YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

THE MATLAB-SIMULINK BASED MODELING AND ANALYSIS OF WIND FARMS

SERHAT KALAYCI

THESIS ADVISOR: DR. HACER ŞEKERCİ

ELECTRICAL AND ELECTRONICS ENGINEERING

PRESENTATION DATE: 15.01.2019

BORNOVA / İZMİR
JANUARY 2019

We certify that, as the jury, we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Jury Members:	**Signature:**
Dr. Hacer Şekerci Yaşar University	…………………
Dr. Nalan Özkurt Yaşar University	…………………
Dr. Abdül Balıkçı Dokuz Eylül University	…………………

Prof. Dr. Cüneyt GÜZELİŞ

Director of the Graduate School

ABSTRACT

THE MATLAB-SIMULINK BASED MODELING AND ANALYSIS OF WIND FARMS

Kalaycı, Serhat
MSc, Electrical and Electronics Engineering
Advisor: Dr. Hacer ŞEKERCİ
January 2019

In this thesis, a wind farm modeling was performed in Matlab-Simulink environment. The lack of similar studies in this area has been seen as the motivation source of the study and it is aimed to be a step stone for future studies.

In addition to modeling the wind farm, some fault conditions and environmental conditions such as wind have been simulated and analyzed.

It was observed how the wind speed change, one of the environment impacts, affects the system. It was also observed that increasing wind speed ascends the produced active power besides the mechanical and electrical response of the turbine to this increment was examined.

As a fault analysis, the programmed short circuit was applied and the effects on the system were observed. For the voltage drop, which is another fault condition, results of the system compared in the terms of STATCOM (Static Synchronous Compensator) applied or not applied and the affirmative results are noticed for the applied case.

A protection block was developed for the hazardous voltage levels that may occur in system and for the extreme wind speed cases. Unwanted situations were simulated so the entire wind farm or only a single wind turbine was disconnected from the grid.

Key Words: Wind farm, matlab, simulink, renewable energy

ÖZ

RÜZGAR TARLALARININ MATLAB-SIMULINK TABANLI MODELLENMESİ VE ANALİZİ

Kalaycı, Serhat
Yüksek Lisans Tezi, Elektrik Elektronik Mühendisliği
Danışman: Dr. Hacer ŞEKERCİ
Ocak 2019

Bu tez çalışmasında Matlab-Simulink ortamında bir rüzgar tarlası modellemesi gerçekleştirilmiştir. Çalışmanın motivasyon kaynağı olarak bu alanda yapılan benzer çalışmaların azlığı görülmüş ve bu çalışmanın gelecek çalışmalar için bir adım taşı olması amaçlanmıştır.

Rüzgar tarlasının modellenmesinin yanında bazı hata durumları ve rüzgar gibi çevresel koşullar da simule edilmiş sonuçları gözlemlenip analiz edilmiştir.

Çevresel etkenlerden olan rüzgar hızının değişiminin sistemi nasıl etkilediği incelenmiş, artan rüzgar hızının üretilen aktif gücü arttırdığı gözlemlenmiş, türbinin bu artışa olan mekanik ve elektriksel cevabı incelenmiştir.

Hata analizi olarak, programlanan kısa devre uygulanmış ve sistem üzerindeki etkileri gözlemlenmiştir. Başka bir hata durumu olan gerilim düşümünde de sistemin STATCOM (Static Synchronous Compensator) uygulanmış olan ve uygulanmamış olan sonuçları karşılaştırılıp uygulanan durumdaki olumlu sonuçlar belirtilmiştir.

Sistemde oluşabilecek tehlikeli gerilim değerleri için ve aşırı rüzgar hızı durumları için koruma bloğu geliştirilmiş, oluşan istenmeyen durumlar simule edilerek rüzgar tarlasının veya tek bir rüzgar türbininin şebekeden ayrılması sağlanmıştır.

Anahtar Kelimeler: Rüzgar tarlası, matlab, simulink, yenilenebilir enerji

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor Dr. Hacer Şekerci for her guidance, support, motivation and patience she provided in every phase of this study. Her guidance helped me in research, practice and writing of this thesis.

I would like to express my enduring love to my parents, who are always supportive, loving and caring to me in every possible way in my life.

Serhat Kalaycı

İzmir, 2019

TEXT OF OATH

I declare and honestly confirm that my study, titled "THE MATLAB-SIMULINK BASED MODELING AND ANALYSIS OF WIND FARMS" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Serhat Kalaycı

Signature

....

January 15, 2019

TABLE OF CONTENTS

LIST OF FIGURES

SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

AC Alternative Current

DC Direct Current

DFIG Double Fed Induction Generator

FACTS Flexible AC Transmission System

FSIG Fixed Speed Induction Generators

GSC Grid Side Converter

HAWT Horizontal Axis Wind Turbine

Hz Hertz

IG Induction Generator

IGBT Insulated Gate Bipolar Transistor

Kg Kilograms

km Kilometers

kW Kilowatt

LVRT Low Voltage Ride Through

MW Mega Watt

PCC Point of Common Coupling

PI Proportional Integral

pu Per Unit

PWM Pulse Width Modulation

PMSG Permanent Magnet Synchronous Generator

RSC Rotor Side Converter

SCIG Squirrel Cage Induction Generators

SG Synchronous Generator

STATCOM Static Synchronous Compensator

SVC Static VAR Compensator

TSR Tip Speed Ratio

VAWT Vertical Axis Wind Turbine

VAr Volt Ampere Reactive

VSC Voltage Source Converter

WECS Wind Energy Conversion System

WRIG Wound Rotor Induction Generator

WRSG Wound Rotor Synchronous Generator

SYMBOLS:

A Sweep Area

P_w Wind Power

P_M Mechanical Power

ρ Air Density

V_w Wind Speed

m meter

s second

°C Celsius

m^3 Cubic Meter

C_p Blade Power Coefficient

λ Tip-speed Ratio

R_{rotor} Blade Length

ω_{rotor} Rotating Speed of Rotor

β Blade Pitch Angle

s Slip

P Active Power

Q Reactive Power

Q_m Generated or Absorbed Reactive Power by STATCOM

X Line Reactance

V Voltage

V_m Measured Voltage of STATCOM Bus

I Current

U Voltage During Fault

U_N Rated Voltage

CHAPTER 1
INTRODUCTION

Wind energy is one of the rapidly growing renewable energy resources among the other renewables. The conversion of this clean and sustainable wind kinetic energy into electrical energy is a multidisciplinary work which consist of aerodynamics, mechanical and electrical system, power electronics, control systems and power systems theory.

For over the past 40 years, wind energy has improved from a small industrial usage in a couple of countries to a large international industry including considerable players in the manufacturing, public sector and development. According to industrial growth, innovations in the technology have resulted bigger size of turbines, related energy cost decreases, complexity designs at for all subsystems, such as from rotor to electronics and control systems and drivetrain.

Sharp rising of unit oil prices has started in 1973 and caused many difficulties for different countries. This made some politicians realize about the finite content of the world's fossil-fuel reserves, and resulted in the awareness governments funding in research programs intended running natural energy (Fleming, 1984).

Wind power's growth depends on some combinations of topics such as; wind energy technology growth, high and interim fuel prices, state's wind power production tax credits, consumer preferences.

In United States, between the years of 2004 and 2007, production capacity of the installed wind turbines increased by 150% and accordingly power production from wind turbines more than double times. Below 2000 Megawatts of wind power production before 1995 has increased to more than 16000 Megawatts by 2007, as U.S. Department of Energy report (Logan, 2008).

The benefits of wind turbines can be counted as follows; not producing carbon dioxide or another pollutant during operation, helps rustic development by revenue of land leases, may provide "green employment" than other power generating ways and does not require water for operating.

Wind turbines can be scaled from a few kW for residential or commercial use to several MW in large wind farms. Named as small or medium size wind turbines are usually below 300kW and can be installed at farms, houses or businesses to stabilize consumption of utility power. Increases of wind turbine size create more power delivery because of captured energy is expressed as a function of rotor radius square.

1.1. Matlab – Simulink Software

Basically, Matlab is a programming platform which has been designed for scientists and engineers. The core of the Matlab is Matlab language, a matrix-based language allows to user in order to express computational mathematics.

Simulink is a graphical environment for modeling and simulations. Matlab runs with Simulink to support model-based design for such works as automatic code creation and test and corroboration of embedded systems in related areas of deep learning, computer vision, signal processing, robotics, control systems, etc.

In the recent years, Matlab-Simulink has become the most popular software in order to model and simulate dynamic systems. Particularly for non-linear systems; new control strategies can be met and for building and approving new mathematical models Matlab-Simulink is a powerful graphical interface.

Studying for wind turbine systems or wind farms is an example for such kind of dynamic systems. Existence of subsystems with variable ranges of the time constants as like; power electronics, turbines, wind, grid system, transformers, etc.

1.2. Modeling and Analyzing a Wind Farm on Matlab-Simulink and Advantages of It

There are basically two types of connections for wind energy conversion. The first one of these types is connecting generator to grid at grid frequency. During the connection to grid, grid supplies the reactive VAr which is required for induction machines. The second type is about connection of the generator system to isolated load in far distant area.

Simulating complex systems such as wind turbines, in a single environment with physical and control systems is crucial for development process. Without sticking to hardware prototypes, engineers are able to include requirements into the process, design at system level, predict and improve system performance. In order to build lower cost turbines with more power, this approach with Simulink helps to engineers.

Simulink has numerous benefits to work with it. It has ability of modeling a nonlinear system that cannot be done by using a transfer function. Another ability of Simulink is applying initial conditions of a system by assuming them as zero.

Simulink’s flexibility maybe it’s most leading advantage with simulating specification of complex systems only by knowing of required equations. Also it can run with discrete or continuous values. By using of mathematical or physical blocks, desired system can be created.

The Matlab – Simulink has a large library for users, with various examples of models from diverse fields of profession.

Simulation and modeling applications also ensure to users unlimited application and testing opportunities by saving time, money and resources.

1.3. Literature Review

A wind farm was designed with Matlab to supply electrical energy according to demand of marble industry at Muğla region (Ceylan, 2006). A design toolbox was developed in this study in order to examine region’s wind conditions and turbine distances to each other to help of designing most efficient wind farm. According to 8 different turbines and 4 different turbine distances, 32 different wind farm results were compared in this study. For the design toolbox; monthly energy productions of turbines, working times of turbines, turbine numbers, farm capacity factors, terrain conditions, unit energy costs, emission savings, wind specifications, rotor power coefficients were used as a data of toolbox. As a result, it has been decided that the unit sales price of electricity will be high, employment will be beneficial, ecological advantages will be beneficial for the establishment of wind farms in the region.

Subject of modeling a doubly-fed induction generator using Matlab/Simulink was handled in a study (Alhazmi, 2015). In the study, another simulation and dynamic analysis performance using Matlab was aimed. Presentation of a DFIG configuration started with defining and modeling all parts of it and then analysis of steady state for the system and its dynamic analysis described, also design of the control system. Mostly wind speed effects were discussed with Matlab results on different variables of a DFIG. Research creates the analyzing of AC/DC and DC/AC converters and shows some analysis on steady-state and dynamic of DFIG. Steady-state analysis provides some relationships on DFIG components during variation of wind speed 2-10(m/s). Furthermore, dynamic analysis defines deriving dynamic equations and modeling DFIG's controllers followed by dynamic response due to wind speed changes and under voltage of the grid.

A paper tries to form a wind power generation system with wind turbines that drive DFIGs (Nicolae, 2014). A DFIG is connected to a three phase 0.4kV network. Though the rotor operates with variable speed, wind turbine with DFIG supplies a constant frequency through the converter with IGBT AC-DC-AC transistors based on PWM control. Three cases were imitated: change of win speed, network voltage dip and single phase fault with grounding seriatim. It's specified using of asynchronous generators in wind power generation is most common way to deal with variable speed. Advantage of DFIG with absorption and generation of reactive power is also mentioned in this study. 5 turbines with power of 0.8MW for each were used to consist of a plant with 4MW by considering the wind speed at 13m/s. Effects of wind speed decrement were observed on the power which exported to network system and also current, voltage, rotor speed, reactive power values. For fault case, single phase short-circuit situation at 24kV network was examined, its results were shared for DC-Link voltage fluctuations in limits, drop of the voltage at bars 0.4kV up to 0.92pu, system state was saved to its rated parameters in 100ms, also control system generated reactive power to keep the voltage at amount of 1pu and herewith during fault isolations, when the reactive power decreased, the voltage showed a positive decrescent peak from 1.02pu. For the voltage dip case, voltage across the bars as 24kV was taken into account as descending from 0.5pu for 5 half periods. During with a voltage drop to 0.62pu higher fluctuations of quantities generated. System protections didn't activated cause of short recovery time after fault.

Modeling of small wind energy system is being presented as a thesis study (Emezuru, 2011). In the study basic model of a wind energy system was designed in Simulink then real data wind speed was applied as input of the model. Model was analyzed for different blades and various wind speeds. To develop the wind energy system, a toolbox which is named Beta Wind was used for this study. All components of wind energy system were used as a data block in the simulation. Parameters that belong to wind turbine, drive train, squirrel cage induction machine were applied to the blocks. Power output results were observed at various values of radius and wind speed. Increase at the value of velocity or radius of wind turbine created large increasing amount of the power that generated by the system.

There is a study about simulation and control of a grid-connected wind energy system (McCartney, 2011). Via Simulink a 2MW wind energy conversion system was presented and simulated. This conversion system of wind energy is consisting of a 2MW permanent magnet synchronous generator connected to transmission grid through a power conversion system. Topology of the conversion system was made up with a passive AC/DC rectifier in collaboration with a PWM DC/AC IGBT inverter, used to connect the DC link with the grid. The inverter has a built-in current control system to improve output power stability by correction of power factor. Firstly output wave forms of PMSG with constant torque and variable torque was observed. A demonstration of output with effects of harmonic filter was showed that are clearer with elements of filters. Additionally, besides that the results of simulation, some difficulties of Simulink were also handled in this study. Such as, self-modeling needed for each block to insert real world loses or a connection of rectifier couldn't be done directly to output of PMSG without an isolation block and this caused increasing of simulation time. Also to overcome the issues that feedback controller relies on past inputs, a unit delay was applied.

A thesis study exists about improving LVRT capabilities of wind farm using STATCOM (Montazeri, 2011). In the thesis study, it was aimed to analyze behavior of DFIG based wind farm for diversified timing schemes of crowbar deactivation and rotor side converter (RSC) resumption, in the case of possible grid fault and also usage of STATCOM for the intention of equilibrate the grid voltage after a fault of three-phase. In the study, aim of STATCOM is to regulate voltage at PCC. So the STATCOM was located where that system needs most voltage support, as mentioned in study reactive power must be injected into the system to derogate fluctuations of voltage and bring the voltage back to its nominal value after clearance of fault. Results of the thesis exhibit that STATCOM evolves "low voltage ride through capability" of wind farm and assists for the process of wind farm without an interrupt. In the thesis, DFIG wind farm connected power distribution system was studied based on Matlab Simulink model. The cases of fault conditions simulated for different crowbar deactivation schemes. In the first case, crowbar was deactivated and rotor side converter was re-enabled after the fault was cleared. In the second case, crowbar was deactivated before fault clearance, while the rotor side converter was re-enabled afterwards. In the third case, crowbar was deactivated and rotor side converter was re-enabled before fault clearance. Existence of STATCOM was considered compulsory for first two cases, without the STATCOM voltage collapse occurred and "low voltage ride through" grid code couldn't fulfill to disconnect wind turbines from the grid.

A power system in Cape Verde was modeled and simulated in Simulink (Teixeira, 2011). DFIG wind turbine, diesel generator, transmission line and load were demonstrated on details. One of three simulation methods, the phasor-domain model was used in the study. Phasor-domain model is better complied to simulate low frequency electromechanical oscillations for long durations of time (seconds to minutes). System consists of 11 DFIG wind generators that total power 9.25MW, there is also 36MW diesel plant which supplies 32MW plant and wind turbines will be connected to 690V/10.5kV grid to supply 2MW, 4MW and 1.5MW plants totally. Performance of power system was simulated by Simulink, during 60 seconds and wind speed changes considered as disturbance. Initially wind speed fixed to 8m/s and at t=20s. it was changed to 14m/s. Rotor speed increased from 0.8pu to 1.2pu. Pitch angle increased 0 to 8 degrees to hold in the mechanical power, active power increased from 2MW to 7MW and the power injected by diesel plant decreased. Effects of variations at wind speed showed by simulation results of steady-state and dynamic performance of 9.25MW wind farm and 36MW diesel plant connected to a power system network. Also it showed that Simulink based phasor model is a simple, fast and certain tool to study whole power systems performance.

A paper compares and analysis two wind farms which are consisting of 500kW turbines and 1.5MW turbines at total power of 9MW (Pappu, 2012). 2 separate wind farms are designed on Matlab-Simulink. A 9MW wind farm is modeled with using eighteen FSIGs and a 9MW wind farm is modeled with six DFIGs. Wind farms in this paper are simulated with three different wind speeds to analyze and compare transmitted active powers and consumed reactive powers. Pitch angle control is provided by a PI controller to limit pitch angle of blades. At the high wind speeds, a trip mechanism isolates related generator from remainder of the system. Both farm configurations are simulated for the same time duration and the same base values are used to make the analysis comparable. For the wind speeds between 3-6m/s, FSIG does not generate active power hence does not consume reactive power. DFIG starts to generate at 6m/s wind speed hence to consume reactive power. At the wind speeds of 9-12m/s, both systems reach their rated capacity by stepping up to 12m/s wind speed, produced active powers and consumed reactive power increase accordingly. For the wind speeds of 21-24m/s, FSIG trips after 5 seconds because of reaching 21m/s and DFIG trips because of reaching 24m/s wind speeds. A three phase fault which lasts 0.1 second is also applied to both wind farms during the wind speed increasing from 9m/s to 12m/s. Results show that DFIG gets more reactive power during fault and takes more time to run close steady state but FSIG use up more reactive power during steady state. DFIG generates more active power for the speeds till 9m/s but after reaching rated speeds in steady state both systems injects same power. With the phase to ground faults which are installed on terminals of equal numbers of wind turbines in each configurations, two more turbines are tripped in DFIG consisted wind farm is observed. Because of AC under voltage less than 0.75pu and lasting of 5 seconds trip is observed. The reactive power consumed by the FSIG is more than consumed by DFIG. Active power generated by DFIGs is 2.5MW and active power generated by FSIGs is 7.2MW after phase to ground fault.

Fault simulations are mentioned for DFIG based wind farms in the study (Mahadanaarachchi, 2009). With 6 units of 1.5MW DFIG turbines a wind farm is modeled in Simulink which has total power of 9MW. At the rate of 575V wind turbines are connected to the 34.5kV network through step-up transformers. 34.5kV network is connected to power system by 240kV step-up transformer. Asymmetrical (phase-ground, phase-phase) and symmetrical (three phase) faults are created within the wind farm and power grid for analysis. Applied three phase fault near to the one wind turbine between t=0.5 and t=0.6 causes very low magnitude of voltage levels almost 0.1pu on three phases of generator terminals but currents of terminals suddenly increase at the fault initiation about 4pu and followed by fast weakening. In this study resistance of the fault is kept constant at 0.001 ohm. Same three phase fault also created at the high voltage side of the grid with same parameters. Similar responses for graphics are observed at the generator terminals both for voltage and current values. In contrast to the case of three phase fault on generator terminals, capacitor banks are used on medium voltage bar and GSC of DFIG partake reactive power to the fault and current transients observed about 0.2 seconds after instant of fault clearance as a result. For the phase to phase fault which is applied to phase A and phase B of the generator terminal during t=0.5 and t=0.6. During fault phase A and B voltages drop considerably and relatively less drop on phase C. After the start of fault it is observed that currents of phase A and phase B go opposite directions in graphically about 4pu, in other words current of phase A equals to negative current of phase B. For the phase C current, a marginal drop observed initially then a transient condition results. At least single phase to ground fault is applied at the same location of generator terminals and at the same time interval of t=0.5 and t=0.6. For the graphically observed voltages, while phase B and phase C voltages result with over voltage over to 1.5pu and phase A voltage drops almost 0pu. In the current of phase A a marginal increase is observed. For the phase B and C decrease of currents also experienced.

It is an article about designing of fixed-pitch angle wind turbine simulator based on Simulink (Jansuya, 2013). Aim of the study is developing and designing a fixed-pitch angle wind turbine simulator. Characteristic power curve is defined by three wind speeds; rated, cut-in, cut-out. At the cut-in wind speed, turbine starts to catch power. Till wind speed reaches to rated value, seized power is expressed as wind speed's cubic function. After reaching to rated speed, aerodynamic power control of blades is needed to keep the power at its rated value. This task can be done by three methods; active stall, passive stall and pitch control. For the control mechanism, inputs are; wind speed, rotor speed and blade pitch angle. Outputs are mechanical power and torque. System was operated under constant and variable wind speed options. For constant speed 10m/s and for variable speed from time 0.5t to 1.5t a variation in ramp was linearly changed between 7m/s to 12m/s. Mechanical torque, rotor speed, turbine power and generator electrical power differences, phase voltage and current were observed. It was seen maximum power transmitted to load at maximum wind speed of 12m/s. Finally, handiness of the purposed wind turbine simulator scheme was approved by identifying the mechanical power and torque at variable wind speed and identifying power transmission of the induction generator into the load.

1.4. Thesis Overview and Outlines

The importance and use of simulation programs in the fields of engineering and science are increasing day by day. Matlab/Simulink is powerful one of these simulation programs with integration of graphical interface and code section.

As seen in detailed literature review of similar studies at first chapter, modeling and analyzing the systems that big and expensive such as wind power conversion systems is crucial. By using simulation systems, testing recently developed systems and interpreting their results, engineers, companies and researchers can save time and resources.

Due to researchers focused on a specific part of wind power conversion systems in their studies, which has been reviewed in the section of similar studies in this thesis, this study was aimed to be a comprehensive work to design a wind farm and its entire peripheral units such as; transmission lines, transformers, static VAr compensators, measurements, protection mechanisms.

To understand how a complete wind power conversion system works and what the difficulties are, simulations were created with integration of multiple wind turbines to supply grid, also presented as establishment for a fundamental wind farm.

Today, as renewable energy becomes more important, the lack of comprehensive simulation work in this area has been seen as a source of motivation and the results of this study have been presented in order to be a stepping stone for future studies.

In Chapter 1, the brief history of renewable energy production and the development of wind energy production are mentioned. An expression about Matlab-Simulink program and importance and capabilities of it also mentioned. Literature review about similar works and studies are shared. By inspiration of these works outlines of this study has formed.

In Chapter 2, components of wind energy conversion systems are shared with system configurations, kinds of turbines and generators. Equations for wind energy calculations are shared.

In Chapter 3, a brief expression is shared about using of Simulink then wind farm is formed on Simulink environment with its components and connected to the grid.

In Chapter 4, different situations are created and applied to wind farm then their results are observed and analyzed. These situations are fault applications, wind speed changes, and development of a basic protection system.

In Chapter 5, results and outputs of the study are argued, also future works and expectations for further studies are mentioned.

CHAPTER 2
WIND FARMS AND CONSTITUENTS

2.1. Fundamentals of Wind Power

Wind is a result of unequal heating of earth surface, atmosphere and oceans by sun and its causal pressure difference. The wind is never stable for any site; weather conditions, local terrain, and the height from ground surface affect it. The most important factor to influence performances is deciding the location where wind turbine or wind farm should be installed.

A wind turbine is a machine which derives electrical energy from kinetic energy of wind. Energy production of a wind turbine is related with interaction of blades, wind speed and mass.

As mentioned in the study (Logan, 2008), evolution of wind energy systems and their markets has been affected by three physical relationships. First, power output of a wind turbine changes with the wind speed's cubic power. If all else kept constant, doubling the wind velocity creates an increase eight-fold at output power. Winds at 70 meters in altitude are steadier and stronger than those closer to earth surface and this factor expresses why wind turbine towers are located higher places. Secondly, power output of a wind turbine changes with the area which is swept out by the blades of turbine. A four-fold increase can be observed at output power if a turbine blade's length is doubled. Third, increase of power output is directly related with air density. Typically, density is higher in winter season and at low altitudes, lower in summer season and at high altitudes.

Generally, industrial type wind turbines are separated into two classes by their spinning; vertical axis or horizontal axis. Although vertical axis machines have advantages for efficiency and serviceability, elevation of its blades to high altitude in air cannot be done easily and this makes horizontal axis machines to dominate markets.

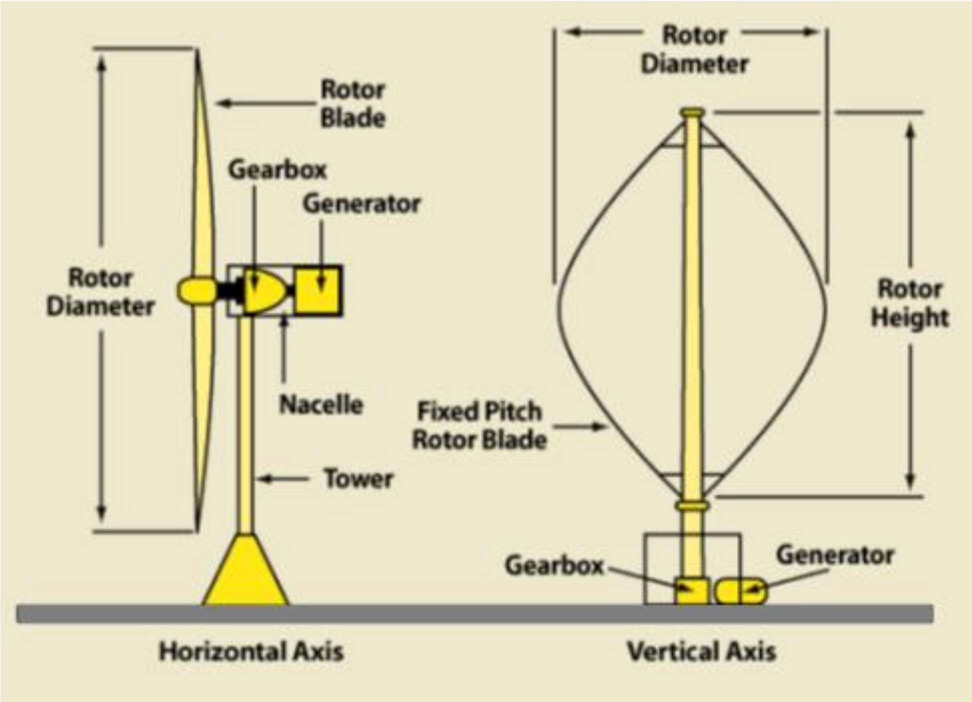

Figure 2.1. Horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) (Masaud, 2013)

Usual modern wind turbines can be operated in two basic modes; these are variable or fixed wind speed turbines. For the fixed-speed wind turbines which spins at nearly a constant speed, rotating speed is specified by gear ratio, frequency of grid, and generator's pole number. At a certain wind speed value system runs with maximum efficiency, at other wind velocities system efficiency degrades. The fixed-speed turbine needs a solid mechanical design to suck high mechanical stress and also it generates fluctuations at output power for grid and causes disturbances. Advantages of the fixed speed turbines are being simple and reliable and low cost also requires less maintenance. Beside these advantages it has some disadvantages such as; lower energy conversion efficiency, high mechanical stress, injection of fluctuations to the grid. Some advantages for variable speed wind turbine systems can be counted as; higher efficiency at energy conversion, evolved power quality, reduced mechanical stress. Beside these advantages, variable speed wind turbines also have disadvantages some like; complexity at control systems and extra costs and losses due to use of converters.

Also a wind turbine can designed as variable pitch or constant pitch that means blades are able to or not able to spin on their longitudinal axis. Pitch control is usually used in large wind turbines. Pitch angle is set for an optimal value in order to seize wind's maximum power. Other protection methods are active or passive stall control, so by aerodynamic controls of blades, wind turbine is protected from possible harm of wind storms. When the wind speed has started to become ahead of rated speed, the blade is reversed out of the wind direction to decrease seized power. When the blades are fully pitched, rotor of the wind turbine is locked by a mechanical brake and this situation is called as park mode (Wu, 2011).

2.2. Wind Energy Conversion Systems

A modern wind energy conversion system consists of different components which are mechanical, electro-mechanical and electronic.

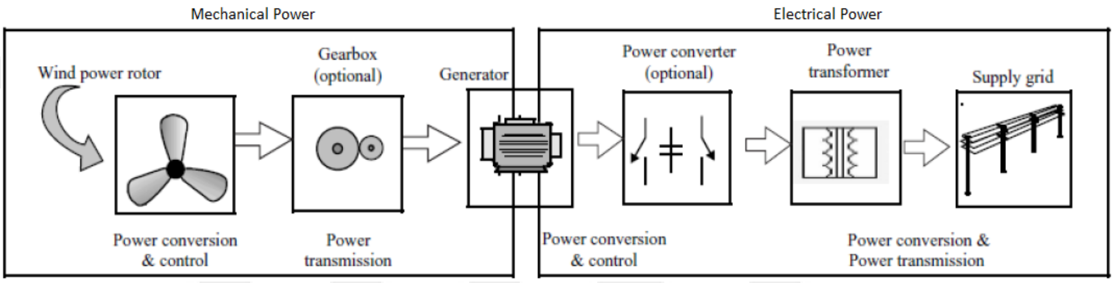

Figure 2.2. Main units of a wind energy conversion system (McCartney, 2010)

Wind turbine produces mechanical energy, wind power rotor is subunit of the turbine and duty of it is drawing out the energy from wind and converting it into the mechanical energy. Gearbox can be used to increase the rotational speed of generator's rotor to better values which are more efficient for an electrical generator. Nevertheless, gearless designs which gearbox was removed in order to reduce expenses and maintenance and increase reliability.

The electrical generator is the component for converting mechanical power which is captured from wind turbine into the electrical energy. Depending on their operating styles and construction, wind generators can be viewed under two titles: induction generators (IG), synchronous generators (SG). For both generators, they have wound rotors, which are fed by slip-rings through brushes or by a brushless electromagnetic exciter. Wound-rotor generator which is also known as DFIG is one of the most used generators in wind energy. Wound rotor synchronous generator (WRSG) is also used with high number of poles operating at low rotor speeds. Squirrel cage induction generators (SCIG) have shorted rotor bars internally and for this reason not brought out for connection with external circuits. The permanent magnet synchronous generator (PMSG) uses a permanent magnet instead of a coil for its excitation field (Wu, 2011).

There are mainly 3 types of configurations used on large wind generators (Li, 2008). First type is fixed-speed wind turbine system with gearbox and squirrel-cage induction generator (SCIG). Second type is variable speed wind turbine system with gearbox and double-fed induction generator (DFIG). Third type is a variable speed system also, however it’s a gearless design of a wind turbine system with direct-drive generator, synchronous generator and full-scale convertor. Following schematics in figure number 2.3. 2.4. and 2.5. are describing these configurations.

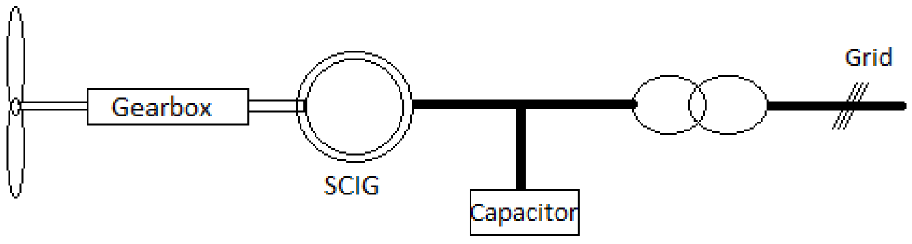

Figure 2.3. Schematic diagram of SCIG which is connected to grid directly

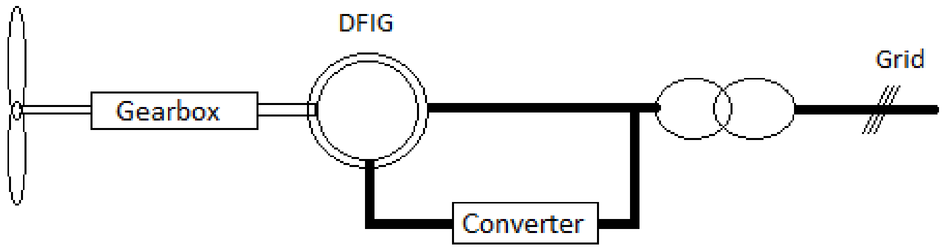

Figure 2.4. Schematic diagram of DFIG

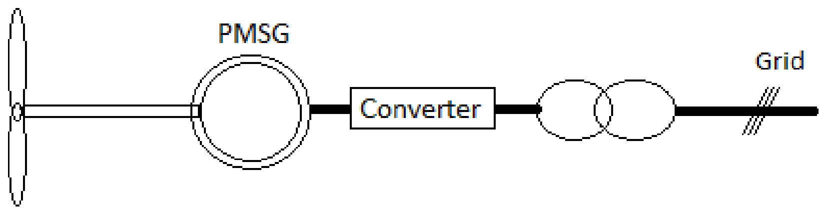

Figure 2.5. Schematic diagram of direct drive PMSG system

These 3 groups of grid connected wind energy conversion systems can be detailed and enhanced by adding other type of generators and control systems.

2.3. Wind Power Calculations

Interaction of wind turbine rotor and wind provides power production. The power of an air bulk that flows at speed V_w through an area A can be expressed as follows:

$$P_w = \frac{1}{2}\rho A {V_w}^3 \text{ (watts)} \quad (1)$$

Where ρ is the symbol of air density in kg/m^3, A is the sweep area by blade in m^2 and V_w is wind speed in m/s. The air density ρ is expressed as a function of air pressure and temperature of air. At sea level and temperature of 15°C, air density is about $1.2 kg/m^3$.

According to German physicist Albert Betz's law, maximum power produced by an ideal turbine rotor and infinite blades from wind is 59.26% of the power exists in the wind. Practically, due to economic and structural reasons, wind turbines are limited to 2 or 3 blades and extracted power's amount is approximately 50% of the available wind power. This limit is known as Betz limit and wind power seized by the blades of wind turbine and converted into the form of mechanical power can be shown as:

$$P_M = \frac{1}{2}\rho A {V_w}^3 C_p \quad (2)$$

C_p is the blade's power coefficient. Theoretical maximum value of this coefficient is 0.59 with respect to Betz limit. This power coefficient for a modern wind turbine varies ranges from 0.2 to 0.5 (Wu, 2011).

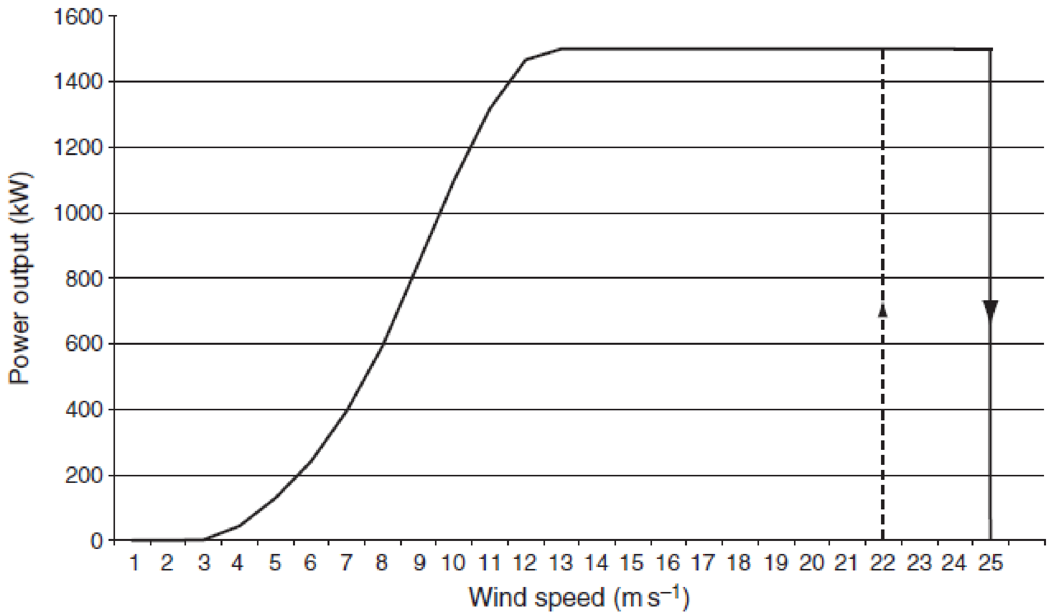

Figure 2.6. Typical power curve of a 1.5MW pitch regulated wind turbine, broken line shows the hysteresis effect (Söder, 2005)

In figure 2.6., it is seen that wind generator in parking mode till wind speed of 2.5m/s(cut-in speed) then an increase of wind speed to rated speed of 12m/s. Wind turbine's operating region is between 12m/s and 25m/s wind speed which 25m/s is cut-out speed.

Wind turbine manufacturers also try to increase the length of turbine's rotor blades. Reason of this effort is relevant with indirect relationship of mechanical power output and tip-speed ratio (λ). The tip-speed ratio (TSR) is the ratio of blade-tip linear speed to the wind speed. The tip-speed ratio defines the ratio of existing power provided by the wind turbine rotor from the wind (Manwell, 2010).

$$\lambda = \frac{\omega_{rotor} \cdot R_{rotor}}{V_{wind}} \tag{3}$$

Where ω_{rotor} is the rotating speed of the blade (rad/s), V_{wind} is speed of wind (m/s) and R_{rotor} is the radius of the turbine blade (m, blade length). TSR and user-defined pitch angle β are used to calculate C_p. Power coefficient of blade C_p can also be expressed as follows:

$$Cp = \frac{\text{Extracted Power}}{\text{Power in Wind}} = \frac{P_{rotor}}{P_{wind}} \tag{4}$$

Figure number 2.7. Which is given below shows the general C_p curves.

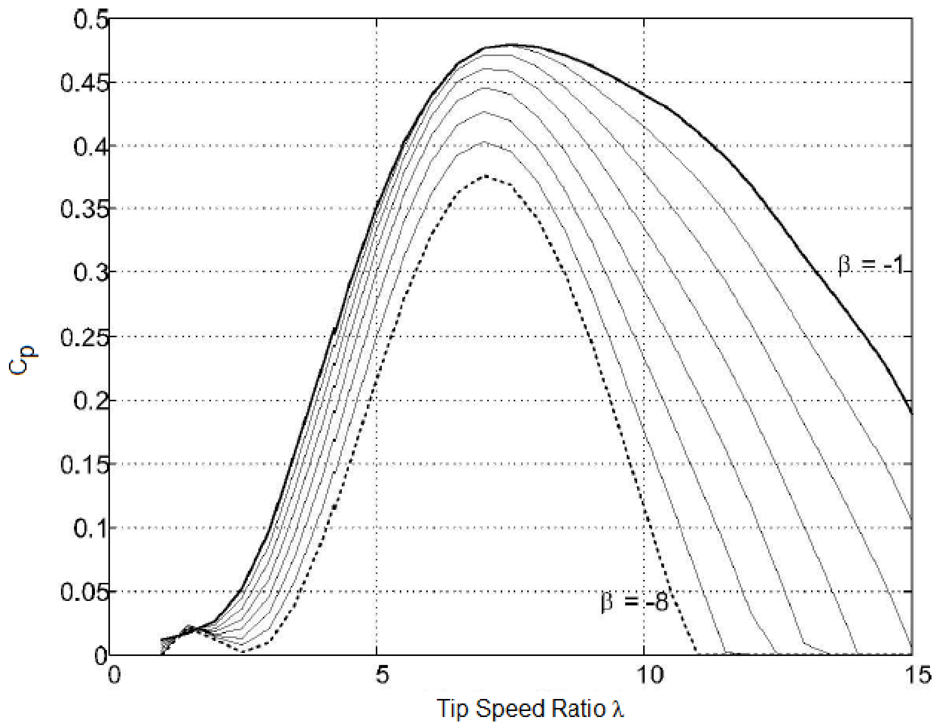

Figure 2.7. General C_p curves for values of pitch vary from -1° to -8° (Santoso, 2011)

2.4. Wind Turbine Electrical Generators

2.4.1. Comparisons, Advantages and Disadvantages of Generator Systems

As mentioned in chapter 2.2. generators that used in wind power are simply divided into two categories; asynchronous and synchronous generators. In the figure, number 2.8. most common grading of the system configurations of the wind energy can be found.

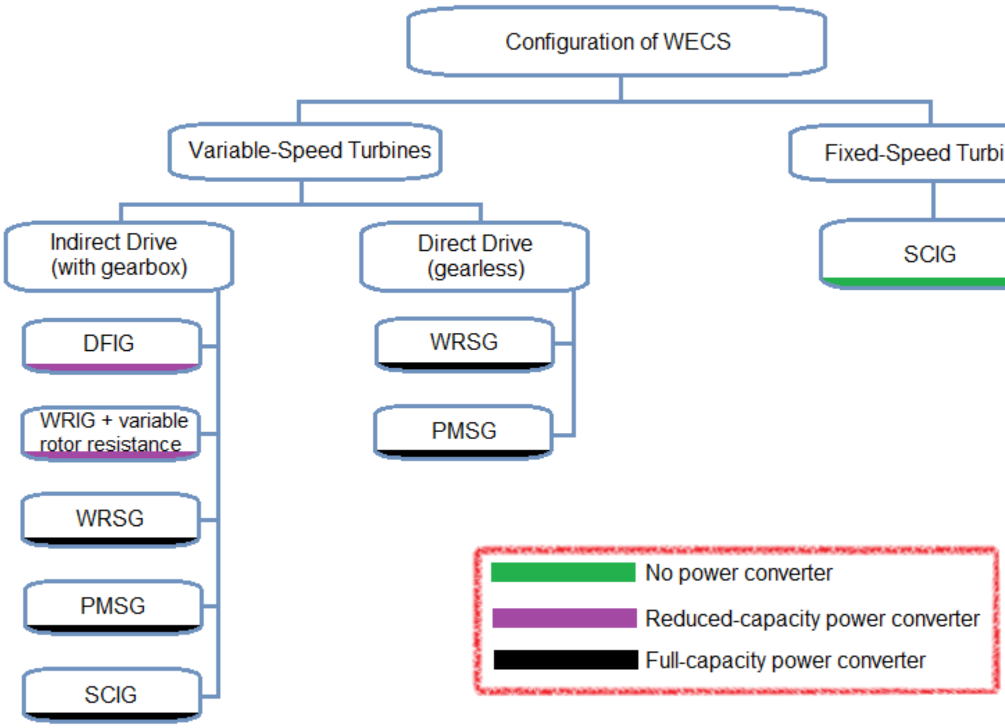

Figure 2.8. Sorting of wind energy system configurations

The fixed-speed turbines run with a squirrel-cage induction generator which bonded directly to grid and don't need any power converting system throughout standard operation. The fixed speed wind generator systems are used with multiple step gearbox systems. SCIG always attracts reactive power from grid, to overcome this situation it has been extended with capacitor banks, smoother grid connection also done with implementing soft starters. SCIG has simple structure, robust and relatively cheaper than other systems. Nevertheless, checked against to variable speed systems, fixed speed system has relatively lower energy transformation efficiency due to reaching its maximum efficiency at one given wind speed.

In the variable speed turbines, there are two sections; indirect drive and direct drive turbines. Direct drive turbine does not need a gearbox. Most important distinction between direct drive and indirect drive turbines is the generator rotor speed. Since the rotor of direct drive generator directly bonded to hub of turbine rotor, direct drive generator rotates at a low speed. In order to inject considerable power, lower speeds make it necessary to produce higher torque. Higher torque implies that a larger size generator and large number of poles required. Direct drive wind turbines have some advantages; simple drive-train, high efficiency and reliability. Smoother grid connection can be achieved by full capacity power converter over entire speed but also it has higher cost and higher power loses in the power electronics. Besides their high reliability and efficiency they have some disadvantages. For PMSG; high cost of permanent magnet material, manufacturing difficulties and demagnetization of material at high temperature can be counted. For WRSG necessity of exciting rotor winding with DC and arranging space for excitation windings, using slip rings and brushes or brushless exciter, and field loses can be counted.

For the variable speed turbines with indirect drive concept there are different models of generators. One of these models is WRIG. Stator of WRIG is directly bonded to grid and its rotor bonded in series with a resistor which is controlled. By controlling the energy injected from the rotor, variable-speed operation can be done. But this power has to be scattered in external resistor. Moreover, compensation of the reactive power and a soft-starter are also needed in this configuration. Another configuration is also known as DFIG. Concept of DFIG is simply consisting of WRIG and a partial scaled power converter on rotor circuit. This concept supports ±30% broad speed range for synchronous speed. Furthermore, power converter system can supply reactive power compensation and neat grid connection. Some disadvantages also exist for DFIG systems; requirement of a multi-stage gearbox, requirement of maintenance due to slip ring used to transfer rotor power, under fault conditions power electronics should be protected because large stator currents cause large rotor currents. In variable speed concept, PMSG system is also used. Compared with DFIG system, advantages of this system can be counted as; better efficiency, generator can be brushless, and disadvantages of it; larger design and more expensive full-scale converter, higher power loses in converter systems. One of the other variable speed systems is SCIG design. Compared with the fixed-speed concept as aforesaid above, this concept has advantages such as; flexible control by full-capacity converter, better in performance for compensation of reactive power and neat grid connection. Besides these disadvantages of this concept is its high cost and power loses in converter system.

Most manufacturers are using indirect drive (geared design) wind turbine systems. It can be seen that major manufacturers of wind turbine industry mostly prefer DFIG with a multiple-stage gearbox (Li, 2008).

2.4.2. Doubly-Fed Induction Generators Basic Concept

Since double-fed induction generator wind turbine model was chosen to use in Matlab/Simulink model in order to create a wind farm in this study, this section gives some explanation for the double-fed induction generator operating concepts and its principles.

Induction machines act as generators when they are operated faster than their synchronous speeds. Such as conventional wound rotor induction generators, DFIGs run on the same principles with additional external converters on the rotor and stator to optimize wind turbine’s operation. These converters help draw and adjust mechanical power from wind better than squirrel-cage induction generators.

The DFIG presents the following advantages; via rotor current, reactive and active power can be controlled individually. Via rotor circuit, magnetization of the generator can be obtained. DFIG also can generate or expend a certain volume of reactive power, in this way voltage control is obtained in the case of feeble distribution grids. Converter size of generator is not decided according to total power of generator but to speed range and slip range of the machine.

Power rating of a DFIG varies between a few hundred kilowatts and a few megawatts. Power flow in stator is unidirectional it injects power to the grid. But rotor has bidirectional power flow depending on operating mode. Through rotor side converter (RSC) and grid side converter (GSC), power can be conducted from rotor to the grid and vice versa. RSC and GSC are connected back to back by a DC link capacitor. Cost of converters and filters is lower than wind energy conversion system with full capacity converters. Additionally, with variable speed operation of DFIG, a DFIG wind energy system can get more power from the wind rather than a fixed-speed wind energy system because of the capacity when the wind speed is lower than its rated value.

Schematic block diagram illustration of a DFIG wind turbine system is given below in figure number 2.9. (Pokharel, 2011).

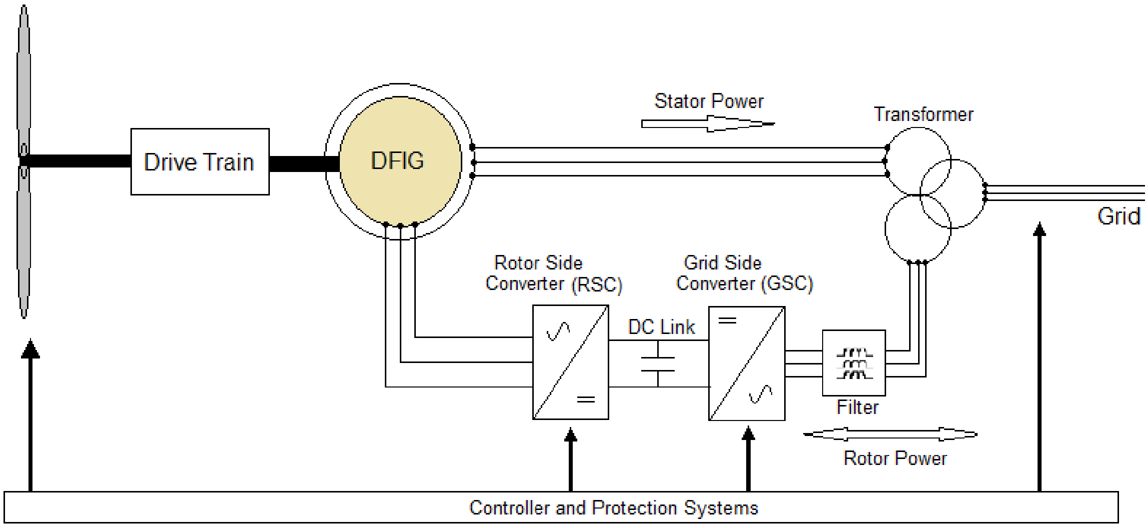

Figure 2.9. Schematic block diagram of a wind energy conversion system with DFIG

Reason of calling the generator as DFIG is the power which is fed from both rotor and stator to the grid. Rotor side circuit only needs to handle with 25-30% of total power to overcome a total control of generator.

The main advantage of DFIG is the ability to keep output voltage's amplitude and frequency at constant grid values without depending on wind turbine rotor speed. By changing rotor supply's frequency with converters, stator frequency is kept at constant value independently from wind speed. Duty of the GSC system is keeping the DC voltage constant between two converters to keep constant the supplied power to grid by rotor in terms of magnitude and frequency. Control of DC voltage is also necessary for proper work of RSC system. RSC system is more complex due to deal with more variables. Active power and reactive power are controlled by RSC system (Aydin, 2016).

For the sub-synchronous operating mode, rotor speed (n_{rotor}) is lower than synchronous speed (n_s). Positive slip power must be got by injecting power from the grid into the rotor through the main of a power converter to generate power. So, DFIG generates power in sub-synchronous speed mode as well. Slip is defined as given in formula number 5.

$$s = \frac{n_S - n_{rotor}}{n_S} \quad (5)$$

Rotor side is not involved to power generation during the synchronous speed mode. Only stator side supplies generated power to the grid. For super-synchronous speed mode, mechanical power (P_M) is divided into two parts; largest part of the power reaches to the grid by stator and rest reaches to the grid by converter.

Figure number 2.10. shows that the operating modes of a DFIG in different speed situations (Pokharel, 2011).

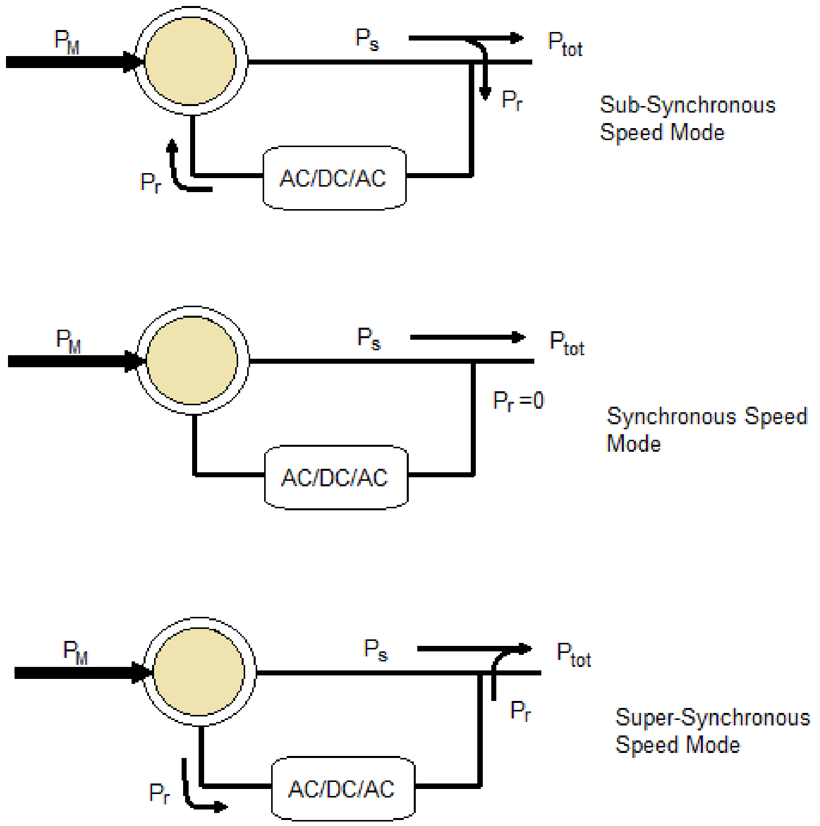

Figure 2.10. Stator and rotor active power flow of a DFIG during different rotor speeds

2.5. STATCOM Implementation to the Wind Farm

Most of the wind turbines are established in far distant places or offshore and power grid is mostly at long distance and it is characterized by under voltage conditions. One of the challenges for the system security in wind energy conversion systems is vulnerability to common-mode tripping because of short circuit faults vulnerability. Once the system has a disturbance such as; lightning strike on transmission lines or a fault of short circuit, wind generators might have to be uncoupled from the grid. For the system stability, tripping the wind turbine generators has a negative influence.

Since limited reactive power aptness of DFIG, it cannot continuously provide necessary reactive power and a result of this situation, voltage fluctuations occur. The problem of voltage fluctuations can be handled by using of dynamic reactive power compensators.

FACTS (Flexible AC Transmission System) devices, provides effective solutions for this problems by their flexible, rapid and control capability. Since their rapid response design, SVC (Static VAR Compensator) and STATCOM (Static-Synchronous Compensator) are two available options to supply controlled dynamic reactive power. Implementation of these two FACTS devices, SVC and STATCOM is made at PCC (Point of Common Coupling) to overcome the voltage stability problems and provide steady voltage level for DFIG based wind farm.

A definition can be given for STATCOM as; which runs as a shunt bonded static VAr compensator. A static synchronous generator without independence of AC system voltage, inductive or capacitive output currents can be controlled (Dong, 2005).

At the busbar where the wind turbines are connected to the network, the STATCOM is connected in shunt to the network. STATCOM is basically consisting of a capacitor, a VSC (Voltage Source Converter) and a coupling transformer which connects the power network and VSC. In figure number 2.11. a schematic block diagram is given for STATCOM.

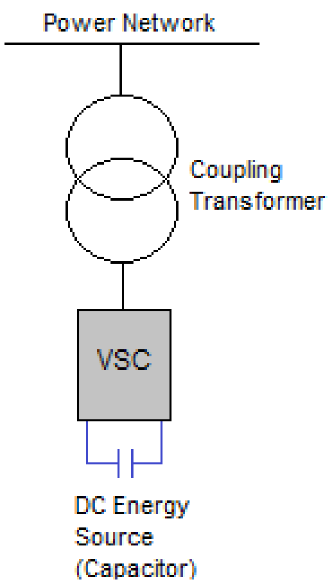

Figure 2.11. Block diagram of STATCOM

By changing the amplitude of the converter with considering to the line bus voltage STATCOM can generate or absorb reactive power. STATCOM generates reactive power when the system voltage is low and STATCOM absorbs reactive power when system voltage is high.

Real power and reactive power injected by the STATCOM is given in the following equations number 6 and 7 (Singh, 2009).

$$P = \frac{V_1 V_2 sin\alpha}{X} \tag{6}$$

$$Q = \frac{V_1(V_1 - V_2 cos\alpha)}{X} \tag{7}$$

Where V_1 is STATCOM output voltage and V_2 is voltage at PCC and α is the angle difference between V_1 and V_2. X is line reactance. If V_1 is higher than V_2, reactive Q flows from V_1 to V_2 that means STATCOM absorbs reactive power and if V_1 is lower than V_2, reactive Q flows from V_2 to V_1 that means STATCOM generates reactive power.

So the real and reactive power outputs of STATCOM can be controlled both by controlling its output V_1 or its phase angle α.

In order to raise the system voltage, generally capacitors are used to fixed speed wind turbines. Mechanically switched shunt capacitors can increase system's voltage stability limit but it is not responsive to voltage varies. Since it can generate more reactive power than the other FACTS devices at the voltages lower than normal voltage range, STATCOM is the best option for the dynamic compensation of reactive power. Independent from AC system voltage, STATCOM can control its output current over the rated maximum capacitive or inductive scale, whereas the maximum reachable compensating current of SVC decreases linearly with AC voltage. Additionally, STATCOM shows a faster reaction as it has no delay incorporated with thyristor firing (Glanzmann, 2005).

CHAPTER 3
WIND FARM MODELING WITH MATLAB-SIMULINK

3.1. Simulink Toolbox

As mentioned in first chapter, Simulink provides a graphical programming environment for modeling, analyzing, and simulating works of dynamical systems. Simulink is especially used in control systems, signal processing, and model-based design. Its essential interface is a graphical block tool and a various set of library blocks. It also offers integration with MATLAB environment and Simulink can either drive MATLAB or be scripted from it.

To start to work with Simulink, firstly MATLAB needs to be started. By clicking the Simulink library button on the upper bar of MATLAB or typing command to start it will start the Simulink Library Browser.

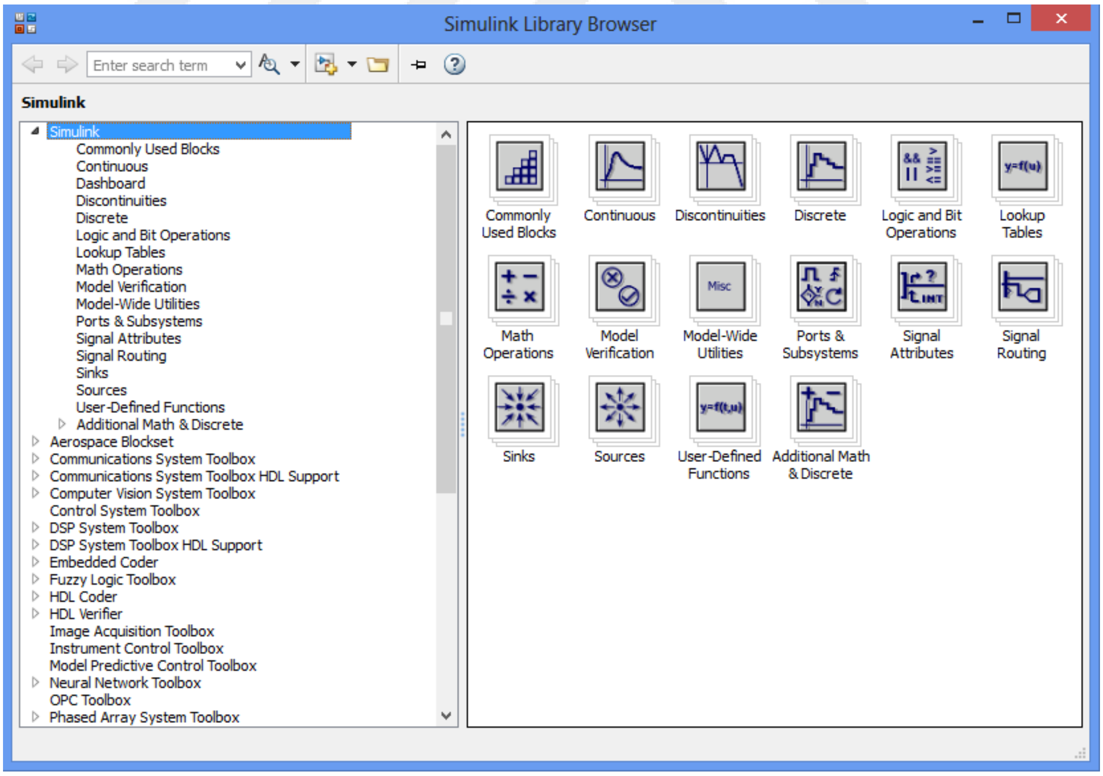

Figure 3.1. Simulink library browser

All fundamental and basic blocks also all blocks which categorized according to special areas can be found in this library. Clicking the new model button on the upper bar of this library browser will create a new working page. User can start to work just by dragging and dropping the desired blocks from the library to the new created working page.

3.2. Creating the Wind Farm

In this study, in order to design a 6MW wind farm, four wind turbines were used which are at the power rate of 1.5MW. Wind turbines are connected to 120kV grid through a 10km 25kV feeder. Wind turbines are using a doubly-fed induction generator (DFIG) be formed of a wound rotor induction generator and AC/DC/AC IGBT based PWM converter. Stator windings of DFIGs are connected directly to 50Hz network while rotors are fed at variable frequency through converters. For lower wind speeds, by optimizing the turbine speed, DFIG technology allows to extrude maximum energy from the wind.

Wind farm model design and its connections can be found in figure number 3.2. In Simulink, to run power system simulations with different timing options such as discrete or continuous or work with phasors, a Powergui block is used. Powergui block is an environment block for electrical power system models. It stores the equivalent Simulink circuit that expresses the state-space equations of the model. Continuous block uses a variable-step solver, discrete block uses fixed time steps, and phasor block uses phasors. The phasor solution method is generally used with electromechanical oscillations of power systems which are formed of large motors and generators over large durations of time (tens of seconds to minutes). Powergui block also let to the user to alter the initial states in order to start the simulation any initial conditions.

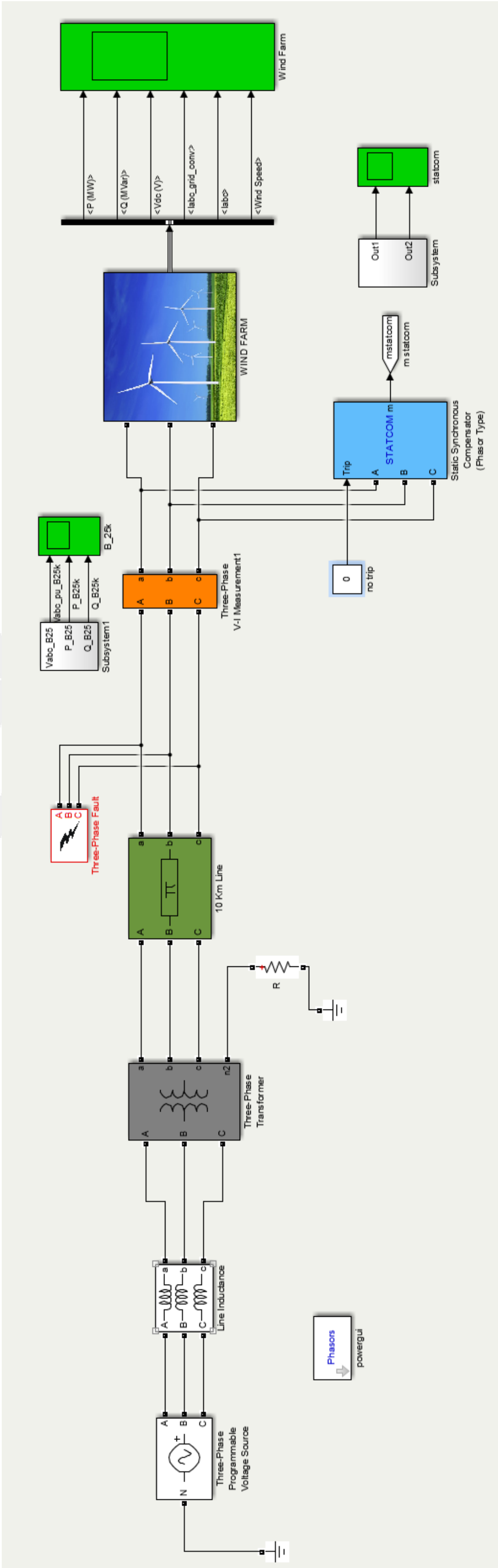

Figure 3.2. Wind farm model design on Simulink

After implementation of Powergui block, a three phase programmable voltage source block is needed to simulate power of 120kV grid side. Three phase programmable voltage source and three phase impedance which has mutual coupling between phases are used at 120kV grid side of simulation model after a 25kV to 120 kV step-up transformer.

By right-clicking on the wind farm block and clicking “look under mask”, inside of wind farm block can be seen as at figure 3.3. Every single wind turbine is connected to step-up transformer at the voltage level of 575V to 25kV and then they are connected to 25kV to 120kV step-up transformer through total 11km line.

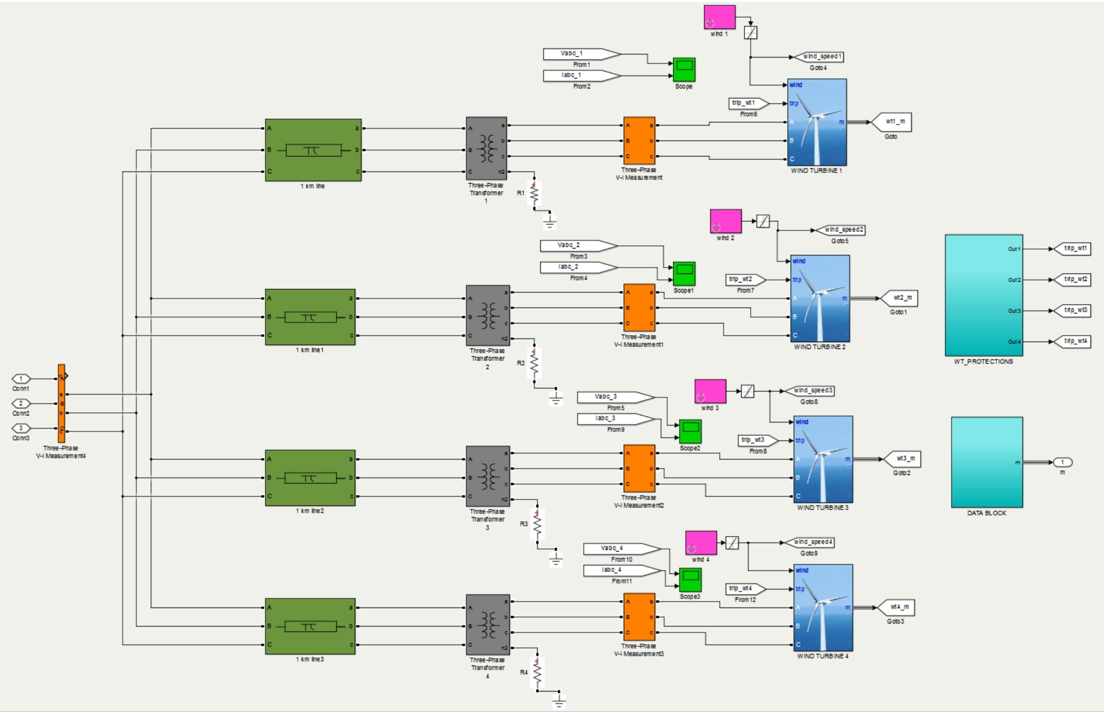

Figure 3.3. Inside of the wind farm block

Wind turbine’s inputs, outputs and connections can be viewed in figure number 3.4. Every wind turbine has a variable wind speed input and trip input to activate protection system for extreme situations. Three phase V-I block is used to observe changes simultaneously via label connected scope blocks.

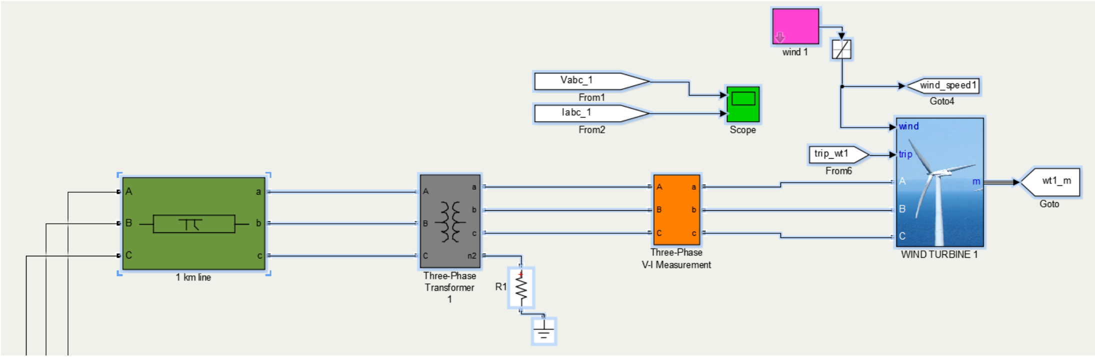

Figure 3.4. Closer view of a single wind turbine's connections

3.3. Wind Turbines

Phasor type DFIG wind turbines are used in this study to create model of a wind farm and analyze it. In figure number 3.5. inner scheme of a DFIG wind turbine can be observed. There is a block for wind turbine and a block for generator and converters. These blocks have also their inner blocks when viewed by right clicking and choosing "look under mask" option.

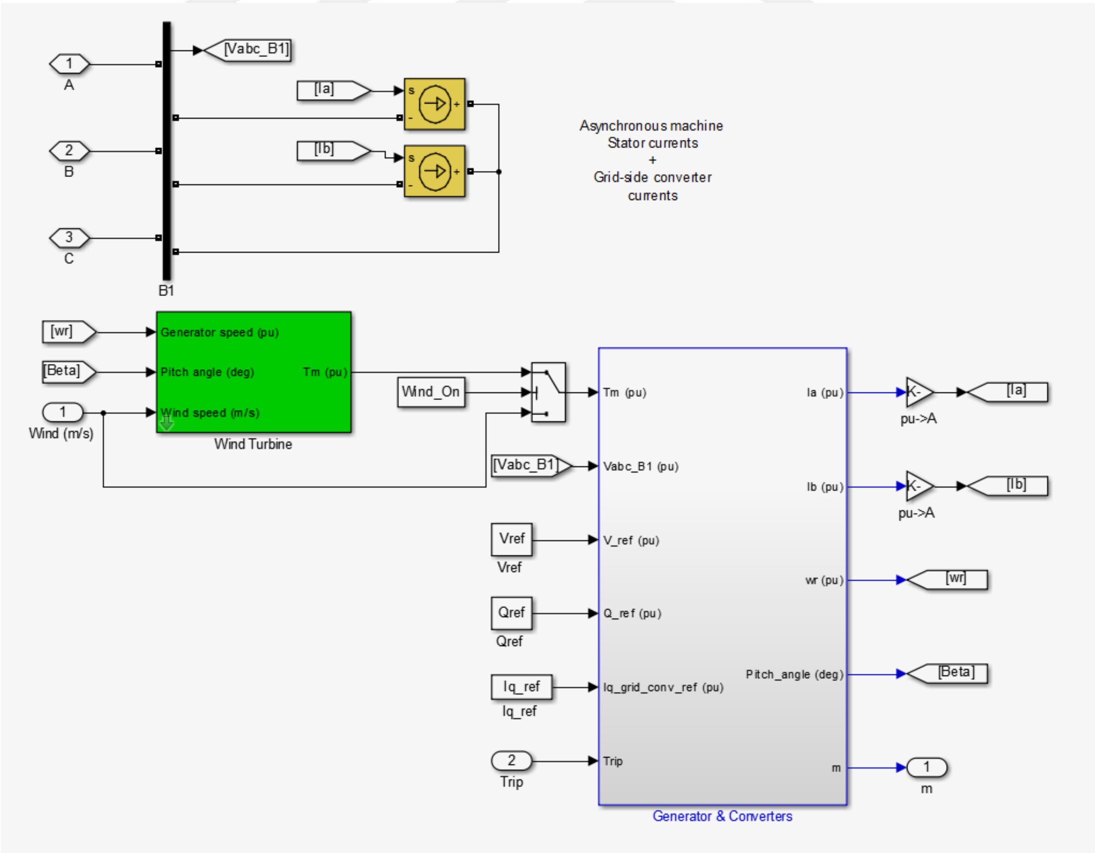

Figure 3.5. Inner scheme of a DFIG turbine

In figure number 3.6. power characteristics and tracking characteristic of used wind turbines can be viewed.

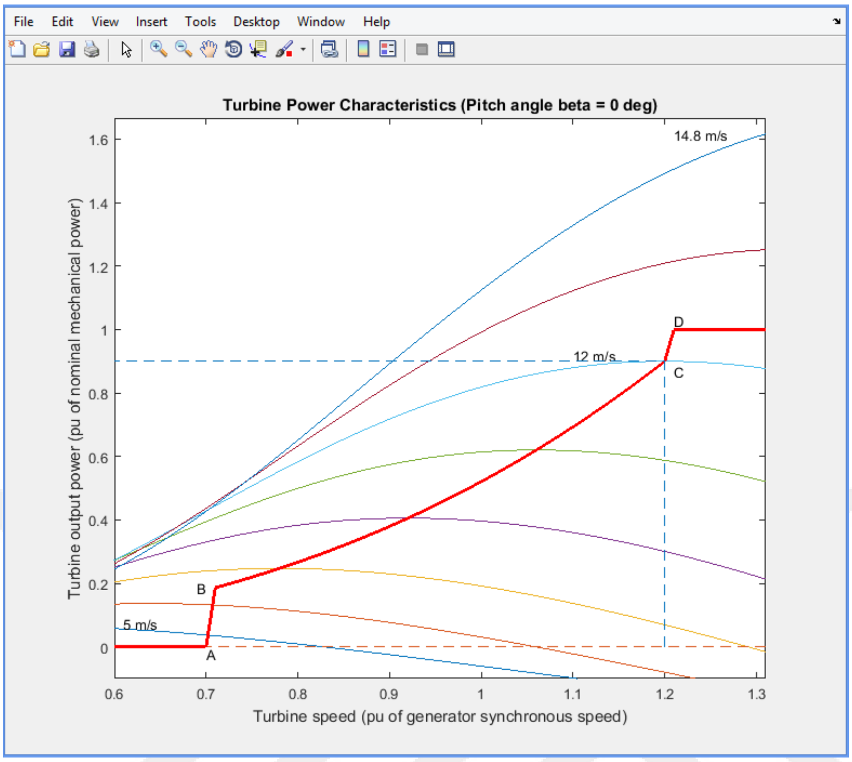

Figure 3.6. Power characteristics and tracking characteristic of a wind turbine

Power of double-fed induction generator based wind turbine is controlled by predefined tracking characteristics. Between the points B and C turbine speed optimization is ensured.

Four points are used to specify the tracking characteristic. Turbine's actual speed ω_r is measured, for the power control loop the corresponding mechanical power of the tracking characteristic is used as reference power. To the speed point A from zero, the reference power is zero. At point B speed must be greater than at point A and between point A and B tracking characteristic is a straight line. Between point B and C the tracking characteristic is maxima of the turbine power versus turbine speed curves. From point C to point D the tracking characteristic is straight also. Power at the point D equals to 1pu (one per unit) and speed of point D must be higher than point C's speed. On the further side of the point D, reference power is a constant equal to 1pu.

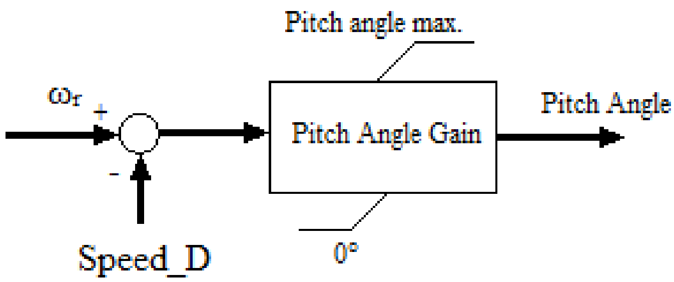

Figure 3.7. Pitch angle control system of wind turbine

Until the speed reaches to the speed of point D, the pitch angle is kept constant at zero degree. The pitch angle is proportional to the speed deviation beyond the point D speed. In figure number 3.7. schematic of this proportional control mechanism can be seen. In order to keep constant the pitch angle at zero degree a PI controller is used to restrict the electrical output power according to appearing mechanical power. Pitch angle is increased by the PI controller when measured power increased more than its nominal value to reduce it.

CHAPTER 4
SIMULATIONS AND ANALYZES

4.1. Turbine Responses to Wind Speed Changes

The figure number 3.4. shows that every wind turbine has a variable wind speed input. These variable speed blocks generate a signal that changes at specified times. Amplitude of wind speed input can be specified for certain time durations.

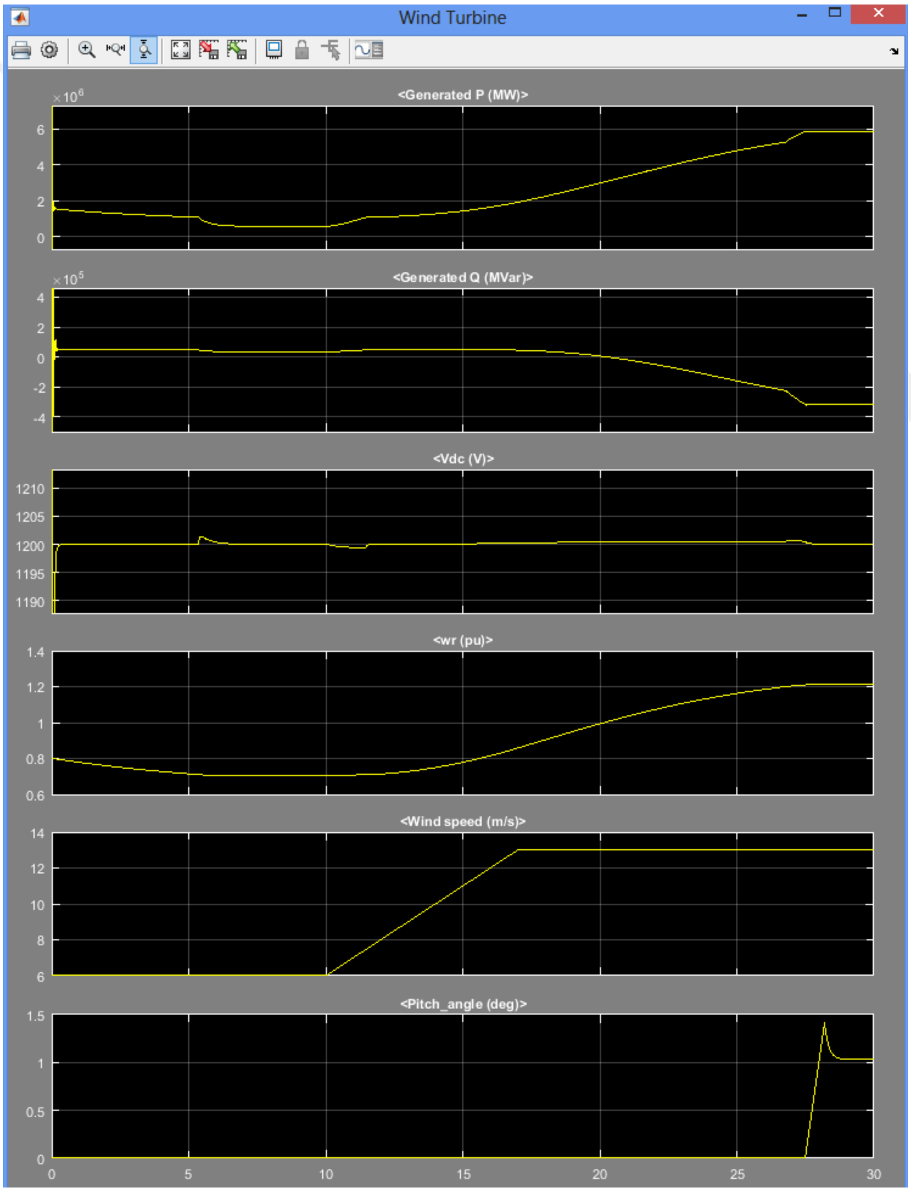

Figure 4.1. Total generated P and Q of wind farm and outputs of a wind turbine for variable speed

For the 30 seconds duration of simulation, initializing wind speed is set to 6m/s, then at t=10s, wind speed increases to 13m/s. In figure number 4.1. details of simulation are shared. As seen on figure number 3.6. tracking characteristic curve of a wind turbine indicates that wind speed at point C is 12 m/s. At t=10s, the produced active power starts growing together with wind speed to reach wind farm's rated power value of 6MW in approximately 15 seconds. During that time turbine speed increases from 0.8pu to 1.2pu. At the start, the pitch angle of wind turbine blades is 0 degree. Beyond the point D of tracking characteristic curve, pitch angle increases from 0 degree to 1.04 degrees by control mechanism as shown in figure number 3.7. in order to limit the mechanical power. Wind turbine's Vdc bus voltage is 1200V. The reactive power is controlled to keep the voltage at 1pu. At nominal power wind turbine absorbs 0.32Mvar to control voltage at 1pu. Before reaching to the higher speeds DFIG generates reactive power at its sub-synchronous mode. Analysis of the waveforms reveals that wind turbine's control system is able to keep a constant voltage across the DC link capacitor from the inverter's intermediate circuit. In figure number 4.1. values of generated P and Q are belong to wind farm, other values below them belong to one single wind turbine.

4.2. Fault Analysis

4.2.1. Single Line-Ground Fault on 25kV Network

As seen on figure number 3.2. a single line to ground fault is applied to the 25kV network at t=8s. 12m/s constant wind speed is available for four wind generators. Changes in active and reactive power and voltage values of 25kV bar can be seen in figures number 4.2. and detailed in figure number 4.3. Decrease of single line voltage level for 0.95pu, increase of other line voltages over 1.6pu and 1.7pu and fluctuations on active and reactive power can be determined. In figure number 4.4. and 4.5. wind turbine values can be observed also, P and Q values are belong to wind farm, other values belong to a single wind turbine.

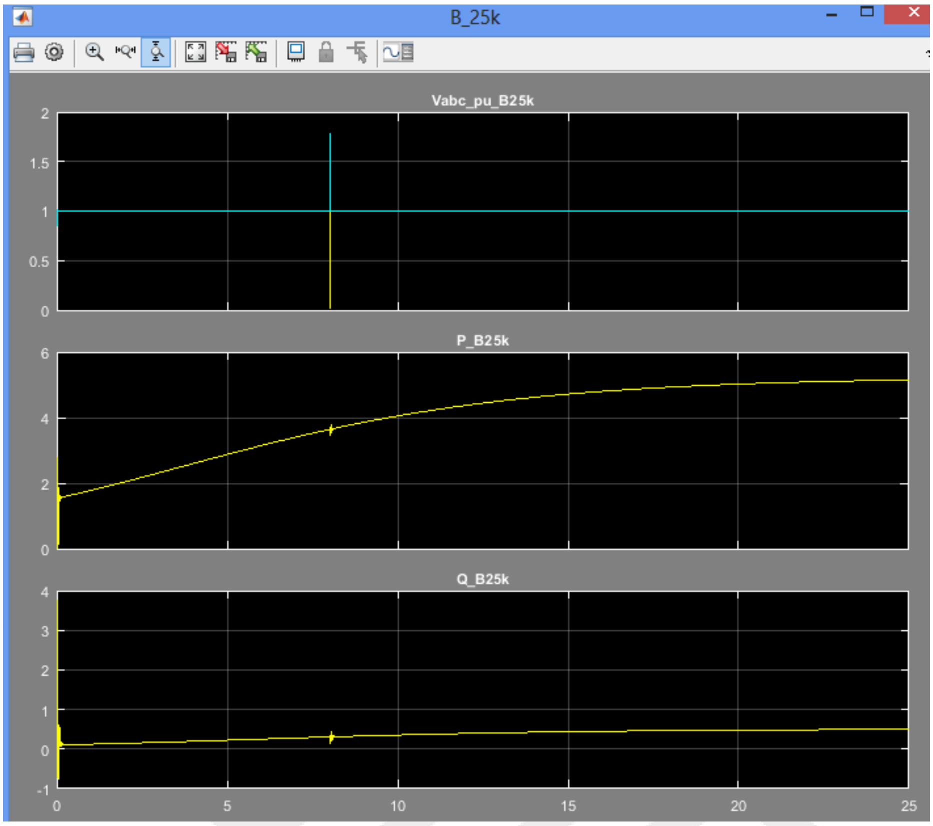

Figure 4.2. Single line-ground short circuit fault effects on 25kV bar

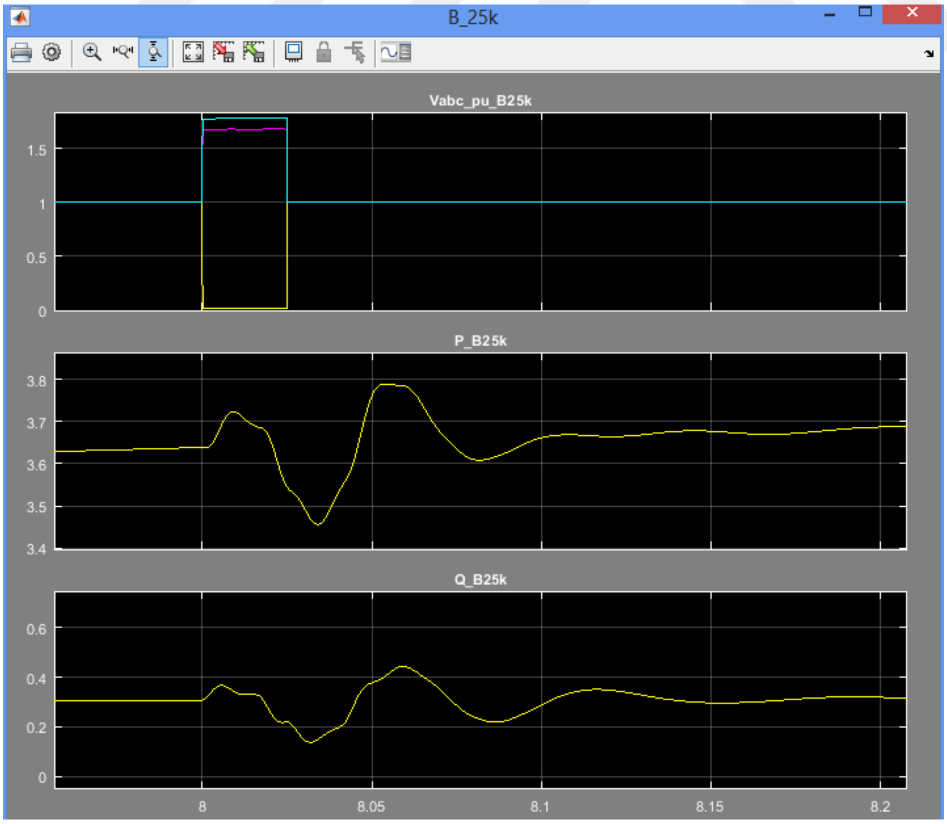

Figure 4.3. Single line-ground short circuit fault effects on 25kV bar in detail

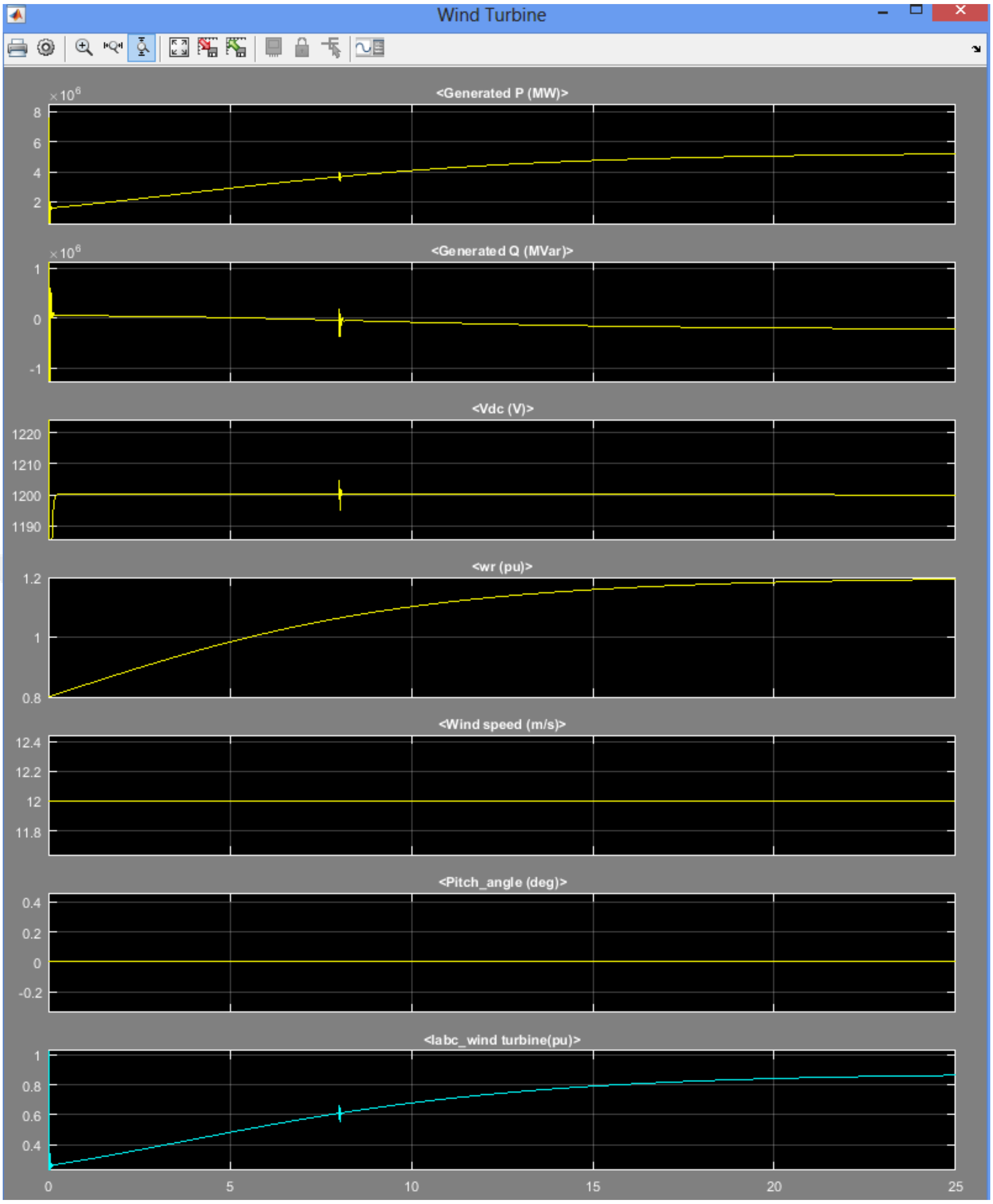

Figure 4.4. Single line-ground short circuit fault effects on wind turbines

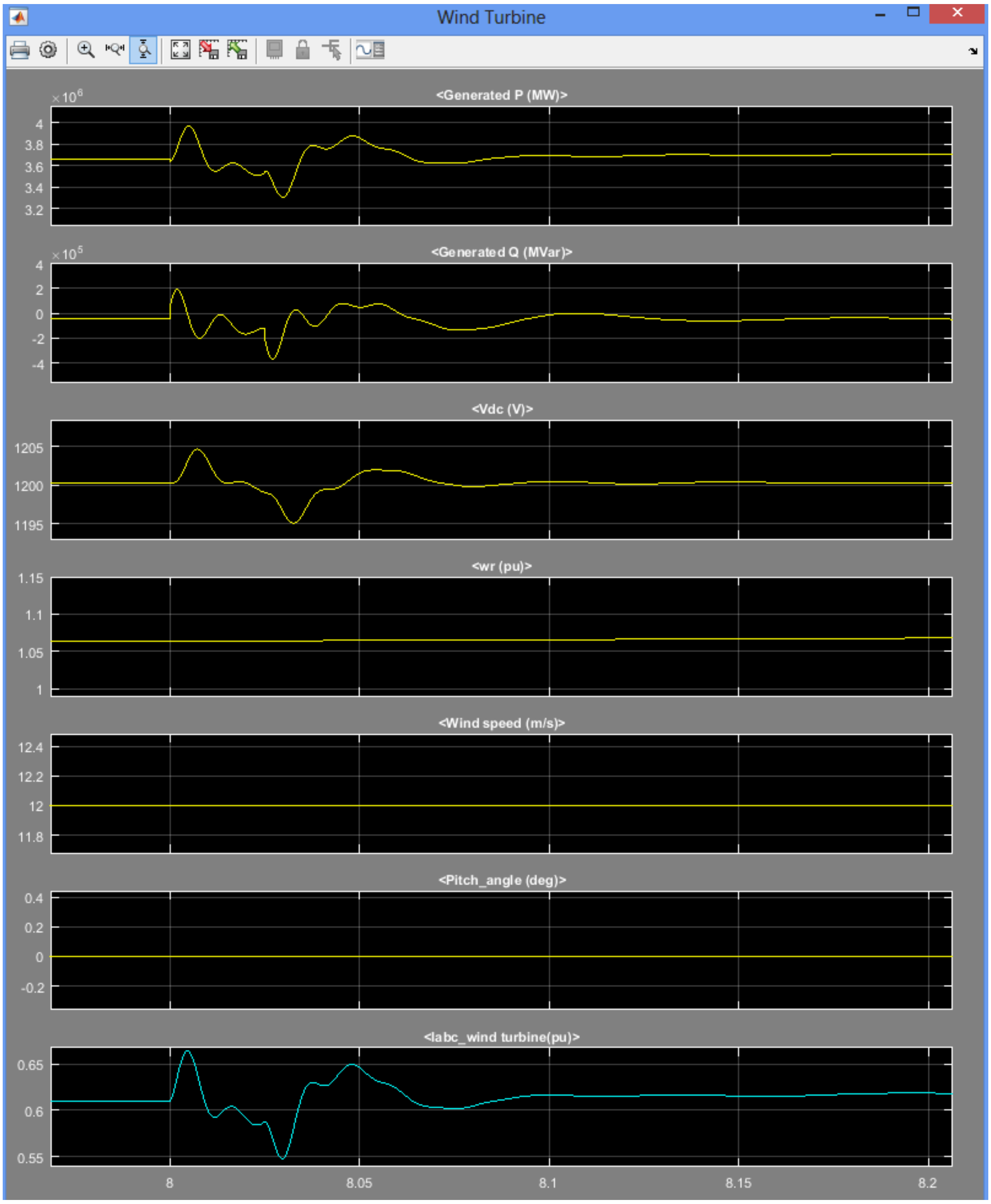

Figure 4.5. Single line-ground short circuit fault effects on wind turbines in detail

Figures number 4.4. and 4.5. show that wind farm and single wind turbine values. P and Q values belong to wind farm's total generated active and reactive powers, values below them belong to a single wind turbine. Fluctuation of DC-Link voltage is within acceptable limits ±3%. DFIG phasor currents Iabc change is about ±0.05pu. Rotor's speed of a single wind turbine alters within very small limits throughout the fault. The system's state is recovered to its rated values in less than 100ms averting its rupture from bars by protection system.

4.2.2. Voltage Sag Simulation on 120kV Side and Effect of STATCOM

0.15pu voltage sag is programmed at 120kV grid side. It occurs at t=20s. Wind turbines are set to constant wind speed of 12m/s during the simulation. A STATCOM is located to overcome disturbances as mentioned in chapter 2.5. Figure number 4.6. and 4.7. show results of voltage sag without STATCOM and figure number 4.8. 4.9. and 4.10. show the results with STATCOM.

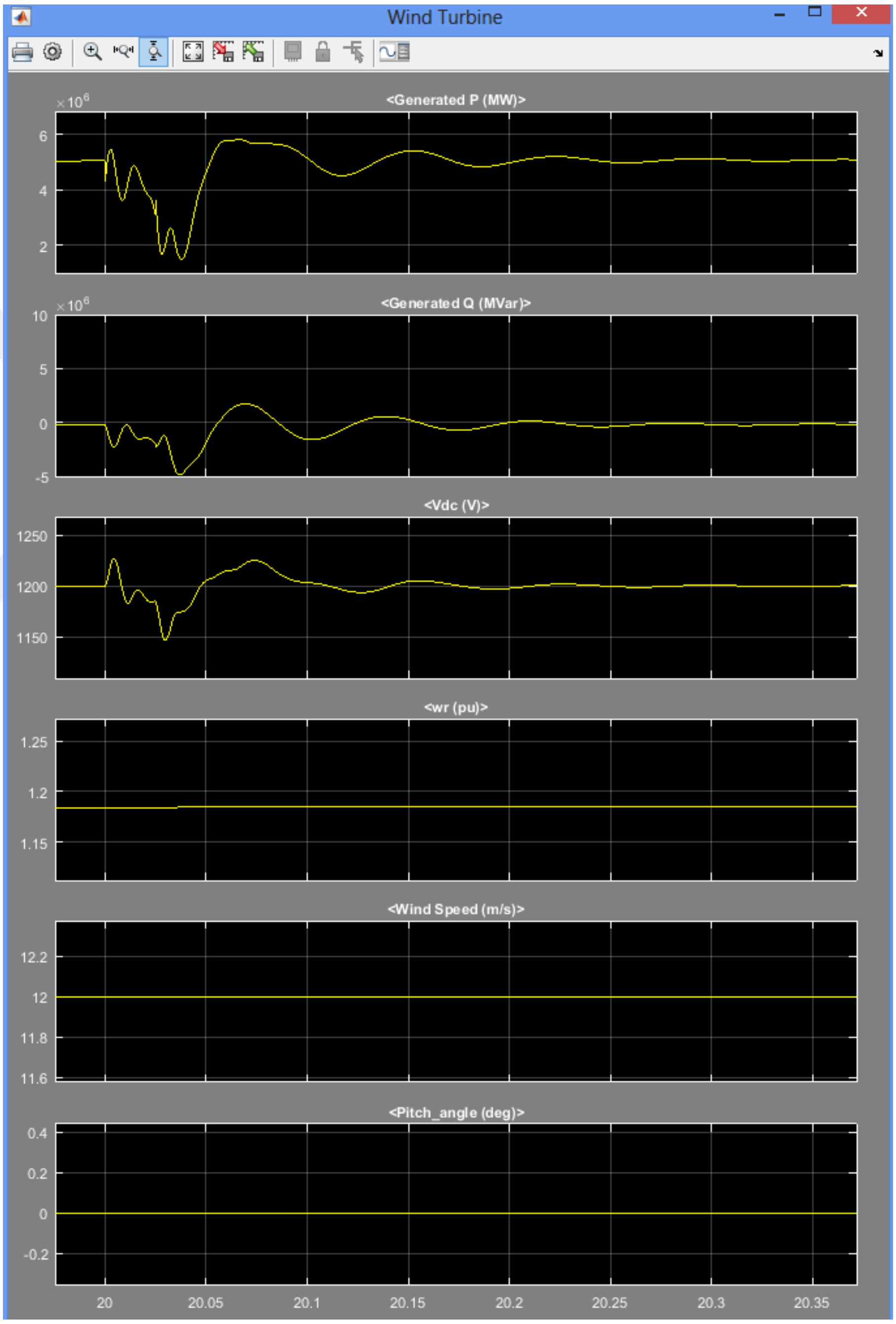

Figure 4.6. Wind turbines generated active and reactive powers and values of single wind turbine without STATCOM

In figure number 4.6. total generated power of wind farm is shown. During voltage sag, amount of generated total P active power drops below 2MW, generated total Q reactive power varies between -5Mvar to 2Mvar and also voltage drop is seen on DFIG's DC-Link voltage from 1200V to 1150V, without STATCOM operation.

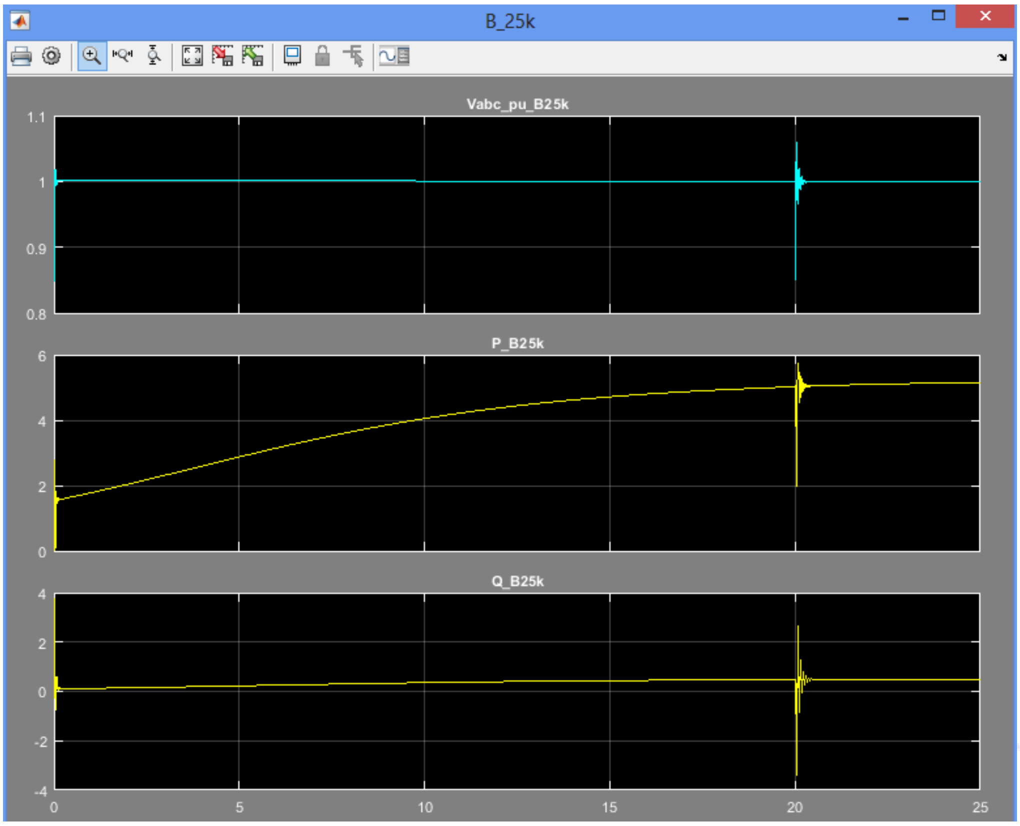

Figure 4.7. 25kV bar values without STATCOM

In figure number 4.7. effects of generated voltage sag are seen. Three phase voltage values drop 0.15pu at t=20s and total P and Q values of 25kV bar also observed with their decrements.

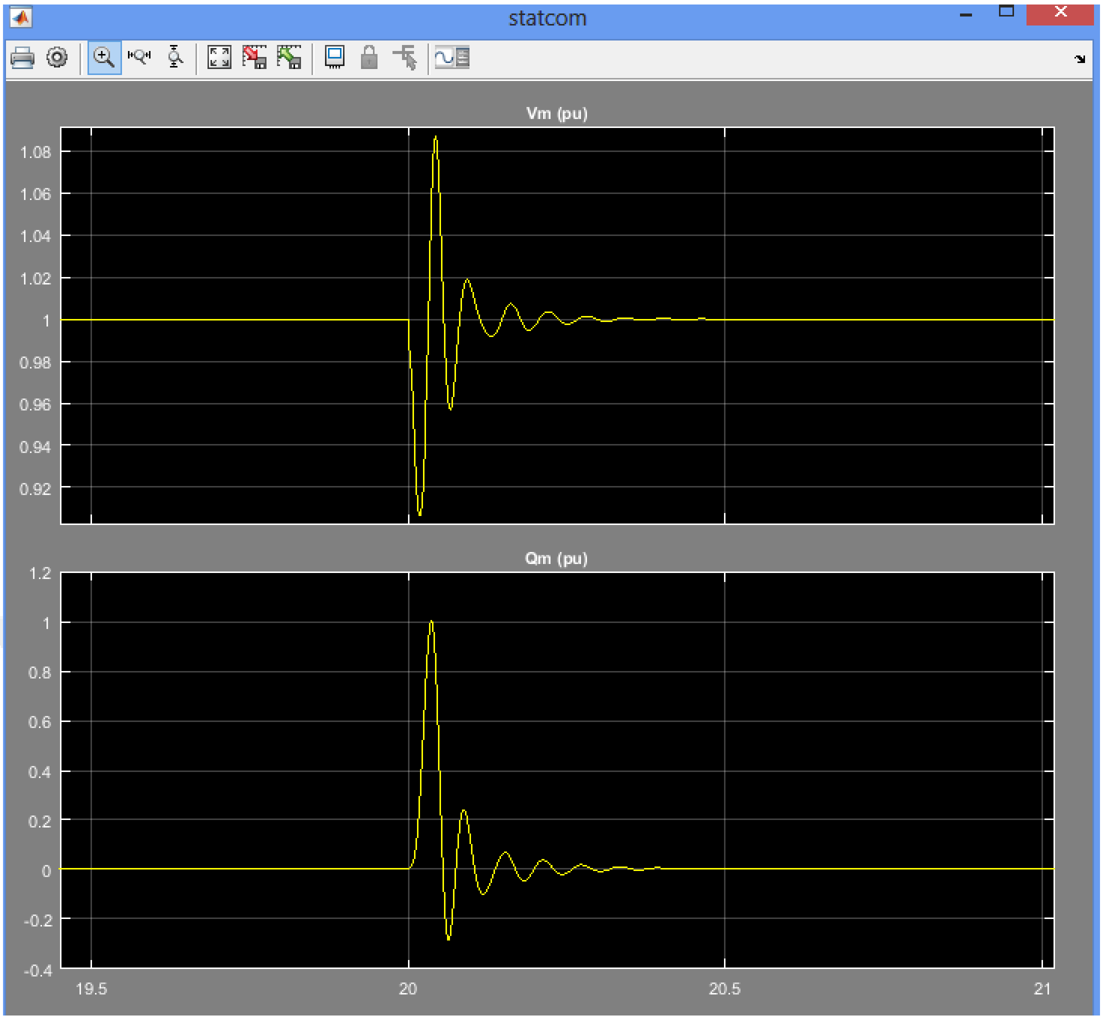

Figure 4.8. Respond of STATCOM for voltage sag

In figure number 4.8. measured bus voltage V_m of STATCOM and generated reactive power Q_m by STATCOM is seen in pu base during voltage sag. STATCOM responds to voltage sag situation with generated 1pu Q_m reactive power.

Determining the rated power of STATCOM and its other parameters such as DC bus voltage or inductor value, vary according to application. Different size or different rate applications can be done. In the studies (Singh, 2004) and (Hassan, 2014) techniques are presented to determine proper size of FACTS.

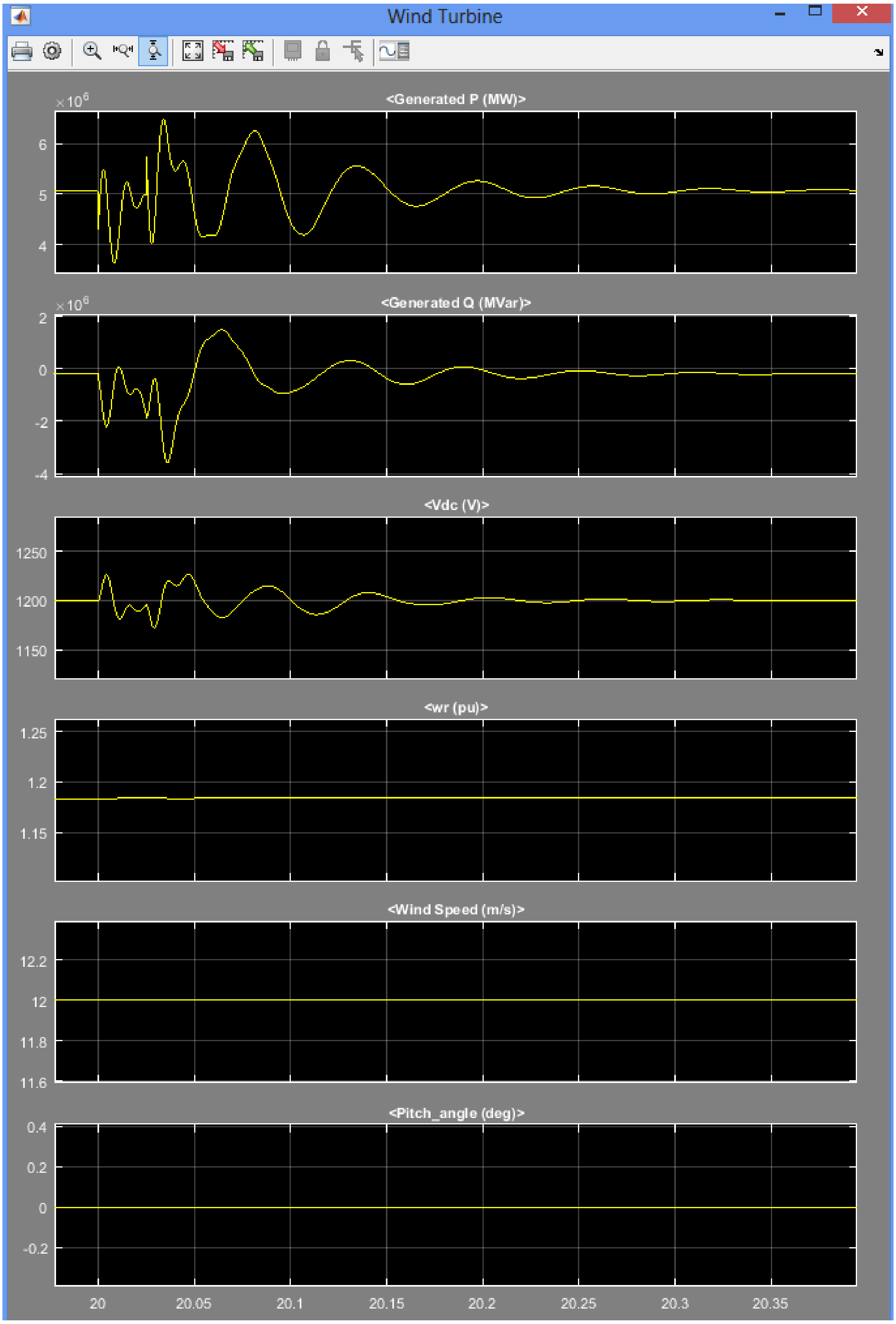

Figure 4.9. Wind turbines generated active and reactive powers and values of single wind turbine with STATCOM

In figure number 4.9. total generated power of wind farm is shown. During voltage sag, amount of generated total P active power drops below 4MW, generated total Q reactive power varies between -3.5Mvar to 1.5Mvar and also voltage drop is seen on DFIG's DC-Link voltage from 1200V to 1175V, with STATCOM operation.

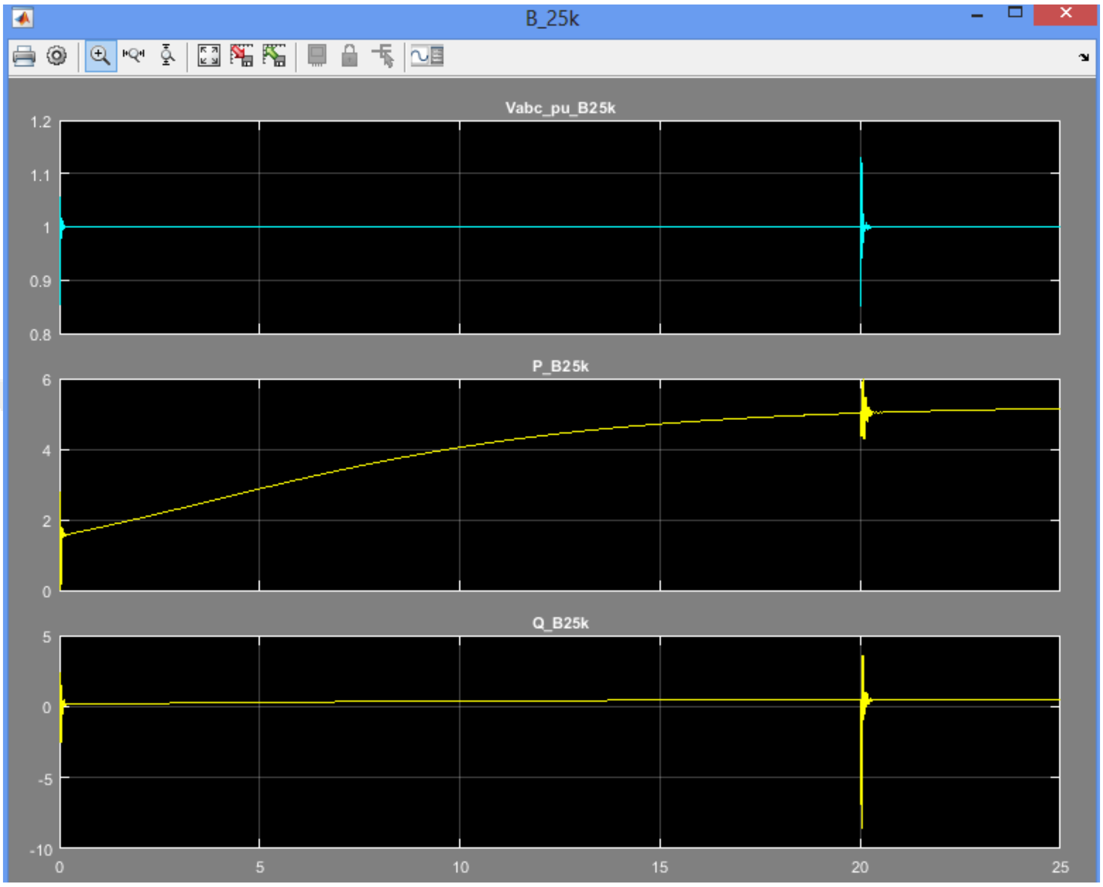

Figure 4.10. 25kV bar values with STATCOM

In figure number 4.10. effects of generated voltage sag are seen. Three phase voltage values drop 0.15pu at t=20s and total P and Q values of 25kV bar also observed with STATCOM operation.

In the case of STATCOM connected study, it responds quickly by supplying additional reactive power almost 1pu. As a result, lower disturbance occurs on 25kV bar and DFIGs need to supply less reactive power to the grid with STATCOM operation. Using more or less power of STATCOM will affect the reactive power generation of wind turbines. At all transient conditions examined in this paper, the wind power generation system is recovering rapid sufficient to avoid the protection system from uncoupling it.

4.3. Implementing a Basic Protection System for Wind Farm

A fundamental protection system was designed for voltage disturbance situations and to keep wind turbine in desired wind speed region. In figure number 4.11. these protection blocks are shown.

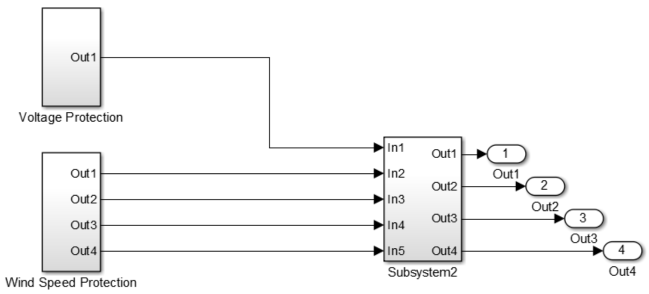

Figure 4.11. Protection system for wind farm

4.3.1. Protection for Exceeded Wind Speed

As mentioned in chapter 2.3. wind turbines have working region for specified wind speeds. This working region is between wind turbine’s cut-in wind speed and cut-out wind speed. Depending on its model, a wind turbine achieve its rated wind speed generally 12-17m/s. Maximum output power of a wind turbine is also named as rated output power.

Especially beyond the cut-out speed of wind turbine, higher speeds become hazardous for wind turbine structure. Hence, under extreme wind events, safe operation of wind turbines increases their life.

A protection system is described in an article (Ghita, 2009). For the situations of under-speed and over-speed, protection system uncouples the wind turbine from the grid. In the case of over-speeding risk of the injected power into the grid over the rated one also mentioned.

In this study, first a various wind speed of increasing from 3m/s to 14m/s is applied to wind turbines and output values of wind farm can be observed in figure number 4.13. Then wind speed of a single wind turbine, wind turbine_1, is increased over to determined cut-out wind speed of 18m/s and results of this state can be viewed in figure number 4.14.

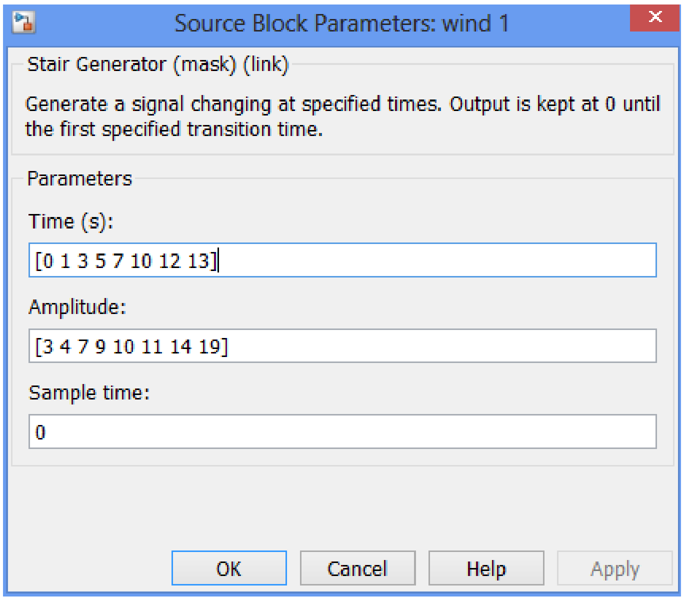

Figure 4.12. Applied wind speed for exceeded speed wind turbine_1

In figure number 4.12. a block's parameters are shown which is used to imply variable wind speed to wind turbines. Only difference is for wind turbine_1, 19m/s wind speed is applied to win turbine_1 at t=13s to exceed cut-out speed.

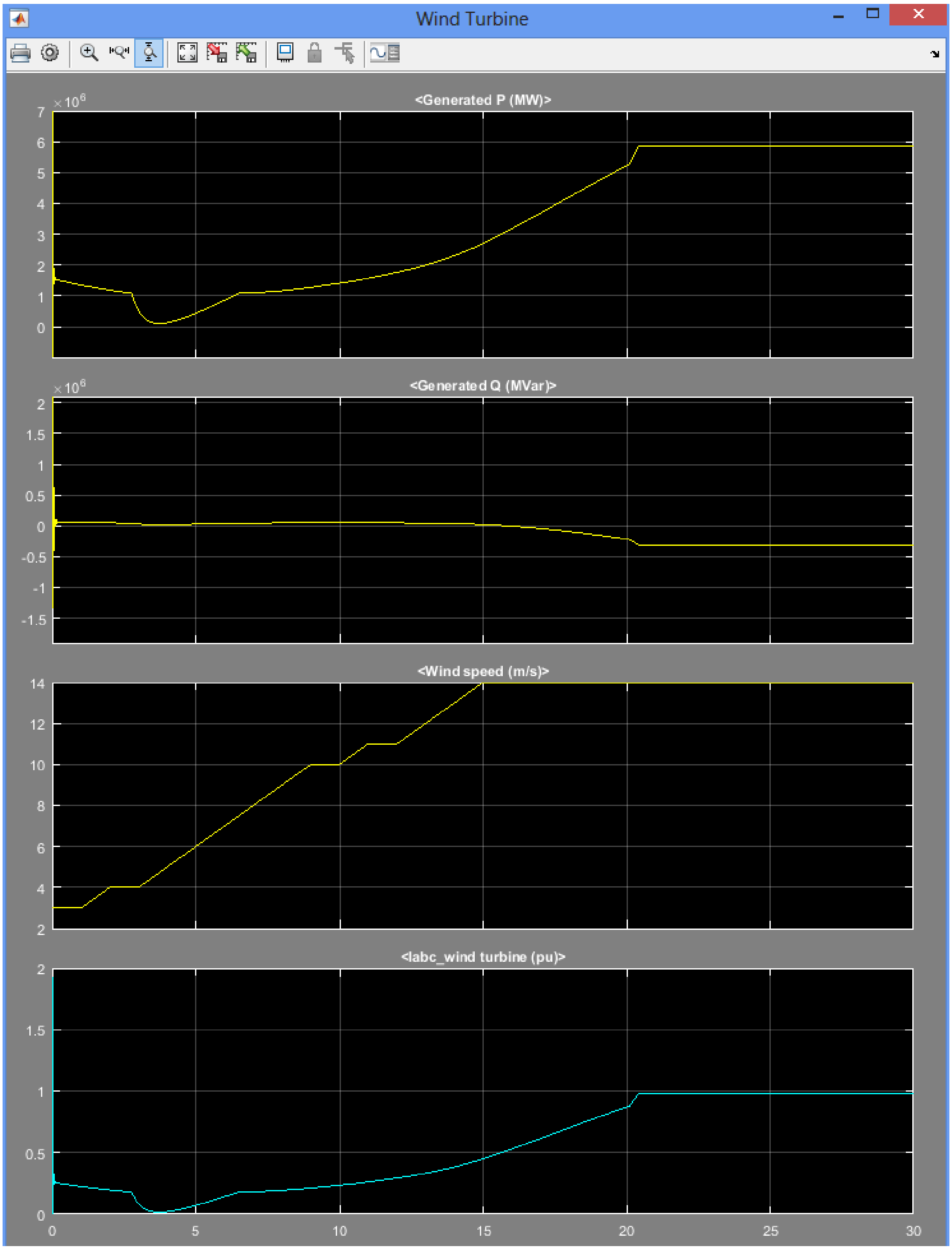

Figure 4.13. Total P and Q output of wind farm, applied wind speed to wind turbine_1 and pu based phasor currents of wind turbine_1

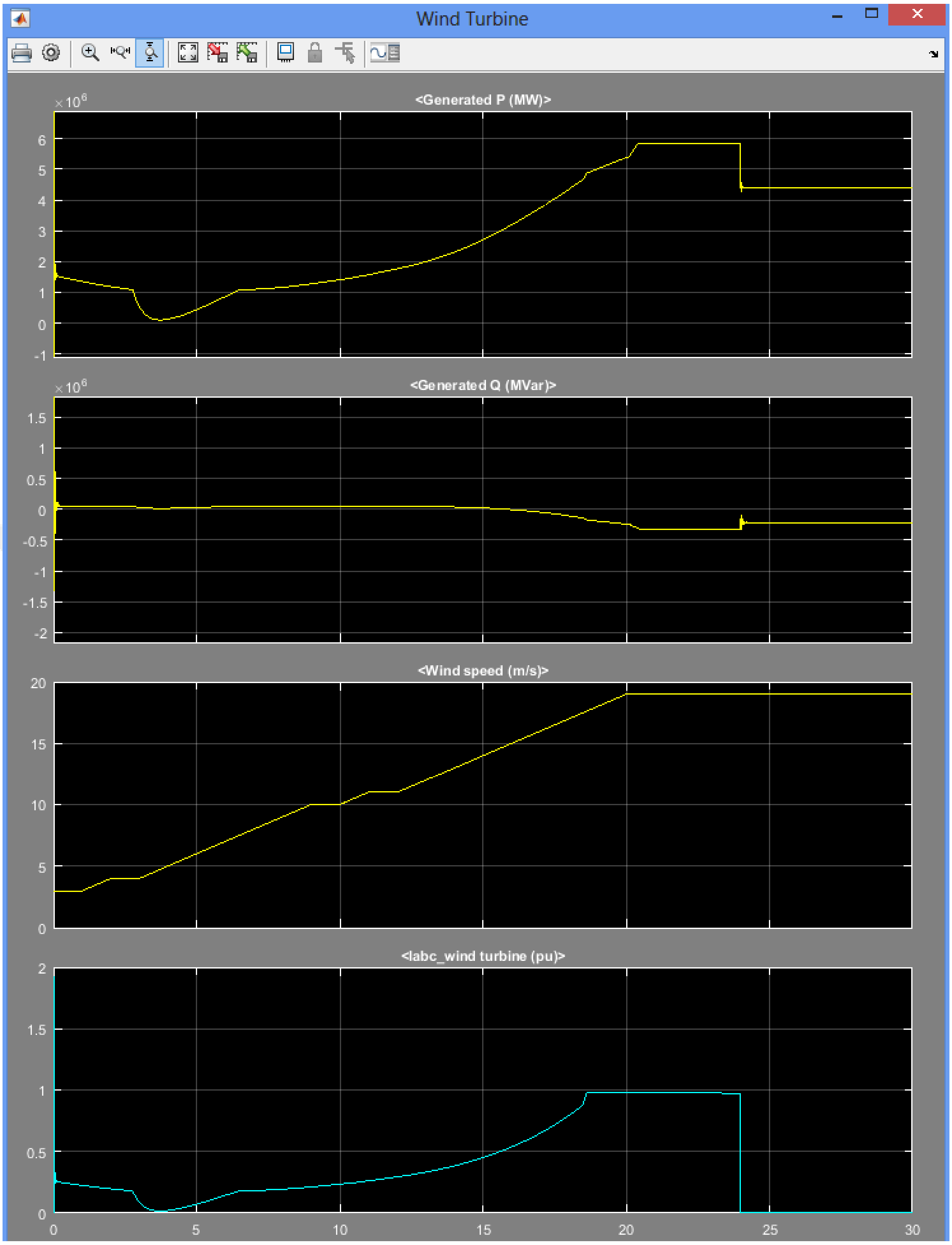

Figure 4.14. Total P and Q output of wind farm, applied wind speed to wind turbine_1 and pu based phasor currents of wind turbine_1, in the disconnection case

After wind speed increment of wind turbine_1 to over it's cut-out speed it disconnects from network at t=24s and wind farm continues to produce active power with lack of single wind turbine's power.

4.3.2. Protection for Voltage Disturbance Situations

In some cases, after appeared disturbances on grid or network, wind farms must be disconnected from grid. For the protection system study, voltage dip example is examined in this chapter. In figure number 4.15. LVRT (Low Voltage Ride Through) requirements are shown for various grid codes where U is voltage during fault and U_N is rated voltage. In the past years throughout grid disturbances and low grid voltages wind farms were allowed to separate from grid. Simultaneous disconnection of wind generating systems can cause larger voltage depression if there is a wide amount of wind energy generation. Also, additional loss of power generation as a result of disconnection may cause a greater production/consumption imbalance and so drop in the system frequency in the larger region (Erlich, 2006). Recent grid codes require that wind farms to remain connected and support grid during and after fault. Disconnection is not allowed above of the borderlines that shown in figure number 4.15. Underneath the borderline wind turbines are allowed to be tripped.

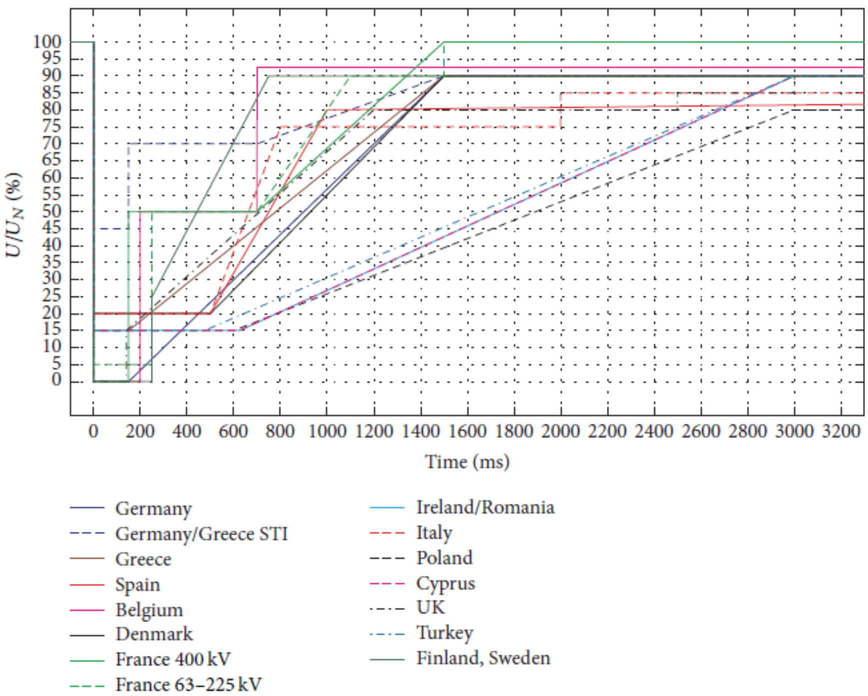

Figure 4.15. LVRT requirements in various grid codes (Sourkounis, 2013)

In order to protect DC-link capacitor and the power electronic switches of the RSC against to very high currents and DC-link overvoltage effect during severe grid voltage faults, DFIG based wind turbines must disconnect from the grid.

In Simulink, according to the figure number 4.15. 50% of three phase voltage dip is applied at t=16s to t=16.25s for 250ms of fault. After 200ms of fault duration wind farm is uncoupled from the grid. 12m/s wind speed is applied to turbine inputs.

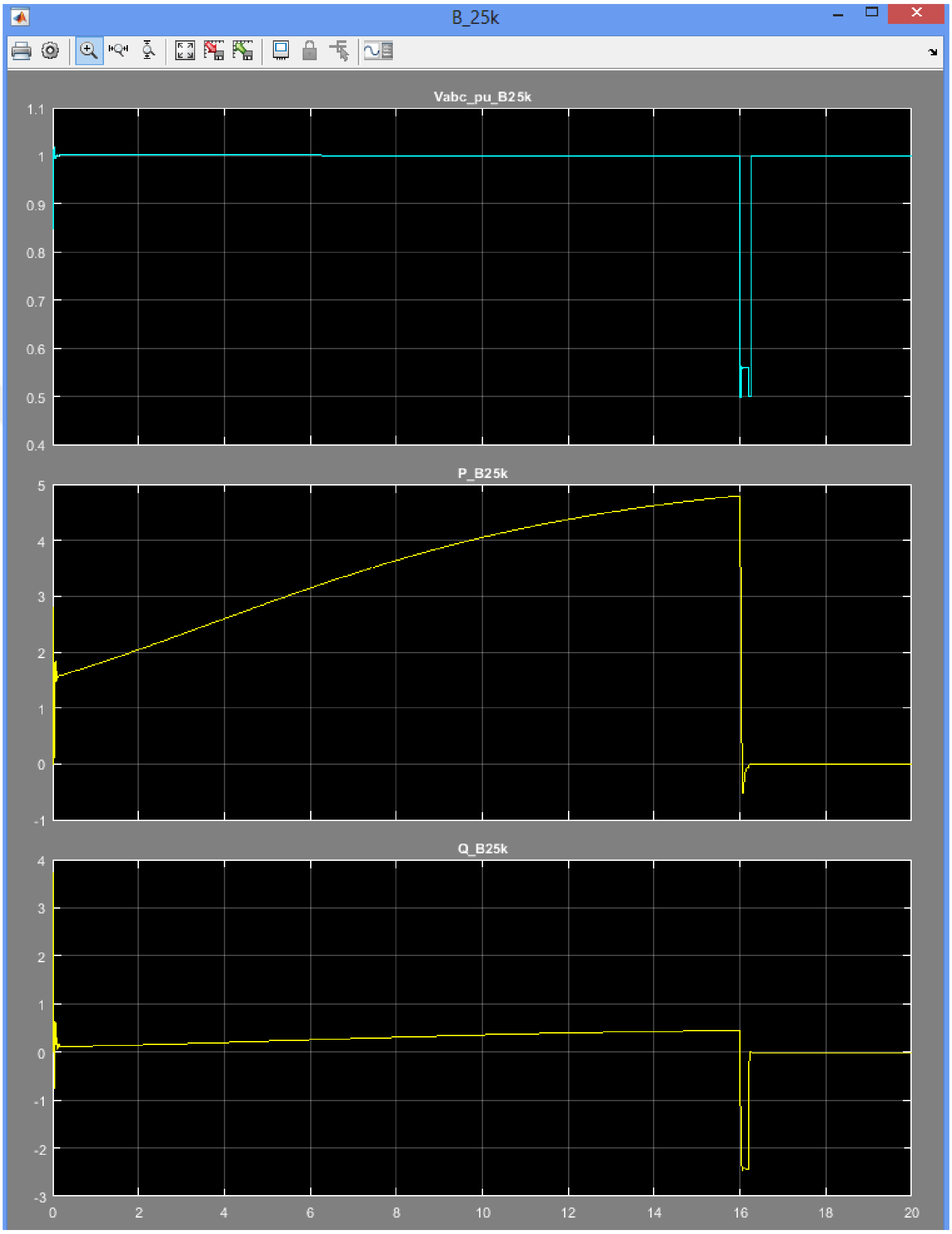

Figure 4.16. Values on 25kV bar

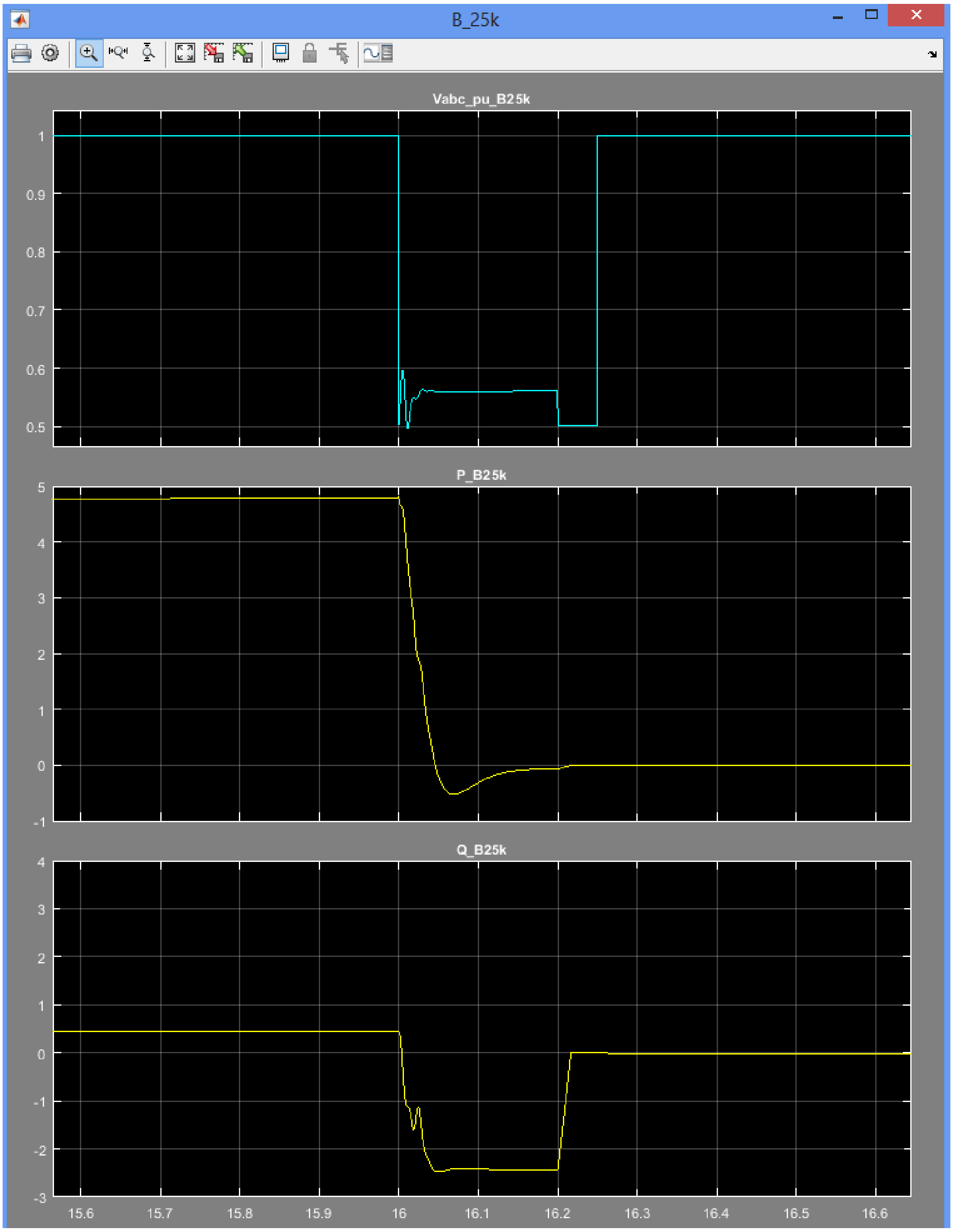

Figure 4.17. Values on 25kV bar in detail

In figure number 4.17. 50% voltage dip on three phases of B25kV bar is seen. P and Q values also decrease and wind farm is disconnected from grid at the time of t=16.2s.

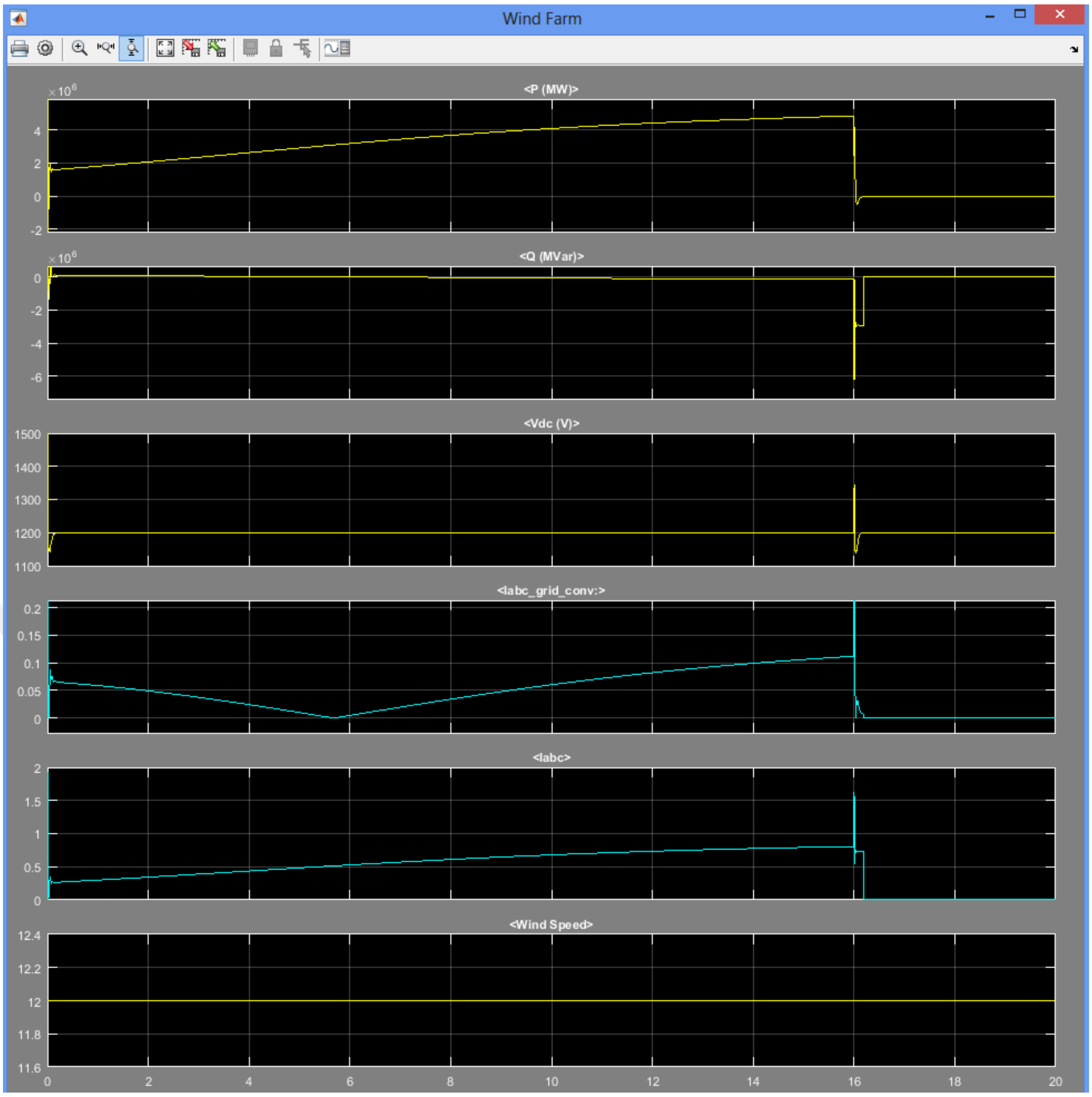

Figure 4.18. Total P and Q values of wind farm and values for single wind turbine

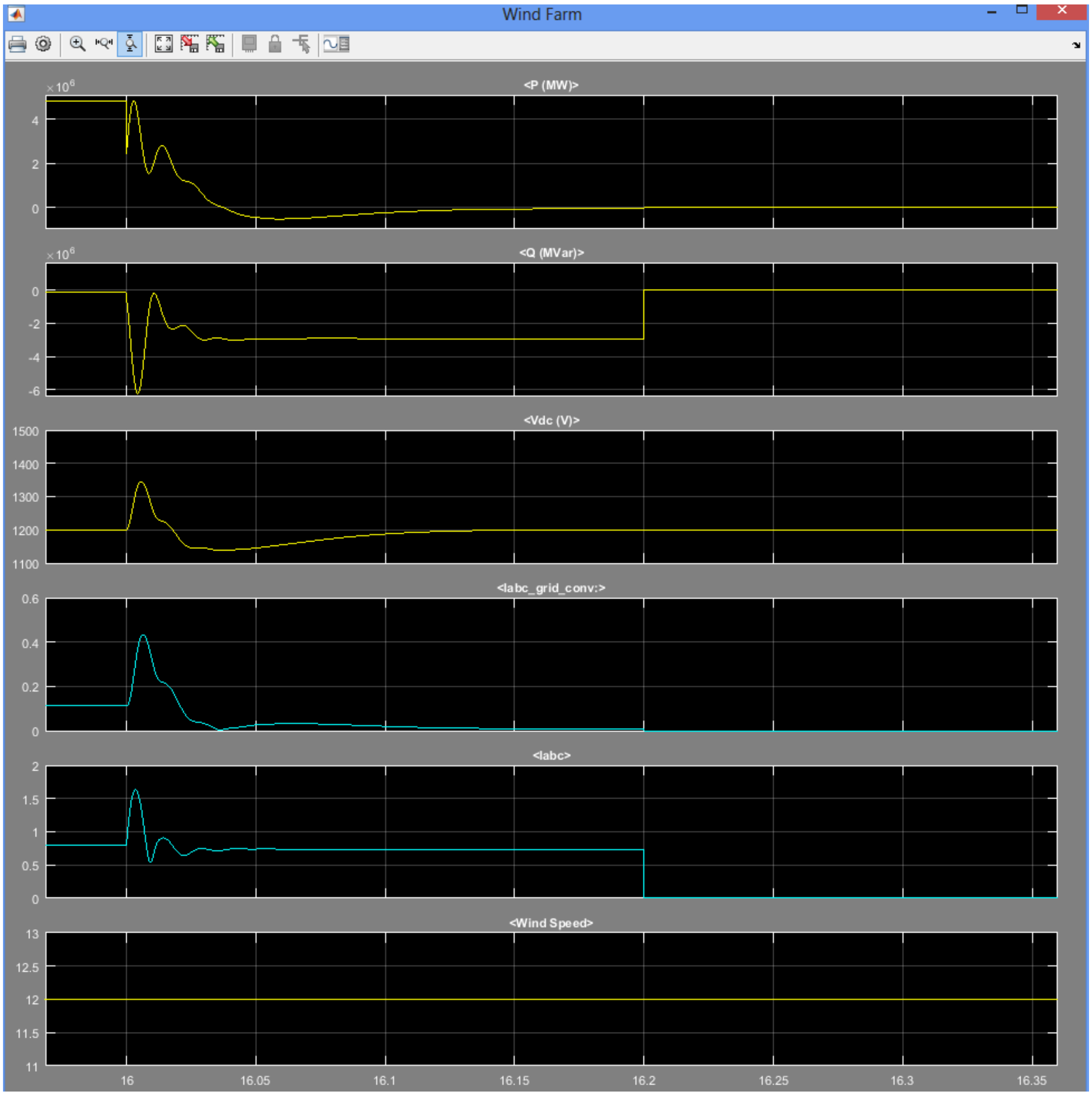

Figure 4.19. Total P and Q values of wind farm and values for single wind turbine in detail

The figure number 4.19. that is detailed form of figure number 4.18. shows the total generated values of P and Q for wind farm. DC-Link voltage of DFIG passes over 1340V and grid side converter currents increase to 0.4pu from 0.1pu and phasor currents of wind turbine increase to 1.6pu from 0.8pu. The system is disconnected from the grid at t=16.2s while the fault in progress.

CHAPTER 5
CONCLUSIONS AND FUTURE RESEARCH

In the first phase of the study, the historical development of renewable energy and the reasons for need are discussed. According to these needs, wind energy development and energy production from wind are increased. Besides these increments and developments, companies, scientists, engineers need also more time and resources for development. At this point, the importance of simulation programs emerges. Simulation and modeling applications provide to their users unlimited trying and testing options. With their easy to use graphical interfaces, simulation programs let to users modeling, testing, and developing possibilities for dynamic systems. As a result of these possibilities, companies and researchers find to chance of saving resources and time. Recognition of the lack of academic studies in the field of simulation, which was seen at the end of the literature review, has been one of the motivation sources for this study.

At the second phase of the study, fundamental and necessary equipment and components are defined and investigated for the study. Industrial type of wind energy conversion systems are examined with the types of vertical and horizontal styles. Structure of the wind energy conversion systems and their working mechanisms are also studied with their mechanical and electrical parts. The DFIG model wind turbine, which has a large share in wind energy production, was decided to be used in the study after view of plus and minus aspects were investigated according to other generators. FACTS devices also examined in this phase and a STATCOM has been decided to implement at PCC of wind farm to see effects of it at voltage sag situation. At the further part of this phase, a wind farm model is created on Simulink environment and connection of it to the grid is done. Wind farm consists of four wind turbines which are at the rate of 1.5MW and totally 6MW. As seen in figures number 3.2. and 3.3. four DFIG based wind turbines are connected to 25kV network by step-up transformers, variable speed wind input is applied to every single of these four wind turbines. After that PCC point network is bounded to a step-up transformer again in order to connect the 120kV grid. Grid is modeled by three-phase programmable source block and also transmission lines are implemented by their own blocks. For the short circuit analysis part of this study a fault block is also implemented on 25kV bar section. A developed basic protection block is also implemented in the block of wind farm that is for the avoiding wind turbines from the situations of voltage disturbances and wind speed changes such under-speed or over-speed. Scope blocks are located on necessary points to track simulations simultaneously and derive the results from them at the end of simulation.

At the last phase of this study, different situations are run on Simulink. In the chapter 4.1. variable wind speed is applied to wind turbines via a time-based step block and a rate limiter. It starts from a lower speed and reaches to rated wind speed. With increased wind speed, rotating speed of rotor increases from 0.8pu to 1.2pu and produced active power P increases. DFIG wind turbines at low speeds seem to feed the network as reactive power Q. Beyond the point of rated wind speed pitch angle increases in order to limit mechanical power input and dependent electrical output power. In the chapter 4.2.1. a single phase-ground fault is created at the t=8s. Voltage level decrease of a single line for 0.95pu, fluctuations on generated P, Q, and DC-Link voltage values are observed. DC-Link voltage level changing stays in acceptable limits, and system state is recovered in the time before disconnecting it by protection system. In the chapter 4.2.2. a voltage sag simulation is created on the 120kV grid side and effects are examined with and without STATCOM block. Affirmative effect of STATCOM is noticed for generated P and Q powers of the farm and fluctuations on DC-Link voltage level of DFIG. The decrease in the generated active power of wind farm decreases, and the fluctuations of the DC-Link voltage of a single wind turbine and fluctuations of the generated reactive power of wind farm occur in a smaller range. Lastly, a basic protection block has been developed for voltage fault and over or under speed conditions of wind speed in order to avoid wind turbines from any harmful affect. In the chapter 4.3.1., an exceeded wind speed is applied for a single wind turbine to view reaction of protection block on it. After speed-out of determined wind speed, system cuts out a wind turbine by disconnecting it from network and wind farm continues production with lack of a single wind turbine with a decrease of produced active power from 5.8MW to 4.4MW. In the chapter 4.3.2., to accomplish of LVRT requirements, a three-phase 50% voltage sag programmed for 250ms and while the fault is in progress, the system has been disconnected from the network by the protection block at 200ms as set.

Finally, this study was thought and aimed to be a step stone for further simulation and design works of any wind turbine or wind farm dynamic simulation study. For future works in the beginning, this study can be developed in terms of time optimization because every additional block or element increases the running time of the simulation. An optimization and development on these blocks can reduce running time of simulation. In Simulink's model parameters configuration section, by changing model solver options and model solver functions, more efficient and accurate results can be achieved. In the same parameters section, an initial conditions state can also be created in order to either accept some parameters for the system or ignore them. On the other hand, created protection block is also can be developed with any additional features, for instance, crowbar can be adapted to RSC of DFIG in order to avoid it from any harm during possible fault condition. For the advanced system designs, mechanical parts of wind turbine components can be modeled and adapted in the Simulink. Since the wind energy conversion systems are made up of hundreds of mechanical parts, the modeling of these mechanical parts in Simulink will increase the suitability of the designed system for real life.

REFERENCES

Alhazmi, M. M. (2015). *Modeling of Doubly-Fed Induction Generator using MATLAB/Simulink* (Doctoral dissertation, California State University, Los Angeles).

Aydin, E., Polat, A., & Ergene, L. T. (2016, December). Vector control of DFIG in wind power applications and analysis for voltage drop condition. In *Electrical, Electronics and Biomedical Engineering (ELECO), 2016 National Conference on* (pp. 81-85). IEEE.

Ceylan, M. (2006). *Muğla bölgesinde mermer endüstrisinin elektrik enerjisi talebini karşılamak için, MATLAB paket programı ile rüzgar çiftliği tasarım çalışması* (Doctoral dissertation, Selçuk Üniversitesi Fen Bilimleri Enstitüsü).

Dong, F., Chowdhury, B. H., Crow, M., & Acar, L. (2005). Improving voltage stability by reactive power reserve management.

Emezuru, Uzor. (2011). Simulation of small wind energy using MATLAB. 10.13140/2.1.2578.2724

Erlich, I., Winter, W., & Dittrich, A. (2006, June). Advanced grid requirements for the integration of wind turbines into the German transmission system. In *Power Engineering Society General Meeting, 2006. IEEE* (pp. 7-pp). IEEE.

Fleming, P. D., & Probert, S. D. (1984). The evolution of wind-turbines: an historical review. *Applied energy*, *18*(3), 163-177.

Ghiţă, C., Deaconu, D. I., Chirilă, A. I., Năvrăpescu, V., & Ilina, D. (2009). Lab model for a low power wind turbine system. In *International Conference on Renewable Energies and Power Quality Valencia (Spain)*.

Glanzmann, G. (2005). *FACTS: flexible alternating current transmission systems*. ETH Zurich.

Hassan, H. A., Osman, Z. H., & Lasheen, A. E. A. (2014). Sizing of STATCOM to enhance voltage stability of power systems for normal and contingency cases. *Smart Grid and Renewable Energy*, *5*(01), 8.

Jansuya, P., & Kumsuwan, Y. (2013). Design of MATLAB/Simulink modeling of fixed-pitch angle wind turbine simulator. *Energy Procedia*, *34*, 362-370.

Li, H., & Chen, Z. (2008). Overview of different wind generator systems and their comparisons. *IET Renewable Power Generation*, *2*(2), 123-138.

Logan, J., & Kaplan, S. M. (2008). Wind power in the united states: Technology, economic, and policy issues.

Mahadanaarachchi, V. P., & Ramakumar, R. (2009, July). Simulation of faults in DFIG-based wind farms. In *Power & Energy Society General Meeting, 2009.*

PES'09. IEEE (pp. 1-8). IEEE.

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: theory, design and application*. John Wiley & Sons.

Masaud, T. (2013). *Modeling, analysis, control and design application guidelines of doubly fed induction generator (DFIG) for wind power applications* (Doctoral dissertation, Colorado School of Mines. Arthur Lakes Library).

McCartney, S. (2010). The Simulation And Control Of A Grid-connected Wind Energy Conversion System.

Montazeri, M. M., Xu, D., & Yuwen, B. (2011, May). Improved low voltage ride thorough capability of wind farm using STATCOM. In *Electric Machines & Drives Conference (IEMDC), 2011 IEEE International* (pp. 813-818). IEEE.

Nicolae, I. D., Nicolae, P. M., & Popa, D. L. (2014, September). Simulation by MATLAB/Simulink of a wind farm power plant. In *Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International* (pp. 258-263). IEEE.

Pappu, S. R., Nimmagadda, S., & Bayne, S. B. (2012, July). Analysis and comparison between two wind farms consisting of 500kW midsize turbines and 1.5 MW turbines. In *Power Electronics and Machines in Wind Applications (PEMWA), 2012 IEEE* (pp. 1-8). IEEE.

Pokharel, B. (2011). *Modeling, control and analysis of a doubly fed induction generator based wind turbine system with voltage regulation*. Tennessee Technological University.

Santoso, S., & Singh, M. (2011). Dynamic Models for Wind Turbines and Wind Power Plants. *NREL (National Renewable Energy Laboratory). Austin, Texas*.

Singh, B., Murthy, S. S., & Gupta, S. (2004). Analysis and design of STATCOM-based voltage regulator for self-excited induction generators. *IEEE Transactions on Energy Conversion*, *19*(4), 783-790.

Singh, B., Saha, R., Chandra, A., & Al-Haddad, K. (2009). Static synchronous compensators (STATCOM): a review. *IET Power Electronics*, *2*(4), 297-324.

Sourkounis, C., & Tourou, P. (2013). Grid code requirements for wind power integration in europe. In *Conference Papers in Science* (Vol. 2013). Hindawi.

Söder, L., & Ackermann, T. (2005). Wind power in power systems: an introduction. *Wind power in power systems*, 25-47.

Teixeira, L., Zhang, Y., & Kang, Y. (2011, March). Simulation of Power System in Cape Verde with Simulink® considering Wind Farm. In *Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific* (pp. 1-4). IEEE.

Wu, B., Lang, Y., Zargari, N., & Kouro, S. (2011). *Power conversion and control of wind energy systems* (Vol. 76). John Wiley & Sons.

APPENDIX 1 – Parameters of Blocks Used In Simulink

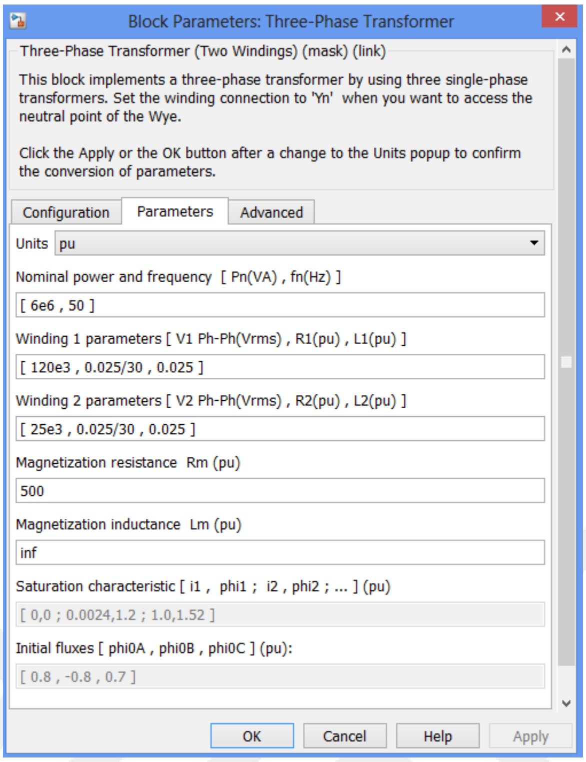

Figure A1.1. Parameters of three phase transformer block on 120kV side

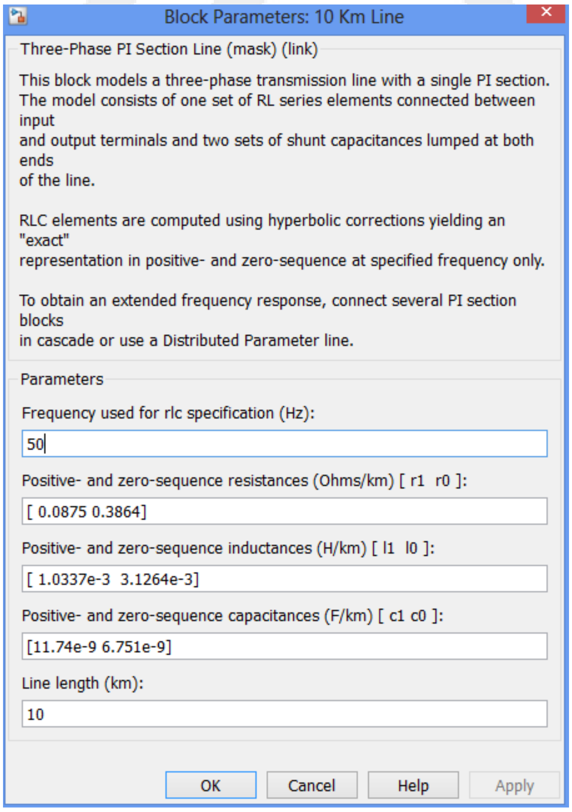

Figure A1.2. Parameters of 10km transmission line block

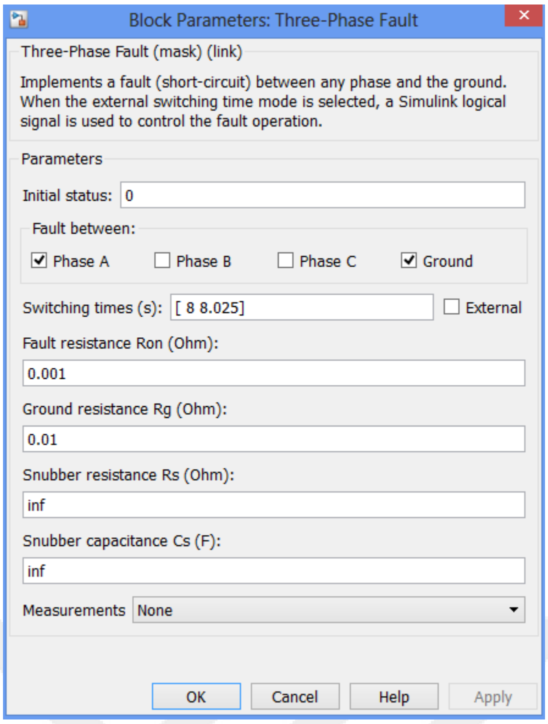

Figure A1.3. Parameters of fault block

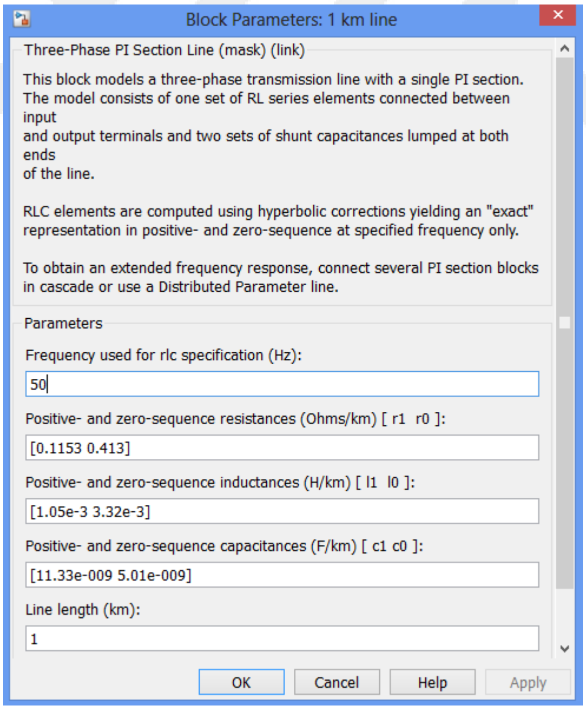

Figure A1.4. Parameters of 1km transmission line block

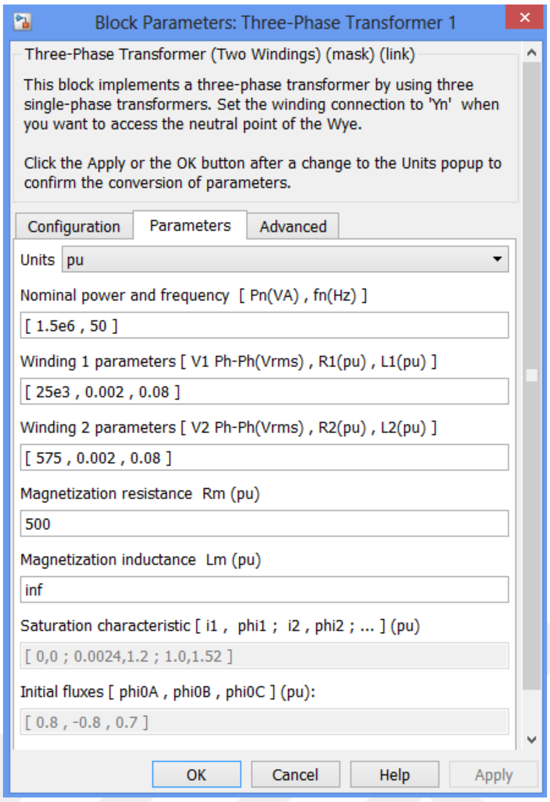

Figure A1.5. Parameters of three phase transformer block on 25kV side

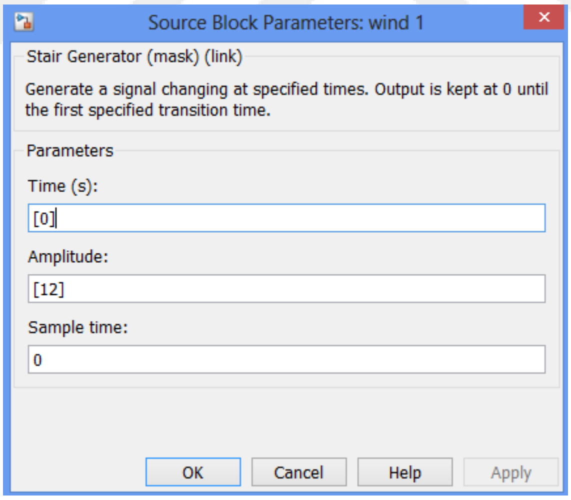

Figure A1.6. Parameters of constant wind speed block

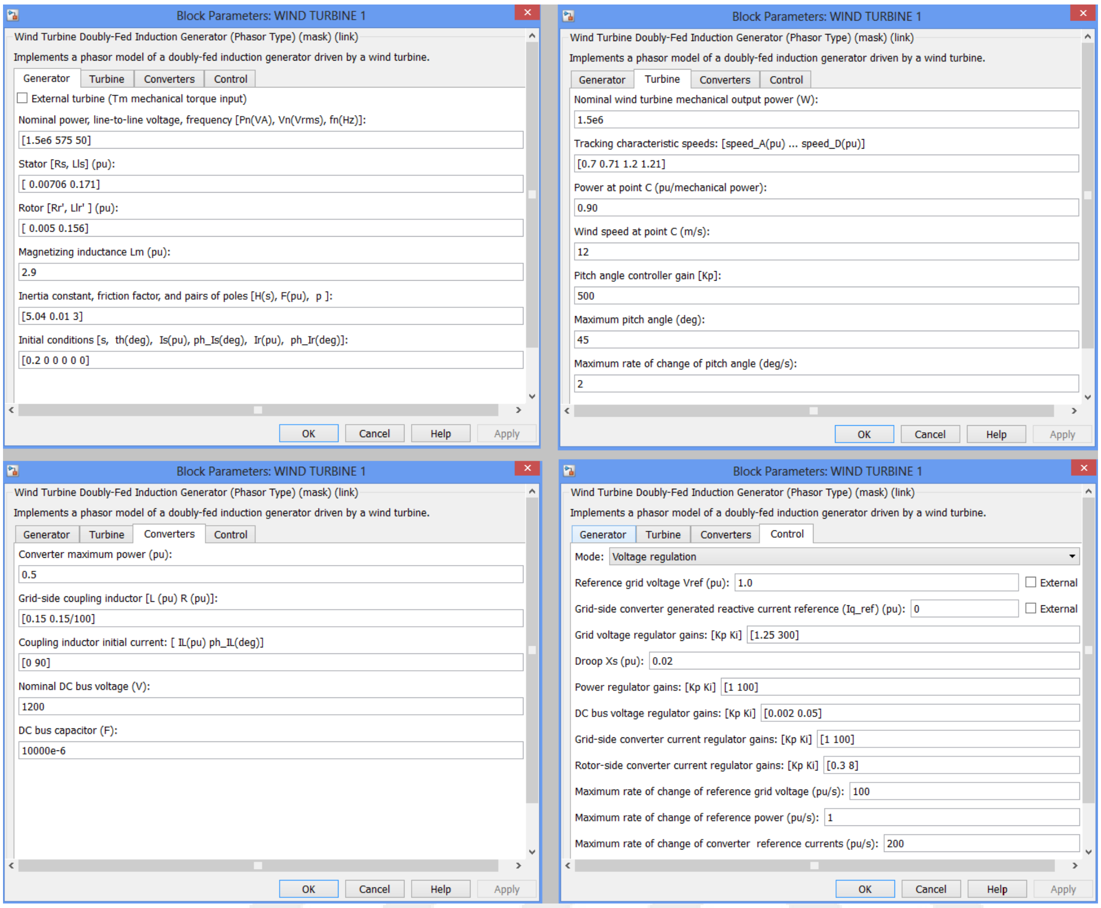

Figure A1.7. Generator, turbine, convertor, control parameters of a single wind turbine