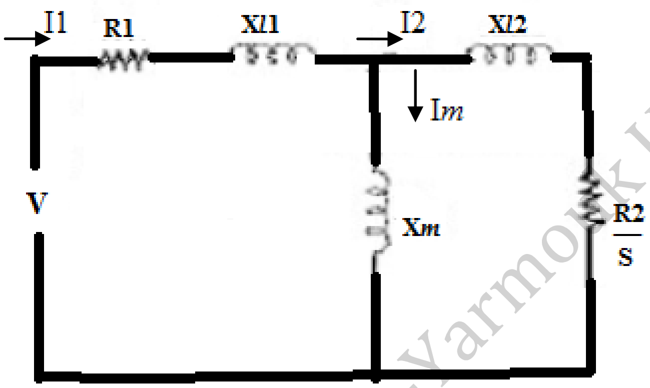


Fig. 20. Steady state equivalent circuit of induction machine [62]

Where,

R_1, R_2: Stator resistance and rotor resistance respectively.

I_1, I_2: Stator current and rotor current respectively.

X_{l1},X_{l2}: Stator and rotor leakage reactance's respectively.

X_m, I_m: Magnetizing reactance and magnetizing current respectively.

V: Terminal Voltage.

S: slip $= \frac{\omega_s - \omega_r}{\omega_s}$.

A sequential method is suggested by Feijoo and Cidras to analyze the power flow of the system where in the state variables (V-voltage, δ-power angle) and the slip of the induction generator are solved alternatively. Newton- Raphson method is modified to include the wind turbine generator bus, where in all three variables are solved simultaneously. The wind turbine generator is modeled as a variable load. The state variables corresponding to nodal voltage magnitudes and angles of the network and slip of induction generators are determined simultaneously by this method. Assuming adequate initial conditions, the method retains Newton's quadratic convergence. In this method the load flow algorithm is reformulated to include the mismatch equation ΔP_{mis} which is defined below. The unified load flow formulation is:

$$\begin{bmatrix} [\Delta \mathrm{P}] \\ [\Delta \mathrm{Q}] \\ [\Delta \mathrm{P}_{\text{mis}}] \end{bmatrix} = \left[\begin{matrix} \left[\frac{\partial P}{\partial \delta}\right] & \left[|V|\frac{\partial P}{\partial V}\right] & \left[\frac{\partial P}{\partial s}\right] \\ \left[\frac{\partial Q}{\partial \delta}\right] & \left[|V|\frac{\partial Q}{\partial V}\right] & \left[\frac{\partial Q}{\partial s}\right] \\ \left[-\frac{\partial P_{\text{mis}}}{\partial \delta}\right] & \left[-|V|\frac{\partial P_{\text{mis}}}{\partial V}\right] & \left[-\frac{\partial P_{\text{mis}}}{\partial s}\right] \end{matrix} \right] \times \begin{bmatrix} [\Delta\delta] \\ \left[\frac{\Delta V}{|V|}\right] \\ [\Delta \mathrm{s}] \end{bmatrix} \ldots\ldots(3.4)$$

Where,

ΔP, ΔQ: are the vectors of incremental changes in real and reactive power.

$[\Delta P_{\text{mis}}]$: is the mismatch equation whose elements are the difference between the power extracted from the turbine and the electrical power developed in the machine.

$\Delta\delta, \Delta V$: are the vectors of incremental changes in nodal voltage magnitudes and angles.

Δs: is the vector of incremental changes in induction machine's slip. Where, $s = s^{i+1} + s^{i}$ and i is the iteration number.

$|V|$: is the voltage magnitude.

$\frac{\partial y}{\partial x}$: is the matrix of partial derivatives of real and reactive powers and mismatch equation with respect to voltage magnitudes and angles as well as the slip. Where, y denote (P,Q,P_{mis}) and x denote (δ,V,S).

$\left[\frac{\partial P_{\text{mis}}}{\partial s}\right]$: is a diagonal matrix whose order is equal to the number of wind farms in the network. Their elements are given by:

$$\left[\frac{\partial P_{\text{mis}}}{\partial s}\right] = \frac{1}{2}\,\rho a v^3 [C_2 - E C_1] C_1 e^{C_6 \Lambda}\,\frac{\omega_0 r/v}{D} + \frac{A}{sC^2}(B - C) \ldots\ldots\ldots\ldots\ldots.(3.5)$$

$$\Lambda = \frac{(1-\theta^3)-(0.035\lambda-0.00028\theta)}{(\lambda+0.008\theta)(1-\theta^3)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where,

$$A = \frac{V^2 X_m^2 R_2/s}{R_1^2+(X_{l1}+X_m)^2}\,;\; B = \frac{2R_2}{s}\left(R_1 + \frac{R_2}{s}\right);\, C = \left(R_1 + \frac{R_2}{s}\right)^2 + (X_{l1} + X_{l2})^2\,;$$

$$D = (\lambda + 0.08\theta)^2\,;\, E = C_2\Lambda - C_3\theta - C_5$$

C1, C2, C3, C4, C5, and C6: Constants related to wind turbines design and specifications, θ: pitch angle, ρ: density of air, a: swept area of the blade, v: wind speed, ω_0: rotor speed of the wind turbine, r: radius of the wind turbine rotor.

For equation (3.3), the order of the jacobian for a power system having Ng (generator buses), N1(load buses), and Nw (wind farm buses with induction generators) is : $(Ng + 2N1 + 3Nw - 1)^2$ [62].

3.5 System stability and security impact

An increasing capacity of integrated wind power has negative effects on large-scale integrated wind farms. The security and stability issues of grid connected wind farms have become an urgent need to be resolved. The steady-state and transient simulation based on the wind turbine model is one of the important means to study the interaction of the wind farms and power system. [63]

There are several researches and studies which have been done by researchers in analyzing and investigating in depth the influence of the grid connected wind farm on the grid security and stability. Analyzing the influence of power flow after wind power connected to the grid, particularly the impact on system voltage and reactive power balance was studied in [64]. Reference [65] has an analysis of the transient voltage stability and frequency stability of the system after wind power integration.

Short circuits or loss of production capacity as well as tripping of transmission lines can be treated as power system faults which are related to system stability. Such kind of faults affects the balance of both real and reactive power and change the power flow. Even though the capacity of the operating generators is suitable, when large voltage drops occur, the unbalance and redistribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. After that, a period of low voltage may occur and possibly be followed by a complete loss of power. For example a wind farm nearby will see this problem. If a fault strikes the transmission line and causes the voltage at point of common coupling of local wind turbines to drop, then local wind turbines were simply disconnected from the grid and were reconnected when the fault was cleared and the voltage returned to normal operating conditions.

Earlier, wind power penetration was low. Therefore, a sudden disconnection of wind turbine or even a wind farm from the grid did not cause any noticed impact on the stability of the power system. As the penetration of wind energy increases, the significance of wind power generation by wind farms is also increase. Production capability will be lost if a large power wind farm is suddenly disconnected. The system may suffer a drop in voltage or frequency and possibly followed by a blackout unless the remaining power plants replace the loss within very short time. As a result, to avoid total disconnection from the grid, there might be a new generation of wind turbines that can ride through the disturbances and faults. It is important to ensure that the wind turbine can restore the normal operation in a simple way and within suitable time in order to keep system stability. Optimization of different types of wind turbine technologies may result in adequate design so as to face the future problems. Dynamic reactive power compensation devices such as STATCOM, SVC, and interface power electronics may also limit these problems and support system stability [66].

Chapter 4

4. Literature Review

Wind energy conversion systems (WICS) have attracted considerable interest in recent years. A major reason for that interest is the increasing installed capacity of the grid connected wind turbines. However, system stability concerns and reactive power consumption for induction generators due to fluctuations in wind profile have been solved by the integration of FACTS devices into the system. This has resulted in an enormous scientific papers and reports which are mainly from academia. The most important achievements in the last two decades are summarized as follows:

- A wind farm modeling with integration of STATCOM is studied in [67]. This scheme increases the upper limits of induction generators dynamic stability in various distortion conditions in grid. An induction generator has found great applications for various reasons such as economical, easy control and easy to use. Induction machines have a problem of providing reactive power for their excitation current. Controlling algorithms are one of the needed cases to adjust input mechanical power to induction generator and generator connection terminal voltage, for wind farms construction. Pitch angle control is used, in order to control wind turbines generated mechanical power. Generally to adjust machine terminal voltage and also apart of required reactive power, constant capacitor banks connected to bus of each unit are used. Since capacitor capacitance rate, required to excite unit's changes as machine ratio changes, so if a constant capacitor bank is installed, machine terminal voltage is function of generator velocity changes. In order to achieve a proper regulation for wind farm voltage, in different papers, different reactive power static compensators that have fast responses to system conditions and changes are studied.

- In [68] Modeling and simulating of a wind turbine and its induction generator system as an electrical source in the power networks is an essential target. One of the popular wind farm concepts in power systems is based on fixed speed wind turbines. A directly grid connected squirrel cage induction generator (SCIG) is coupled to the wind turbine rotor through gearbox. This generator accepts only very small rotational speed variations, therefore these wind turbines are considered to operate at fixed speed. Because SCIG consumes reactive power, compensating capacitor banks are currently added to provide the induction generator magnetizing current as well as improving the power factor. Specifically for Fixed Speed Wind Turbines (FSWT), reactive power sources existence is a major concern, not only for meeting the reactive power requirements of the wind farm, but also to support the system voltage. The wind farms with FSWT are composed of a large number of wind turbines with directly grid coupled SCIG and compensating capacitors, operating on an internal electrical network (lines and transformers) that connects the wind farm to the grid. Fixed speed wind turbines basically consist of SCIG that are directly connected to the grid via a step-up transformer. Traditionally, the required reactive power for the machine excitation is provided by the capacitor banks installed at its terminals. However, for events such as the sudden drop of voltage in the power system, capacitor banks cannot provide dynamic compensation. In these cases, dynamic compensation devices such as static VAR compensation (SVC) or STATCOM can represent a more suitable solution. The STATCOM is one of the key flexible alternating current transmission system (FACTS) devices. Based on a voltage source converter, the STATCOM regulates the system voltage by absorbing or generating reactive power. Contrary to a Thyristor-based SVC, STATCOM output current (inductive or capacitive) can be controlled independent of the alternating current (AC) system voltage.

- The voltage stability of the bus load in various static and dynamic load systems that are fed by a wind farm has been examined by Ali Ozturk and Kenan Dosoglu . In the control of load voltage and reactive power, ten MVar static synchronous compensator (STATCOM) and static var compensator (SVC) is used. In voltage and reactive power control, the results of time response and damping oscillation have been found. The results achieved have proved that SVC and STATCOM yield good results when used in terms of voltage stability of the system. When the load connected to a bus load in STATCOM controlled wind farm which is installed into the circuit, the effects of terminal voltage, reactive power and speed regulation have been examined in terms of rotor stability performance, and STATCOM control has been observed to yield good results [69].

- Lie Xu, Senior Member, IEEE, Liangzhong Yao, and Christian Sasse have investigated the System stability of wind farms based on fixed speed induction generators and the use of the static var compensator (SVC) and static synchronous compensator

(STATCOM) for wind farm integration is also investigated. Due to the nature of asynchronous operation, system instability of wind farms based on FSIG is largely caused by the excessive reactive power absorption by FSIG after fault due to the large rotor slip gained during fault. It was found that the SVC and STATCOM considerably improve the system stability during and after disturbances. Compared to SVC, STATCOM gave a much better dynamic performance, and provided a better reactive power support to the network, as its maximum reactive current output was virtually independent of the voltage at the point of common coupling (PCC). As the number of wind farms in a power network has increased, the connection requirements for wind farms have tended to become increasingly similar to those for conventional synchronous generators. Wind turbines using fixed speed induction generator (FSIG) provide a simple, rigid, and cost effective solution. However, a wind farm implemented using FSIG based wind turbine has difficulties in meeting the proposed Grid Code (requirements and regulations) in terms of the fault ride through, reactive power and voltage control requirements. Previous research has revealed that faults which occur on the transmission line can lead to wind generator over-speed and cause instability of the network voltage [70].

- Dynamic and steady-state characteristics of a commercial wind power generation system containing four wind-turbine induction generators connected to a utility grid are analyzed in [71]. The simulated power-flow results are validated by comparing with the field measured results of the studied WPGS. Various steady-state results of the studied WPGS under different configurations, cable conditions, and rotor resistances are performed. Dynamic simulations of the studied four WTIG under unbalanced and balanced faulted conditions are also examined. Dynamic characteristics of one WTIG with and without a static VAR compensator (SVC) connected to WTIG's terminal for voltage support are also compared. It can be concluded from the simulated results that the proposed models can be effectively employed for both steady-state and dynamic simulations of the practical commercial WPGS under various operating conditions and disturbance conditions.

- In [72] modeling of the wind farms with the connection to a weak rural distribution system are presented. The voltage profile is the main issue when considering stable operation of a wind farm. In order to maintain the wind farm's stable operation and avoid over-speed of the induction generators, some control strategies which use FACTS devices are presented to improve stability margin considering loads level variation among the feeder. Simulation results include these techniques to improve the stability margin of voltage.

- Growing number of wind turbines is changing electricity generation profile all over the world. Therefore, challenges for power system operation are increased, which was designed and developed around conventional power plants with directly coupled synchronous generators. In result, safety and stability of the electrical network with high wind energy penetration might be compromised. For this reason Transmission System Operators (TSO) impose more stringent connection requirements on the Wind Power Plant (WPP) owners. On the other hand flexible AC transmission systems

(FACTS) devices offer enhancement of grid stability and can facilitate grid code compliance for WPP. The state of the art in FACTS for WPPs with AC connection has been presented in [73], FACTS devices with their properties are described. Examples of few existing FACTS applications for wind farms are given. Flexible AC Transmission Systems (FACTS), which were developed in order to dynamically control and enhance power system performance. Stability is the key aspect for introducing FACTS devices. Therefore, is seems quite natural, that one of the today's research topics is employment of FACTS devices for enhancing wind farm performance with respect to the grid codes and power system stability.

- The reaction of wind energy installations to gird disturbances is studied in [74]. For the variable-speed turbine installations, the influence of using various levels of reactive power in-feed from the wind energy installation is investigated. Recently voltage-source or current-source inverter based various FACTS devices have been used for flexible power flow control, secure loading and damping of power system oscillation. Some of those are used also to improve transient and dynamic stability of wind power plant (WPP). In [74], the static reactive compensator (STATCOM) based on voltage source converter (VSC) PWM technique to stabilize gird connected squirrel cage wind power plant is proposed. A simple control strategy of STATCOM is adopted at the wind generator terminal is needed. A new system control is used as the control methodology of STATCOM, rather than conventional controller. The steady state capacitor value used with induction generator is reduced by certain percentage when STATCOM is used with WPP. Recently voltage-source or current-source inverters based flexible AC transmission systems (FACTS) devices such as static var compensator (SVC), static reactive compensator (STATCOM), dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and unified power flow controller (UPFC) have been used for flexible power flow control, secure loading and damping of power system oscillation.

- Patel and Dipesh M investigate the Static Synchronous Compensator (STATCOM) application to achieve continuous operation of wind turbine equipped with cage based induction generators during grid faults. It is shown that a Static Synchronous Compensator (STATCOM) enhances voltage profile of power grid containing induction generator based wind farm [75].

- In [76] two schemes for enhancing voltage stability of grid connected wind generator system has been studied. These are: variable susceptance control through SVC and reactive power compensation through static compensator system (STATCOM). Simulation results show that both schemes are well capable of providing voltage stability and damping transient arising from reasonable level of disturbances. The STATCOM, however, demonstrates superior performance because of its fast response capability as well as its ability to provide compensation independent of system voltage support. Under normal conditions, the wind generators may function well, but changes in turbine input and load may cause oscillations in frequency and voltage, leading to eventual voltage collapse. This is primarily attributed to the lack of support excitation to the system. The transient performance can normally be enhanced by blade pitch control on the turbine side or, voltage, current and power control on the generator side. The performance of STATCOM has been compared with the variable susceptance terminal voltage dependent SVC control. Comparison of responses shows that STATCOM control scheme provides better voltage profile and well damped transients following large disturbances.

- The contribution of wind power in conventional generation is increasing rapidly nowadays. Hence a better understanding of wind power plants is required. But the wind power plants generally containing induction generators exhibit a rather different behavior than the conventional power plants which use synchronous generators. In [77] Transient stability of a wind farm based on conventional fixed speed Induction generator when it has been integrated with a weak grid is analyzed and studied. A comparative analysis of the transient stability improvement of a FSIG wind plant has been done when it is supported with FACTS like SVC and STATCOM of equal ratings Induction and synchronous generators do not exhibit similar behavior during power system stresses (transients). Moreover, increase in wind power based generation requires a reliable transmission system for power evacuation to the load centers. As the wind farms are mainly concentrated in far flung and rural areas their interconnection with the grid becomes a problem. This problem is mainly due to the existence weak transmission grids in the rural areas. Earlier when the share of wind power generation as compared with the conventional generation was low, during transient conditions; whenever the power system reached on the verge of instability the wind farm was disconnected from the grid and was reconnected when transients passed away.

- In [78] the effect of wind speed changes on the active and reactive power penetration to the wind energy embedded distribution network has been analyzed. Four types of wind speed changes namely; constant, linear change, gust change and random change of wind speed are considered in the analysis. The study is carried out by three-phase, non-linear, dynamic simulation of distribution system component models. Results obtained from the investigation are presented and discussed. The active power generated by the WTIGs depends upon the wind speed. With the variation in active power generation, the reactive power consumption also varies. When the reactive power requirements of WTIGs exceed the reactive power supplied by the fixed capacitors, the difference reactive power is drawn from the grid. At lower active power generation, reactive power is supplied to the grid due to the less consumption of reactive powers by the WTIGs. But at higher active power generations, active power is injected to the grid and reactive power is drawn from the grid.

- The fluctuating real power injection and (in case of fixed-speed induction turbines) to the varying absorption of reactive power which leads to voltage deviations throughout the network that could affect system stability and power quality for costumer is one of the problems that has been solved in [79]. Firstly, variable speed operation is described for wind generators, then the use of Flexible Alternating-Current Transmission Systems (FACTS) controllers with fixed speed induction generator is considered. Load flow analyses and dynamic studies have to be made in advance to analyze how the decentralized power production from renewable energies would affect the load flow conditions in the grids.

- The steady state impact of Flexible AC Transmission system (FACTS) controller on Wind generators interconnected to the grid is studied in [80]. Fixed speed induction generators are considered in the analysis, which are represented by their steady state model. Due to the weak link between the point of common coupling (PCC) and rest of the grid, the feasibility of connecting more number of wind turbines would be reduced. So in this paper, two schemes are selected for strengthening the grid. In order to improve the voltage profile, Static VAR compensator (SVC) is used. To include SVC, simultaneous and sequential methods of power flow analysis are followed. In this paper, Power flow analysis is performed for Wind Energy Conversion System (WECS) included 9 bus distribution system which yields steady state slip of induction generator along with voltage and angle.

- Some flexible AC transmission systems (FACTS) devices have been proposed recently for compensating the reactive power of induction generator during network disturbances. However, integration of FACTS devices to wind farm definitely increase the overall cost. Therefore, in [81], they focuses on a new topology, where fixed speed WTGSs are installed in a wind farm with variable speed wind turbines (VSWT) driving permanent magnet synchronous generators (PMSG). VSWT-PMSG uses a fully controlled frequency converter for grid interfacing and it has abilities to control its reactive power as well as to provide maximum power to the grid. A real grid code defined in the power system is considered to analyze the low voltage ride through (LVRT) characteristic of fixed speed WTGSs. Simulation results clearly show that the proposed topology might be a good solution to augment the LVRT requirement of fixed speed WTGSs.

In the literature review mentioned above, we can see that STATCOM has approved a better and faster capability than SVC in maintaining system stability and eliminating the voltage collapse. In addition, only one system disturbance or fault was simulated in the abovementioned test systems.

In this research study, two successive disturbances was simulated at point of common coupling (double line to ground fault followed by three phase to ground fault) which is not depicted in the literature review for such kind of studies. It was also found that SVC can give a better and faster performance than STATCOM which is a result opposing some findings in the literature review. It was noticed in the next chapter that SVC can be better than STATCOM for the first disturbance (double line to ground fault) in maintaining system stability point of view. However, STATCOM gives a better stability performance than SVC for the second disturbance (three phase to ground fault).

Chapter 5

5. Simulation and Results

5.1 System Description

Figure 21 presents the schematic diagram of the proposed system under work. The system consists of a 12 MW wind farm; 4 wind turbines rated at 3 MW for each WTIG, and the induction generators connected with the turbines operate at 0.9 power factor. An overhead transmission lines of 25 km long, a 132/33 KV (47 MVA) transformer compromises the grid side, in addition to 4 sets of 33/0.575 KV (4 MVA) transformers for wind farm side. Each WTIG has its own MW rating, 33/0.575 KV transformer, KVAR rating.

The grid is formed by a three – phase balanced A.C voltage source, 2500 MVA short circuit power and (X/R) ratio of 3 at 132KV voltage. The parameters of all components are presented in table 2, 3, 4 and 5.

SCIG is used in this study, and the 25 Km overhead transmission lines was modeled as π section, the lines between point of common coupling and wind farm transformers which are 1 km long were also modeled as π sections. STATCOM and SVC are connected at point of common coupling (PCC) which represents the overhead transmission line for reactive power compensation. Overall simulations are carried out by using SimPower System library section of the MATLAB/SIMULINK .

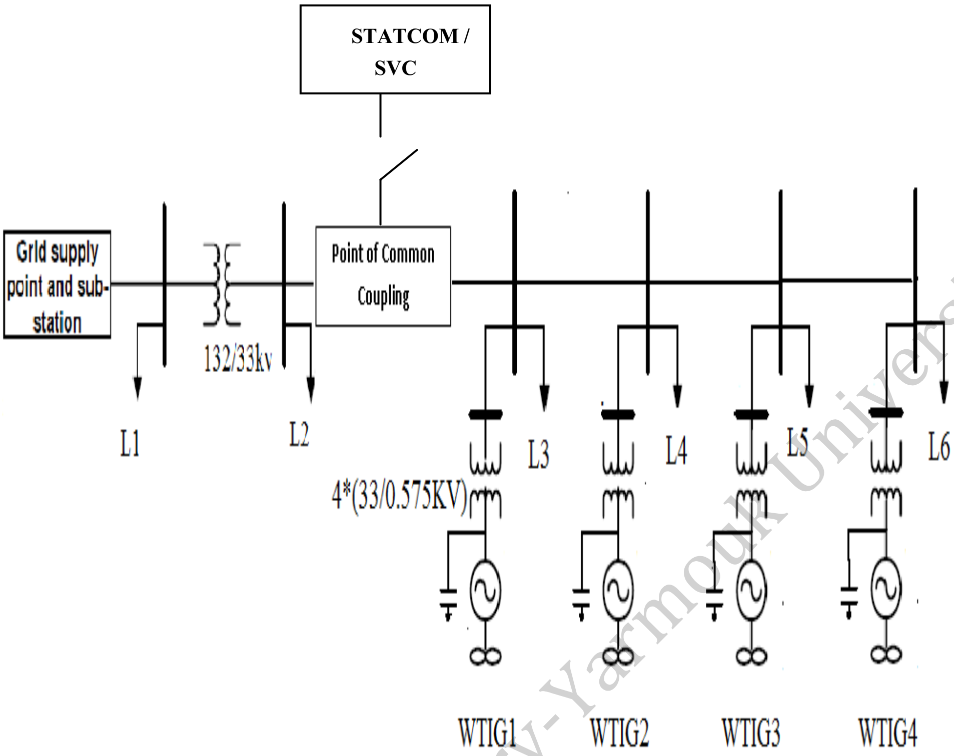


Fig. 21. Schematic diagram of the proposed system

The wind turbine induction generator characteristics developed in Simpower system library at Matlab/Simulink indicate that when using a base wind speed of 9 *m/s*, the base power and voltage and all other parameters either for the wind turbine or the generator should be assumed as shown in table 2.

Figure 22 depicts the wind turbine characteristics as they developed in SimPower System library in Matlab/Simulink.

Table 2. Wind Farm Parameters

Wind Turbine	Symbol	Value	Unit
Base power	S_B	1.5	MW
Base wind speed	W_B	9	m/s
Maximum power at base wind speed	$P_{t\,max}$	1	$p.u$
Base rotational speed	w_B	1	$p.u$
Pitch angle controller gain	$K_{P,}\ K_i$	5, 25	
pitch angle	β	0	deg
Generator			
Base power	S_B	1.5/0.9	MW
Base voltage	V_B	0.575	K_V
Stator resistance	R_s	0.004843	$p.u$
Stator inductance	L_s	0.1248	$p.u$
Rotor resistance	R_r	0.004377	$p.u$
Rotor inductance	L_r	0.1791	$p.u$
Magnetizing reactance	L_m	6.77	$p.u$
Inertia Constant	H	5.04	S
Compensating capacitors			
Capacitive reactive power 1	Q_{C1}	400	k_{var}
Capacitive reactive power 2	Q_{C2}	500	k_{var}
Capacitive reactive power 3	Q_{C3}	600	k_{var}
Capacitive reactive power 4	Q_{C4}	700	k_{var}

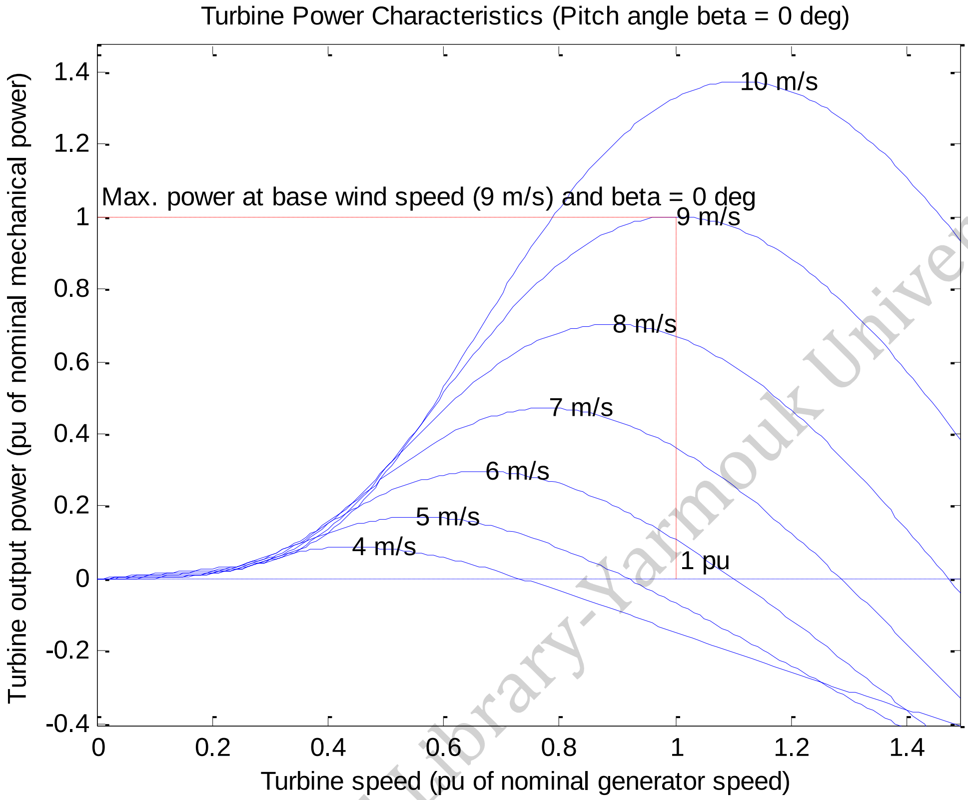


Fig. 22. Wind turbine characteristics

Table 3 depicts the parameters used for the wind farm side transformer and the grid side transformer. Transmission line resistance, inductance and capacitance are also shown in table 4. Table 5 shows the various loads being utilized in the proposed system. Every load has his own active power P (MW), inductive reactive power QL (KVAR) and capacitive reactive power Qc (KVAR).

Table 3. Transformer Data

Parameter	Value	Unit
Wind farm side transformer data (33/0.575 KV)		
Rated power	4	MVA
$V_{secondary}\, L-L(RMS)$	0.575	K_V
$V_{primary}\, L-L(RMS)$	33	K_V
Inductance	0.025	p.u
Grid side transformer data (132/33 KV)		
Rated power	47	MVA
$V_{secondary}\, L-L(RMS)$	33	K_V
$V_{primary}\, L-L(RMS)$	132	K_V
Inductance	0.08	p.u

Table 4. Transmission line parameters

Parameter	Value	Unit
Resistance	0.1153	Ω/k_m
Inductance	1.05	mH/k_m
Capacitance	11.33	nF/k_m

Table 5. Load Parameters

	P (MW)	QL (KVAR)	Qc (KVAR)
Load 1	1.5	20	120
Load 2	1.2	20	0
Load 3	1.5	20	120
Load 4	1.2	20	0
Load 5	1.2	20	0
Load 6	1.2	20	0

5.2 Simulation and Results

5.2.1 Simulation results in healthy conditions.

A wind farm consisting of four wind turbines connected to medium voltage grid is considered firstly without taking into account the occurrence of any short circuit. The generated power is then transferred to the high voltage grid with rated voltage of 132 KV through a 25 Km overhead line. The stator winding of the SCIG is directly connected to the 60 Hz grid and the rotor is driven by a zero pitch angle wind turbine in order to generate maximum power. The induction generator speed must be slightly above the synchronous speed so as to generate power. So, speed varies approximately between 1 p.u at no load and 1.005 p.u at full load. The nominal wind speed producing the nominal mechanical power is 9 *m/s* where 1 p.u equals 3 MW.

Reactive power compensation varies with the variation in wind speed. Therefore, fixed capacitor banks are assumed to be connected at the terminals of each generator pair but they partly compensate the reactive power absorbed by the induction generators because for events such as sudden drop in voltage in the power system, capacitor banks cannot provide dynamic compensation. Consequently, STATCOM or SVC as dynamic var compensators is assumed to be connected at point of common coupling.

The generated active power, reactive power, voltage at point of common coupling without using any kind of FACTS devices (normal case) are shown in figure 23, 24, 25. As seen from these figures the voltage at point of common coupling approaches 0.954 p.u and the generated active power injected from the wind farm is nearly 6 MW but the reactive power at PCC is about 4.3 MVAR.

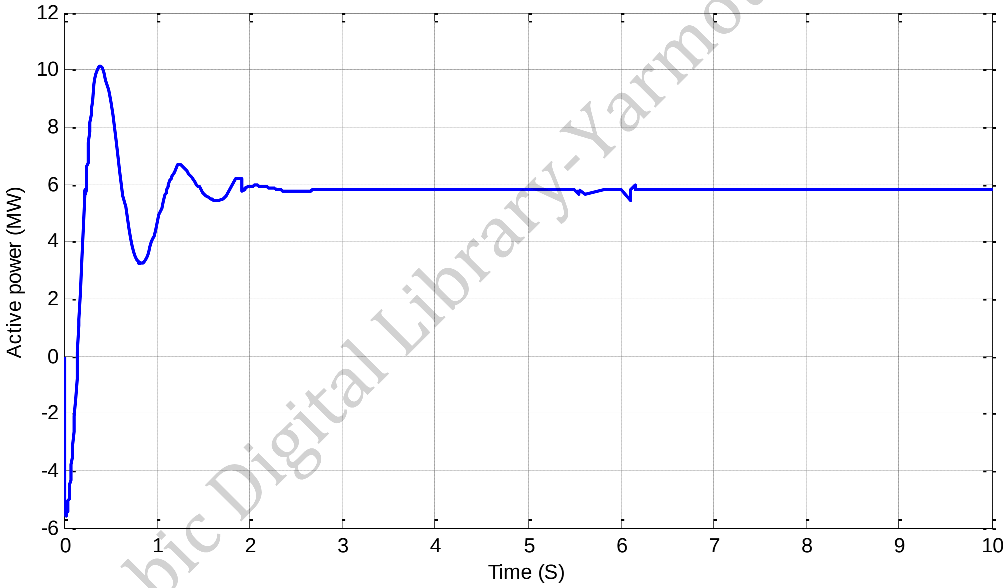


Fig. 23. Active Power at PCC

It can be noted from figures 23, 24, 25 that there is some kind of oscillations especially in the first two seconds before the steady state value. These oscillations appeared as soon as AC generators were operated in parallel or from the concept of the power vs. phase-angle curve gradient interacting with the electric generator rotor inertia. Another source of oscillations is due to generator rotor masses swinging relative to one another. Such oscillations are commonly found in power system stability studies [82].

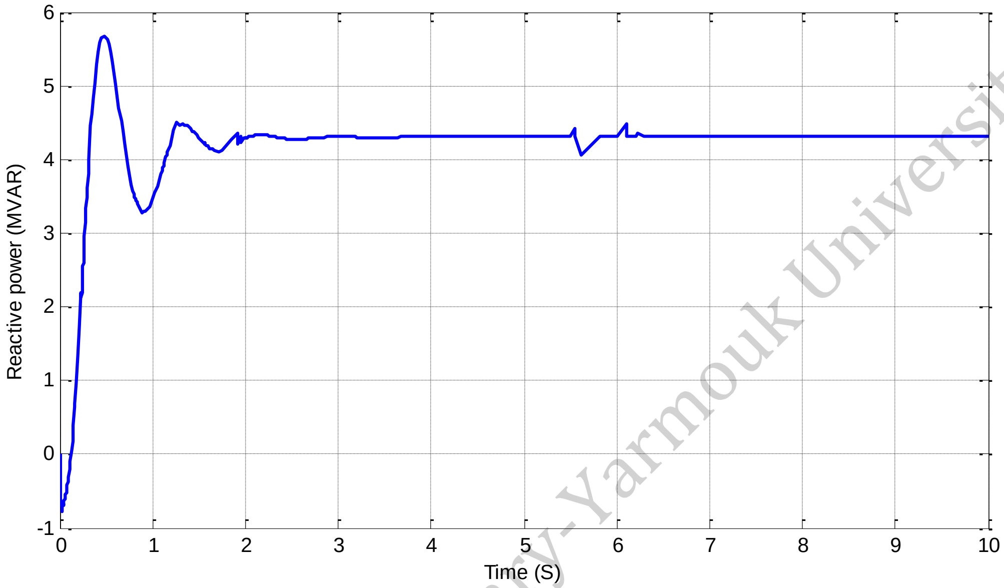


Fig. 24. Reactive power at PCC

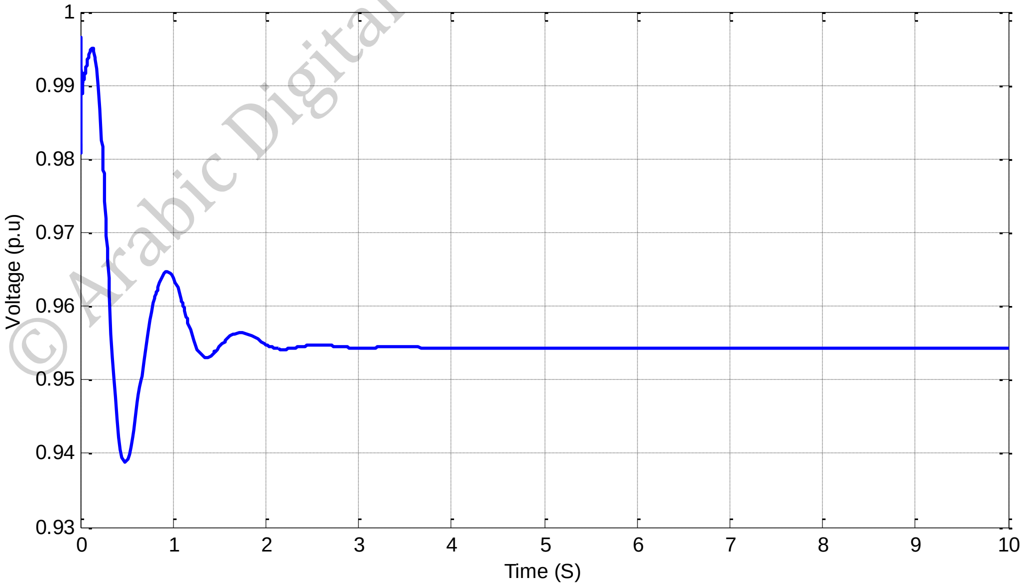


Fig. 25. Voltage at PCC

In order to support the voltage and provide reactive power compensation at PCC, STATCOOM and SVC are attached at PCC for that reason. Therefore, simulations are carried out with STATCOM and with SVC.

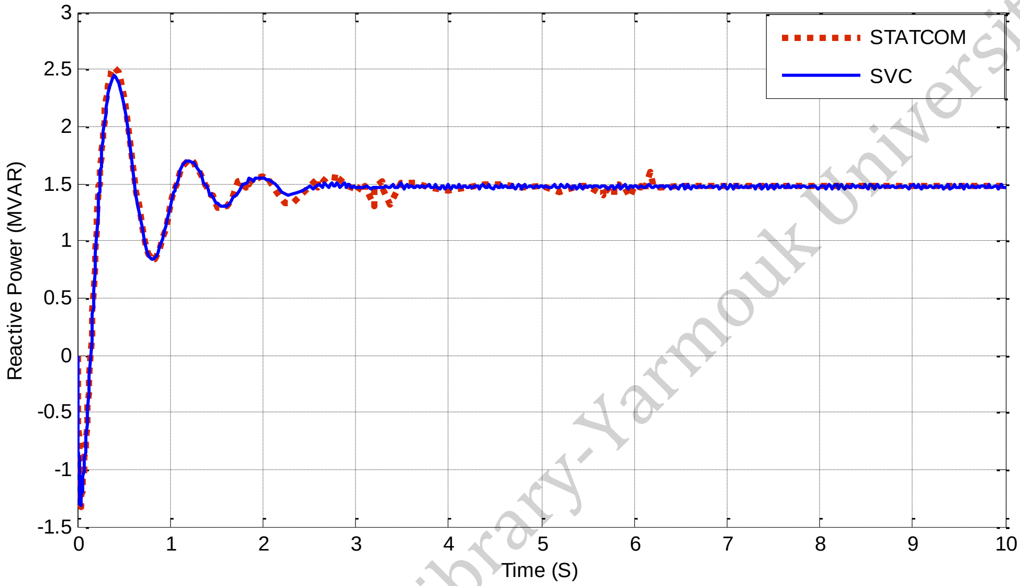


Fig. 26. Reactive power at PCC with FACTs

Figure 26 shows the simulation results after integrating the STATCOM and SVC to the system. As we can see from figure 26, the reactive power at point of common coupling is improved and reaches approximately 1.5 MVAR while it was 4.3 MVAR before adding the FACTS devices. This means that the reactive power compensation was efficiently provided by the dynamic var compensators. It should also be noted that the two kinds of FACTS devices in this study support the needed reactive power which is absorbed by the induction generators and give the same performance in improving the reactive power, but it is worth noting that the SVC has less oscillations than STATCOM in reactive power improvement.

Figure 27 shows also the simulation results after integrating the two kinds of FACTS devices. STATCOM and SVC has approximately the same performance in improving the voltage stability at point of common coupling. The voltage reaches approximately 0.993 p.u while it was 0.954 p.u before adding them to the system. STATCOM and SVC have efficiently supported the system voltage stability. It should be noted that STATCOM has less oscillations than SVC in improving the voltage stability.

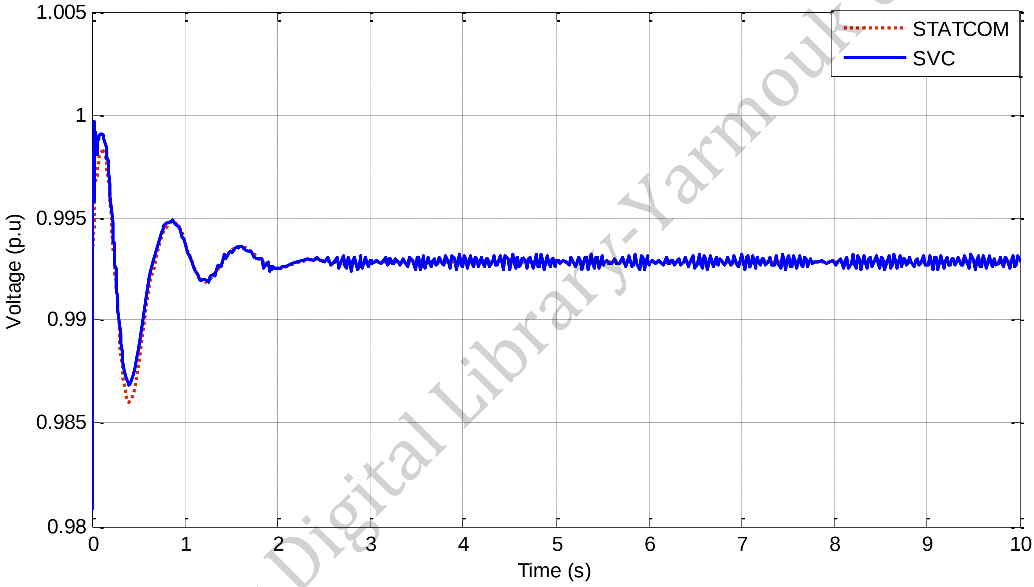


Fig. 27. Voltage at PCC with FACTs

5.2.2 Simulation results in faulty conditions

A system event by means of double line to ground fault (DLG) followed by three phase to ground fault was simulated at PCC in this study. Improving the transient stability margin of the grid can be obtained by the utilization of the given two FACT devices (STATCOM, SVC). In order to compare the performance of these two FACT devices, three parameters were monitored during this system event. These parameters are the voltage and reactive power at PCC and the wind farm generators rotor speed.

Voltage recovery time at PCC and the damping time period of rotor speed oscillation were compared relatively when FACTS devices (STATCOM, SVC) of equal converter rating are integrated to the grid.

As seen from figure 28, the voltage before the occurrence of the fault was 0.954 p.u (pre-fault value) but after the DLG fault occurred, the voltage dipped down to zero at t=3s then at t=3.2s the voltage gets back to its pre-fault value. After 3 seconds which means at t=6s, another 3 phase to ground fault has occurred at PCC. The fault recovery was at t=6.2s. It can be noted from the figure that even after the fault recovery, the voltage at PCC did not recover to its pre-fault value but stills approximately at 0.668 p.u. The insufficient reactive power needed for the excitation of induction generators in such system even will not allow the voltage returning to the steady state value.

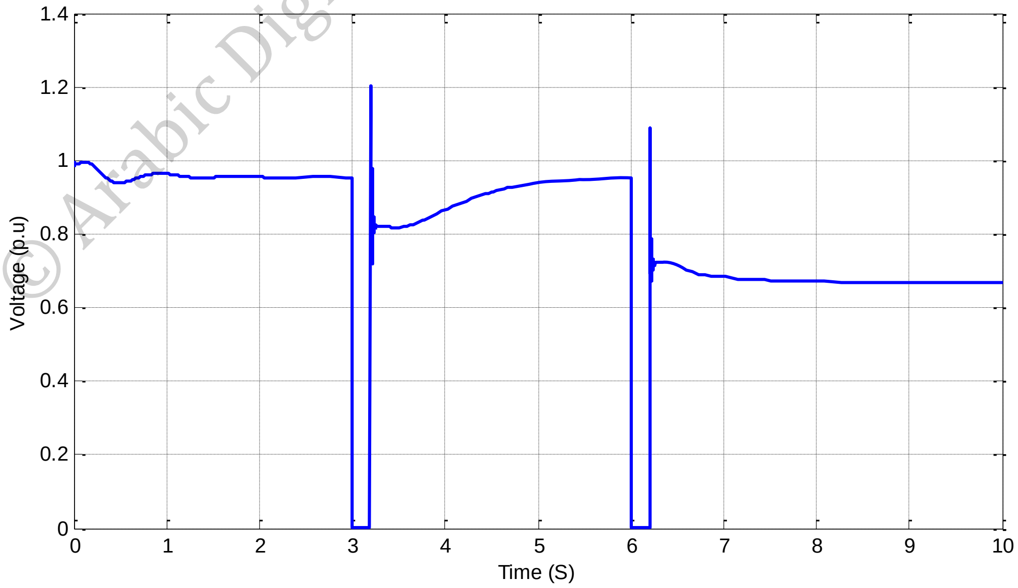


Fig. 28. Voltage at PCC without FACTS

As a result of the voltage collapse or voltage instability which can be noticed from the last figure, the need for a dynamic var compensator is a must due to a large reactive power requirement by the wind generator during the system disturbances at point of common coupling. The STATCOM and SVC can solve this problem.

Figure 29 depicts the voltage recovery performance of SVC and STATCOM due to a system event at PCC. It is clearly shown that after the fault recovery, the voltage at PCC gets back to the pre-fault value. In maintaining voltage stability point of view or the voltage recovery time, It's also worth noting that the action of SVC is better than the action of STATCOM for the first disturbance (DLG) fault, while the action of STATCOM is better than SVC action for the second disturbance (3 phase- ground) fault.

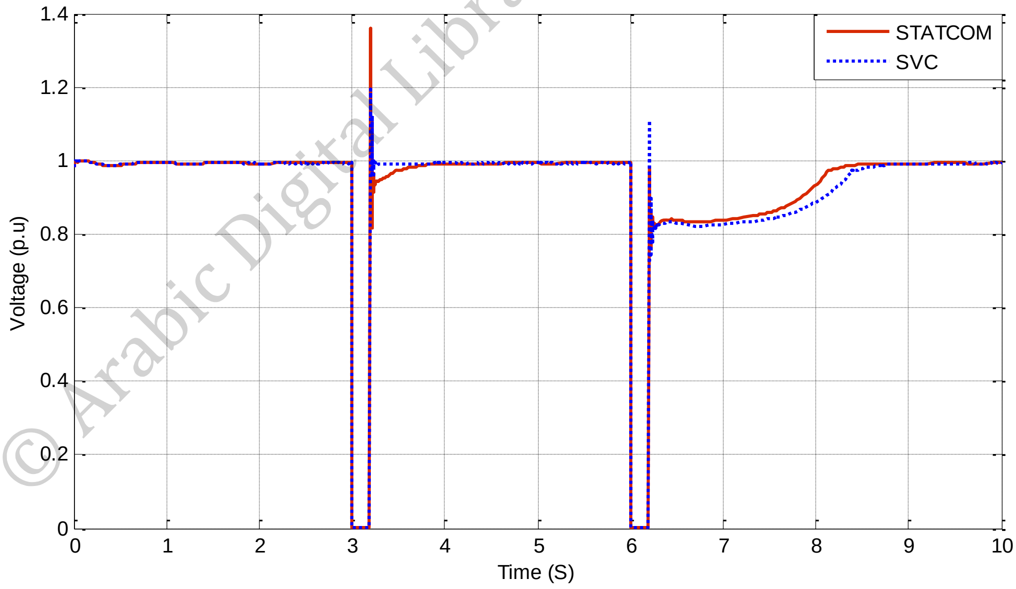


Fig. 29. Voltage at PCC with FACTS

The reactive power at PCC without the integration of FACTS devices can be seen in figure 30. It can be observed at PCC that the reactive power increases after the first disturbance to

12.5 MVAR and gets back to its pre-fault value after sometime. While for the second disturbance, it increases to approximately 17 MVAR and never gets back to its pre-fault value. This rise of reactive power for both disturbances was occurred because the wind turbine generators provide the reactive power during the two faults.

The reactive power at PCC with the integration of FACTS devices are shown in figure 31. It is clearly shown that the integration of FACTS devices reduces the reactive power for the two disturbances to approximately 1.5 MVAR which is the pre-fault value. But, for the second disturbance (3 phase to ground fault), it should be noted that STATCOM is better and faster than SVC in recovering the reactive power to its pre-fault value. While in first disturbance (DLG fault), SVC is better than STATCOM in recovering the reactive power to its pre-fault value.

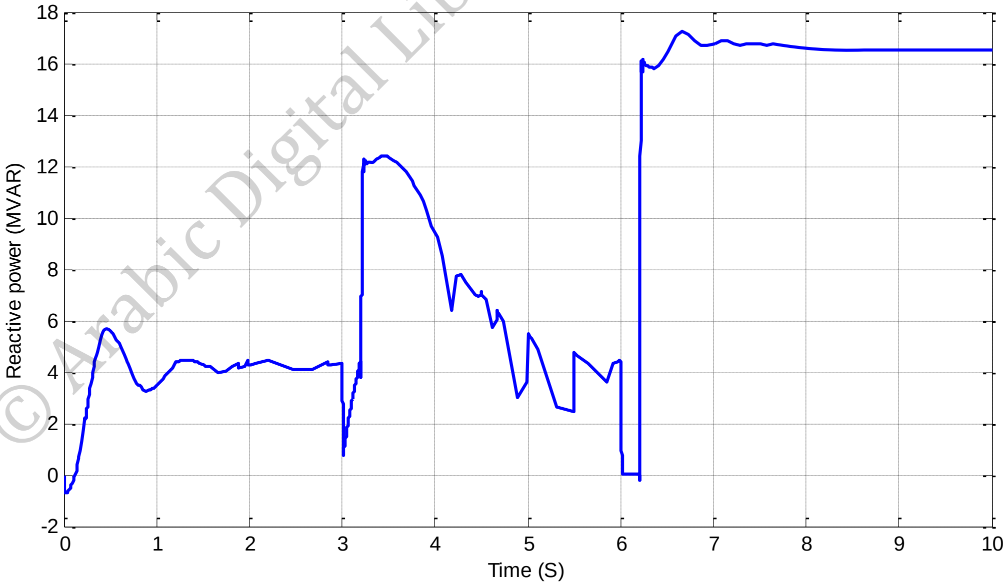


Fig. 30. Reactive power at PCC without FACTS

In addition to the reactive power and voltage at PCC, wind farm rotor speed is also monitored so as to determine its stability and its behavior with and without the integration of FACTS devices to the power system.

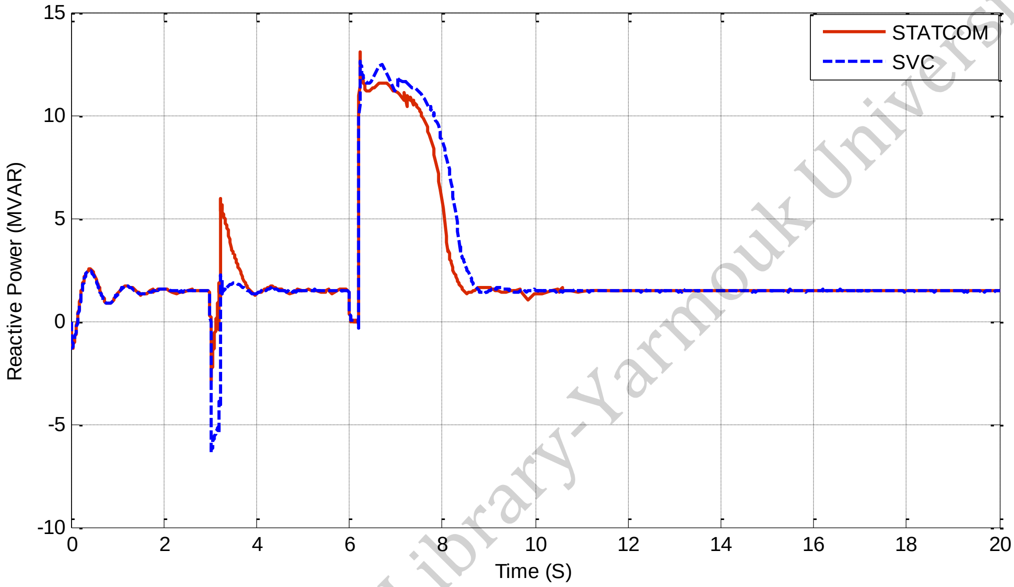


Fig. 31. Reactive power at PCC with FACTS

Figure 32 shows the rotor speed of the wind generators without FACTS integration. It can be noticed from the figure that during the first disturbance, the rotor speed has a slight change. But, for the second disturbance the rotor speed increases rapidly and consequently the possibility of the generators to remain connected to the grid is almost impossible. This problem can be solved by the integration of FACTS devices at PCC as depicted in figure 33.

It can be seen that although the rotor speed of the wind farm have reached instability, FACTS devices can recover the steady state or the pre-fault value. By comparing the recovery times of the rotor speed with SVC and STATCOM, it is clear that the SVC has fewer oscillations than STATCOM for both disturbances. However, SVC and STATCOM increase the rotor speed stability approximately in the same way.

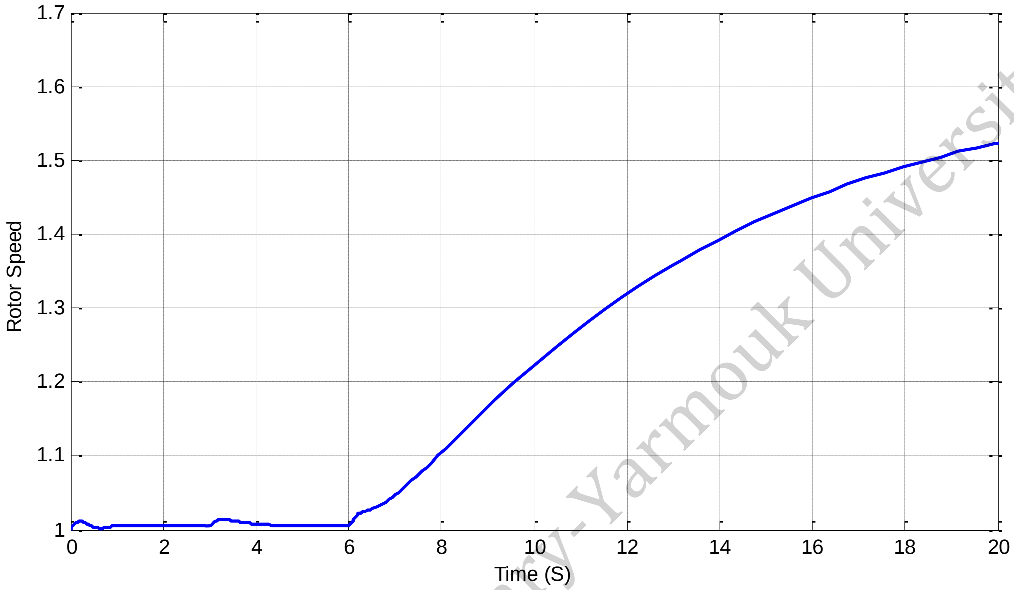


Fig. 32. Wind farm rotor speed without FACTs

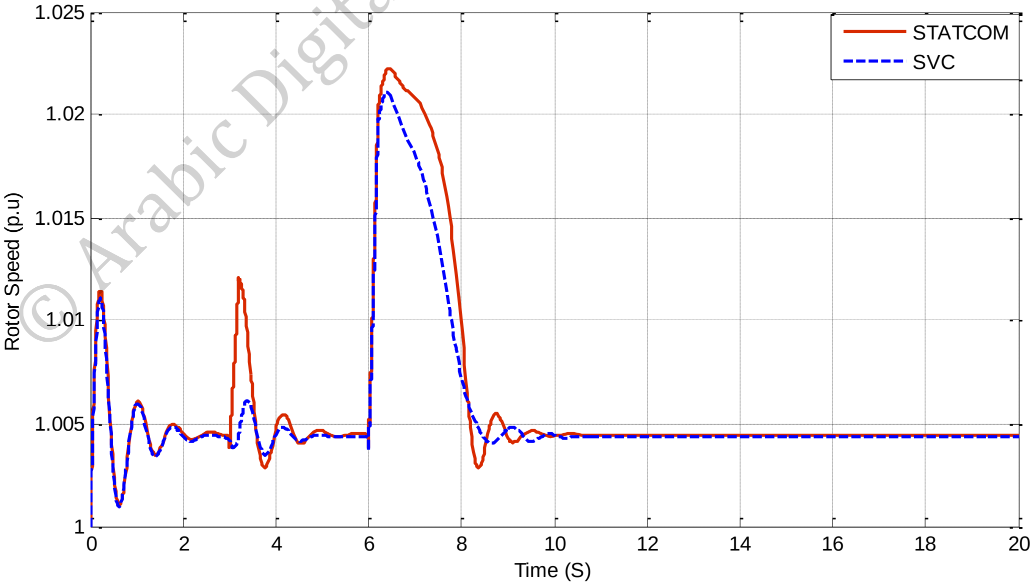


Fig. 33. Wind farm rotor speed with FACTs

Chapter 6

6. Conclusion and Future Work

In recent years, a remarkable and numerous improvements had achieved because of electric energy generation by utilization of wind energy. Power system stability study is function of wind farms connection conditions to the grid. This study investigates the stability of FSIG wind farm in healthy and faulty conditions. FACTs devices are the most common power electronics based reactive power compensators that can be connected at PCC so as to improve the transient performance of the power system and support the grid voltage.

The transient performances of a wind farm equipped with shunt capacitor banks and one of the FACTS devices (STATCOM, SVC) which has equal converter ratings (equal MVARs rating) have been studied without taking into account the occurrence of any short circuit. Also at the same time, the occurrence of (DLG) fault followed by (3 phase to ground) fault at a point on the transmission line connecting the wind farm with the medium voltage grid has been studied.

It can be observed from the results that:

- For a FSIG wind farms, system instability is precisely caused by the redundant reactive power absorption of a wind farm generator after short circuit condition due to large rotor slip.
- Shunt capacitor banks doesn’t provide sufficient reactive power support. When the network is weak, some kind of dynamic reactive power compensation is necessary.

- In healthy conditions (without short circuits), STATCOM and SVC have the same performance in improving the voltage stability of the system and they provide successfully the reactive power support to the network to compensate the large amount of reactive power absorbed by the FSIGs.
- In faulty conditions, STATCOM has better capability in voltage recovery and reactive power support than SVC. But, both of them have the same performance in stabilizing the wind farm generators rotor speed.
- STATCOM / SVC of high converter ratings (10 MVAR) will provide better reactive power support to the network and thus improving the system stability.
- It can be observed from the results that if the converter ratings of STATCOM & SVC are equal, STATCOM is mostly faster and more effective than SVC in system stability improvement.
- As indicated from the obtained results, it's worth noting that the FACTS devices such as (STATCOM, SVC) can be used prosperously in a wind farm connected to medium voltage grid for improving transient stability of wind farms.
- As well as wind farms become larger and further away from the point of connection, reactive power compensation provided by STATCOM / SVC might become primary condition in order to meet grid code requirements for the wind farm connection.
- It was found that STATCOM becomes stable in a shorter time span relative to SVC.
- Taking the obtained results into consideration in terms of damping oscillation, the fluctuation in SVC is less than STATCOM especially for the rotor speed.
- It was observed that both STATCOM and SVC have made the voltage and reactive power changes closer to reference value and made them stable.

- The dynamic responses of the proposed system with the usage of FACTS have shown that the studied wind power generation system may withstand large faulted conditions and return to stable operation after the fault is cleared.

This thesis has taken many different works to be accomplished. However, several future suggestions are of a great concern. Some of these future suggestions are listed in the following:

- From smart grids point of view, providing shunt active filter with suitable controller instead of FACTS could be used with the proposed model in order to support the reactive power of the system.
- The transient behaviors of the FSIG based wind turbine under the disturbances of other grid failures should be studied.
- The effect of saturation should be included in the transformer model as well as the induction generator model.
- An overall protection schemes should be developed for the FSIGs, which includes speed and frequency deviation protection, under and over voltage protection, in addition to the protection scheme for the power converter.
- In the context of smart grids, providing the model with developed control strategies is a major key for fault ride-through capability.
- A complex system with many nonlinear loads implemented in Matlab/Simulink can be an essential challenge in the stability of the simulation itself. So, one of the suggested issues is to optimize the models for the best use in Matlab/Simulink.

- DFIG could be studied by considering the same proposed model. Also, the ratio of the tap changers for power transformers should be considered for a more realistic voltage level regulation.
- The interaction and the impact of different wind turbine generators connected to the grid could be studied. Each generator kind will give a different characteristics and behavior.
- One of the artificial intelligence techniques such as the genetic algorithm or particle swarm optimization could be used in order to optimize a parameter to yield an effective performance.
- Such a study could be applied for multi wind speeds rather than base wind speed.

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"تأثير دمج انظمة النقل المرنة على محطة توليد طاقة رياح موصولة مع الشبكة الكهربائية المتوسطة تحت الظروف الطبيعية والخاطئة"

اعداد الطالب : قصي سالم

اشراف الدكتور: ابراهيم الطويل

الملخص:

في هذه .تحظى طاقة الرياح باهتمام ملحوظ من قبل الباحثين والشركات بسبب خصائصها كمصدر طاقة نظيف ووافر تهدف هذه الدراسة .الأطروحة, تم عمل دراسة متعمقة ومكثفة على محطة توليد طاقة رياح موصولة مع الشبكة الكهربائية تحت ظروف الى اكتشاف استقرارية النظام والذي هو محطة توليد طاقة رياح موصولة مع الشبكة الكهربائية المتوسطة ومعوض (SVC) تشغيلية مختلفة بالاضافة الى اكتشاف سلوك النظام في حال استخدام معوض القدرة المراكسة الثابت لغايات الربط مع محطات توليد الرياح. في هذه الدراسة تم افتراض محطة (STATCOM) القدرة المراكسة المتزامن تم .قدرتها اثنا عشر ميغا واط مكونة من اربع توربينات هوائية ومربوطة مع الشبكة الكهربائية المتوسطة توليد رياح اقتباس نماذج التوربينات الهوائية وانظمة النقل ومحولات الجهد ونموذج الشبكة الكهربائية ونماذج معوض القدرة من فرع انظمة القوى في (STATCOM) ومعوض القدرة المراكسة المتزامن (SVC) المراكسة الثابت ومعوض (SVC) . ووجد من خلال ملاحظة النتائج ان معوض القدرة المراكسة الثابت Matlab/Simulinkبرنامج . يدعمان فولتية النظام والقدرة المراكسة للنظام في حالة الظروف الطبيعية (STATCOM) القدرة المراكسة المتزامن .من جهة اخرى, تم الملاحظة بأن هذه المعوضات تدعم وبشكل هائل استقرارية النظام خلال وبعد الظروف الخاطئة للنظام. اثبت معوض القدرة المراكسة المتزامن افضلية عمله بالمقارنة مع معوض القدرة المراكسة الثابت من ناحية وقت استرجاع الفولتية ودعم القدرة المراكسة للنظام. لكن من ناحية استقرارية سرعة الدوّار, كلاهما اثبت نفس الاداء في ارجاع النظام الى حالة الاستقرارية