

STUDY OF PERFORMANCE AND ISSUES OF INTEGRATION OF FIXED SPEED SCIG WIND TURBINES TO POWER SYSTEM GRID

*Thesis submitted in partial fulfillment of the requirements for the award of
degree of*

**Master of Engineering
In
Power Systems & Electric Drives**



Thapar University, Patiala

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CERTIFICATE

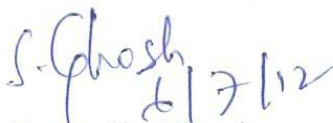
I here certify that the work which is being presented in this thesis entitled “STUDY OF PERFORMANCE AND ISSUES OF INTEGRATION OF FIXED SPEED SCIG WIND TURBINES TO POWER SYSTEM GRID” in partial fulfillment of the requirement for the award of degree of Master of Engineering in Power Systems and Electric Drives submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under supervision of Dr. Smarajit Ghosh, Professor, EIED and Mr. Inderpreet Singh, Lecturer, EIED.

The matter presented in this thesis has not been submitted the award of any other degree of this or any other university.



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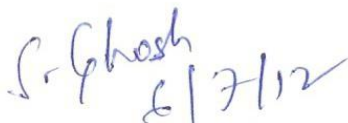
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ABSTRACT

The selection of the technology used in wind turbine is an essential factor in any operation of building a wind farm. The Fixed speed wind turbine that uses SCIG has some superior characteristics such as it does not require slip rings, robust mechanical design, and due to its operational simplicity, the fixed speed SCIG wind turbine has lower cost as compared to the other types of wind turbines. This thesis work is done to study the performance and issues of fixed speed SCIG wind turbine that works in multi MW range. The studies was done through calculation its power curve and investigate the effects of wind speed at starting and wind gust on the wind turbine and also the rate of change of pitch angle. The study also was through different circumstances and issues at steady state like changes in grid side voltage, re-switching transient, improving power factor, effect of network faults at common coupling point, and the ways to ride through these faults by the assistance of shunt capacitor and using of STATCOM. The multi connections of wind turbines to make a single wind farm with capacity of (36 MW) also studied through the way of starting of all the turbines in the wind farm and also in LVRT method for unsymmetrical faults at PCC point and voltage dip at grid side for duration of (100 ms).

LIST OF CONTENTS

| C O N T E N T S | P A G E N O. |
|---|---------------------|
| CERTIFICATE | i |
| ACKNOWLEDGEMENT | ii |
| ABSTRACT | iii |
| LIST OF CONTENTS | iv-vi |
| LIST OF FIGURES | vii-x |
| LIST OF ABBREVIATIONS | xi |
| LIST OF NOMENCLATURES | xii |
| CHAPTER 1 | 1-8 |
| 1.1 OVERVIEW | 1 |
| 1.2 INSTALLED CAPACITIES AND SIZES OF WIND TURBINES | 2 |
| 1.2.1 Installed Capacity and Growth Rate | 2 |
| 1.2.2 Small and Large Wind turbines | 3 |
| 1.2.3 Sizes of Wind turbines | 3 |
| 1.3 LITERATURE REVIEW | 4 |
| 1.4 OBJECTIVES OF THE PRESENT WORK | 7 |
| 1.4 ORGANIZATION OF THE THESIS | 7 |
| CHAPTER 2 | 9-18 |
| 2.1 INTRODUCTION | 9 |
| 2.2 WIND ENERGY CHARACTERISTICS | 9 |
| 2.2.1 Tip speed ratio, λ | 10 |
| 2.3 POWER CURVE | 11 |
| 2.4 WIND TURBINE TECHNOLOGIES | 12 |
| 2.4.1 Horizontal - and - Vertical - Axis Wind Turbines | 12 |
| 2.4.2 Fixed and Variable Speed Wind Turbines | 13 |
| 2.4.2.1 Generators systems for fixed and variable speed wind Turbine | 13 |
| 2.5 WIND TURBINE COMPONENTS | 15 |
| 2.6 SPEED CONTROL OF WIND TURBINES | 16 |
| 2.6.1 Control Strategies | 16 |

| | |
|---|--------------|
| CHAPTER 3 | 19-30 |
| 3.1 INTRODUCTION | 19 |
| 3.2 OPERATION PRINCIPLE OF FIXED SPEED WIND TURBINE USING SCIG | 20 |
| 3.2.1 Pitch control of fixed speed wind turbine | 21 |
| 3.3 DETERMINATION OF THE POWER CURVE OF A (3 MW) FIXED SPEED S.C.I.G. WIND TURBINE | 23 |
| 3.4 EFFECTS OF INTEGRATION OF FIXED SPEED SCIG WIND TURBINE TO POWER SYSTEM GRID | 26 |
| 3.4.1 Direct grid connection of fixed speed SCIG wind turbine | 26 |
| 3.4.3 Performance during network faults | 26 |
| 3.4.4 Re-switching transients | 27 |
| 3.4.5 Low-Voltage-Ride-Through (LVRT) | 27 |
| 3.4.6 Increasing wind farm capacity | 28 |
| 3.5 FLOWCHART OF STUDYING THE PERFORMANCE AND ISSUES OF THE FIXED SPEED S.C.I.G WIND TURBINE | 29 |
| CHAPTER 4 | 31-59 |
| 4.1 DYNAMIC PERFORMANCE OF WIND TURBINE USING SCIG WITH DIRECT GRID CONNECTION DURING SYSTEM START-UP | 31 |
| 4.2 EFFECTS OF WIND SPEED AT STARTING AND WIND GUST | 34 |
| 4.3 EFFECT OF RE-SWITCHING TRANSIENT | 36 |
| 4.4 EFFECT OF VOLTAGE SAG, SWELL AND INTERRUPTION AT 120 KV GRID SIDE ON THE WIND TURBINE | 39 |
| 4.4.1 Effect of voltage Sag | 39 |
| 4.4.2 Effect of voltage Swell | 40 |
| 4.4.3 Effect of voltage interruption | 40 |
| 4.5 REACTIVE POWER COMPENSATION OF THE S.C.I.G. FIXED SPEED WIND TURBINE | 42 |

| | | |
|---------|---|--------------|
| 4.6 | PERFORMANCE OF THE (3 MW) FIXED SPEED WIND TURBINE DURING FAULTS | 43 |
| 4.6.1 | Single line to ground fault type | 44 |
| 4.6.2 | Double lines to ground fault type | 45 |
| 4.6.3 | Line to line fault type | 45 |
| 4.6.4 | Three phases symmetrical fault type | 46 |
| 4.7 | LOW VOLTAGE RIDE THROUGH (LVRT) OF THE (3 MW) FIXED SPEED S.C.I.G. WIND TURBINE | 47 |
| 4.8 | RESETING THE PROTECTION SYSTEM AFTER CLEARING THE CAUSE OF THE TRIPPING SIGNAL | 50 |
| 4.9 | INCREASING WIND FARM GENERATING CAPACITY | |
| 4.9.1 | Connection of multi wind turbines in a single wind farm (12 MW) | 52 |
| 4.9.2 | Different wind speeds at multi wind turbines in a single wind farm (12 MW) | 54 |
| 4.9.3 | Connection of multi wind turbines in a single wind farm (36 MW) | 55 |
| 4.9.3.1 | LVRT of (36 MW) wind farm | 57 |
| 4.10 | SUMMARY | 59 |
| | CHAPTER 5 | 60-62 |
| 5.1 | CONCLUSIONS | 60 |
| 5.2 | SCOPE OF FUTURE WORKS | 62 |
| | REFERENCES | 63-65 |
| | APPENDIX A | 66-68 |
| | APPENDIX B | 69 |

LIST OF FIGURES

| FIGURE NO. | FIGURE NAME | PAGE NO. |
|------------|---|----------|
| (1.1) | Global annual and cumulative installed wind power capacity | 2 |
| (1.2) | Top 10 Cumulative Capacity December 2011 | 3 |
| (1.3) | Evolution of wind turbine size (\emptyset = rotor diameter) | 4 |
| (2.1) | Swept area of wind turbine blades | 10 |
| (2.2) | Illustration of power coefficient / speed ratio curve, C_p / λ | 11 |
| (2.3) | Typical wind turbine power curve | 12 |
| (2.4) | Horizontal and vertical wind turbines | 13 |
| (2.5) | Generators systems for fixed speed wind Turbines | 14 |
| (2.6) | Generators systems for variable speed wind Turbines | 15 |
| (2.7) | VESTAS V15, general view and nacelle section | 16 |
| (2.8) | speed control methods of wind turbines | 17 |
| (2.9) | Power Curves for Different speed Control methods | 18 |
| (3.1) | Configuration of fixed-speed SCIG wind energy conversion system | 20 |
| (3.2) | System operating points and maximum power points (MPP) at different wind speeds | 20 |
| (3.3) | power coefficient versus tip speed ratio characteristics, for different values of the pitch angle | 22 |
| (3.4) | control system of pitch angle | 23 |
| (3.5) | Qualitative turbine mechanical power versus wind speed curve | 23 |
| (3.6) | wind turbine power characteristics | 24 |
| (3.7) | Power curve for the (3 MW) wind turbine | 24 |
| (3.8) | STATCOM and a wind turbine in the system for Voltage quality and LVRT | 28 |
| (3.9) | STATCOM configuration and principle of operation | 29 |
| (4.1) | Single line diagram of 3MW wind turbine connected to the (120 kv) grid | 31 |

| | | |
|--------|---|-------|
| (4.2) | Dynamic response of SCIG with direct grid connection | 32 |
| (4.3) | operation of wind turbine at rated wind speed | 33-34 |
| (4.4) | active power and voltage of the SCIG at (5.6 m/s) of wind speed | 35 |
| (4.5) | voltage, active and reactive power of the turbine at (10.6 m/s) of wind speed | 35 |
| (4.6) | active power of wind turbine at change of wind speed from (10 to 18 m/s) | 36 |
| (4.7) | active power and pitch angle at change of wind speed (10 to 18 m/s) when the maximum change of pitch angle is (11 deg/s) | 37 |
| (4.8) | effect of re-switching transient in (270 ms) from the disconnection | 38 |
| (4.9) | effect of re-switching transient at fault occurrence and after (170 ms) from the protection tripping signal | 38-39 |
| (4.10) | simulation of the wind turbine at different voltage sags values for (500 ms) | 40 |
| (4.11) | simulation of the wind turbine operation at (1.29 pu) voltage swell in (120 Kv) grid side for (500 ms) | 41 |
| (4.12) | simulation of the wind turbine operation at different interruptions of power at (120 Kv) grid | 41 |
| (4.13) | the difference in the torque and reactive power for the (3 MW) SCIG at the re-switching transient and power interruption for (200 ms) | 42 |
| (4.14) | voltage, reactive power and power factor at bus B_25 when the capacitive VAR of capacitor is (400 MVAR) | 43 |
| (4.15) | voltage, reactive power and power factor at bus B_25 when the capacitive VAR of capacitor is (925 KVAR) | 44 |

| | | |
|--------|---|-------|
| (4.17) | performance of the wind turbine at double lines to ground fault for (490 ms) and different types of (VAR) values of the capacitor | 46 |
| (4.18) | performance of the wind turbine at lines to line fault for (490 ms) | 46 |
| (4.19) | performance of the wind turbine at 3 phases symmetrical fault for (260 ms) | 47 |
| (4.20) | generated VAR and voltage of the STATCOM at three phase symmetrical fault for (100 ms) | 48 |
| (4.21) | simulation of wind turbine voltage and reactive power with (7.2 MVA) STATCOM and without it at (line to line fault) with (400 KVAR) of capacitor | 48 |
| (4.22) | simulation of wind turbine voltage and reactive power with (7.2 MVA) STATCOM and without it at (double lines to ground fault) with (400 KVAR) of the capacitor | 49 |
| (4.23) | simulation of wind turbine voltage and reactive power with (4.7 MVA) STATCOM and without it at (double lines to ground fault) with (925 KVAR) of the capacitor | 49 |
| (4.24) | simulation of wind turbine voltage and reactive power with (4.7 MVA) STATCOM and without it at (line to line fault) with (925 KVAR) of the capacitor | 50 |
| (4.25) | effect of tripping signal, resetting the protection system and resume the generation operation of the fixed speed wind turbine | 51 |
| (4.26) | operation of 4 units of (3 MW) wind turbine without STATCOM compensation and with (400 KVAR) of capacitor | 52-53 |
| (4.27) | operation of 4 units of (3 MW) wind turbine without STATCOM compensation and with (925 KVAR) of capacitor | 53-54 |

| | | |
|--------|--|-------|
| (4.28) | changing in wind speeds at (12 MW) of wind turbines | 54-55 |
| (4.29) | Active power, current and voltage in PCC point during the changing in wind speeds at (12 MW) of wind turbines | 55 |
| (4.30) | simulation of (12 wind turbines of (3 MW) capacity) to make (36 MW) wind farm, all units started at the same time | 56 |
| (4.31) | simulation of (12 wind turbines of (3 MW) capacity) to make (36 MW) wind farm, each (4 units) started after (5 s) in cascade style | 57 |
| (4.32) | LVRT of (36 MW) wind farm with (35 MVA) rating of STATCOM | 58 |

LIST OF ABBREVIATIONS

| ABBREVIATION | CLARIFICATION |
|-------------------------------|---|
| FSWT | fixed speed wind turbine |
| SCIG | squirrel cage induction generator |
| WRIG | the wound rotor induction generator |
| HAWT | horizontal-axis wind turbine |
| VAWT | vertical-axis wind turbines |
| <i>P</i>_{ref} | reference of active power |
| <i>Q</i>_{ref} | reference of reactive power |
| WRSG | The wound rotor synchronous generator |
| PMSG | rhe permanent magnet synchronous generator |
| FS-FP | fixed-speed fixed-pitch |
| FS-VP | fixed-speed variable-pitch |
| VS-FP | variable-speed fixed-pitch |
| VS-VP | variable-speed variable-pitch |
| WECS | wind energy conversion system |
| SVC | static Var Compensator |
| STATCOM | static synchronous compensator |
| MPP | maximum power point |
| FACTS | flexible AC Transmission Systems |
| PCC | common coupling point |
| C.B | circuit breaker |
| P (MW) | active power at the terminals of wind turbine or Bus B ₅₇₅ |
| Q (MW) | reactive power at the terminals of wind turbine or Bus B ₅₇₅ |
| V | voltage of the wind turbine at bus B ₅₇₅ |
| V , B 25 | voltage at PCC point or bus B ₂₅ |
| I | current of the wind turbine at bus B ₅₇₅ |
| I, B 25 | current PCC point or bus B ₂₅ |
| PF | power factor at bus B 25 |
| P (MW) , B 25 | active power at PCC point or bus B ₂₅ |
| Q (MW), B 25 | reactive power at PCC point or bus B ₂₅ |

LIST OF NOMENCLATURES

| SYMBOL | DESCRIPTION |
|-----------------|---|
| ρ | Air density (approximately 1.225 kgm^{-3}) |
| \bar{V} | Upwind free mean wind speed in m/s |
| A | swept area of rotor blades in m^2 |
| C_p | Power coefficient (the reduction factor of power transferred from wind to the wind turbine rotor) |
| λ | The tip speed ratio (the ratio of the tangential speed at the blade tip to the actual wind speed) |
| l | length of the blade |
| r | radius of the hub |
| ω | angular speed of wind turbine blades |
| P_m | mechanical power of the wind turbine |
| ω_m | mechanical speed of the generator inside wind turbine |
| β | Pitch angle of blade of the wind turbine |
| λ_i | Initial value of tip speed ratio when $\beta = 0 \text{ deg}$. |
| n_{rotor} | The wind turbine speed that depends on generator speed and gearbox transmission ratio |
| $n_{generator}$ | The generator speed that depends on the number of pole and frequency of the grid |
| R | gearbox transmission ratio |
| p | Number of poles pair of the wind turbine generator |
| f | Rated frequency of the grid in Hz |
| P | Active power in MW |
| Q | Reactive power in MVAR |
| V_1 | Voltage at transmission line |
| V_2 | Voltage at STATCOM converter |
| δ | the phase difference between V_1 & V_2 |
| x | Reactance between V_1 & V_2 |

INTRODUCTION

1.1 OVERVIEW

During the present energy crisis, renewable energy sources have emerged as the most preferable alternatives for generating electric power. Presently, wind energy is the most developed of the renewable technologies due to the massive number of wind turbines that installed around the world, as well as many projects currently in progress. Wind energy technology has made major progression since the generation of wind turbines from the early 1980s with a few tens of kilowatts power rating wind turbines to today's megawatt capacity of wind turbines.

The wind power sector includes some of the world's largest energy companies and the top 10 of them are as sorted by megawatts installed worldwide: (Vestas, GE Wind Energy, Gamesa, Enercon, Suzlon, Siemens, Acciona, Goldwind, Nodex and Sinovel) [1]. Currently, five countries (China, USA, Germany, Spain and India) occupy more than 74 % of worldwide wind energy Cumulative capacity [2]. Here, it is also found most of the expertise related to wind energy generation and its integration into the power system in those countries and the utilization of this renewable source of power is fast spreading to other areas of the world.

According to the fact that the wind power source is free and clean is, of course, economically and environmentally significant but the more important and essential point at issue is that the cost of the electricity is fixed, once that plant has been built and also this cost may reduce with the developments of used technologies [3]. In the earlier time wind power production did not have any serious effects on the power system operation and control, but now it plays an active role in the grid because of the wind power penetration level is increasing rapidly with the different used technologies. The issues that related with the integration of wind farms to the power system are not only related with its fixed electricity cost but also with the grid stability. In the past, wind turbines were disconnected during faults on the grids, but this led to dynamic instability and blackouts. A new requirement is that the wind turbines remain connected with the grid, ride through the problems, without disconnection from the grid through built-in capacity for active grid support [4].

Practically, this means that wind turbines must behave as conventional thermal and nuclear power plants. Nowadays most of the studies are concerned with the study of the improvements of operation and performance of the different technologies of the wind turbines because in the next future wind energy will occupy a big size of electric energy production for many countries around the world.

1.2 INSTALLED CAPACITIES AND SIZES OF WIND TURBINES

1.2.1 Installed Capacity and Growth Rate

Installed wind power capacity has been progress gradually growing over the last two decades. Figure (1.1) shows the evolution of installed capacity worldwide as of 2011 [2]. The installed capacity of global wind power has increased exponentially from approximately 6 GW in 1996 to 238 GW in 2011.

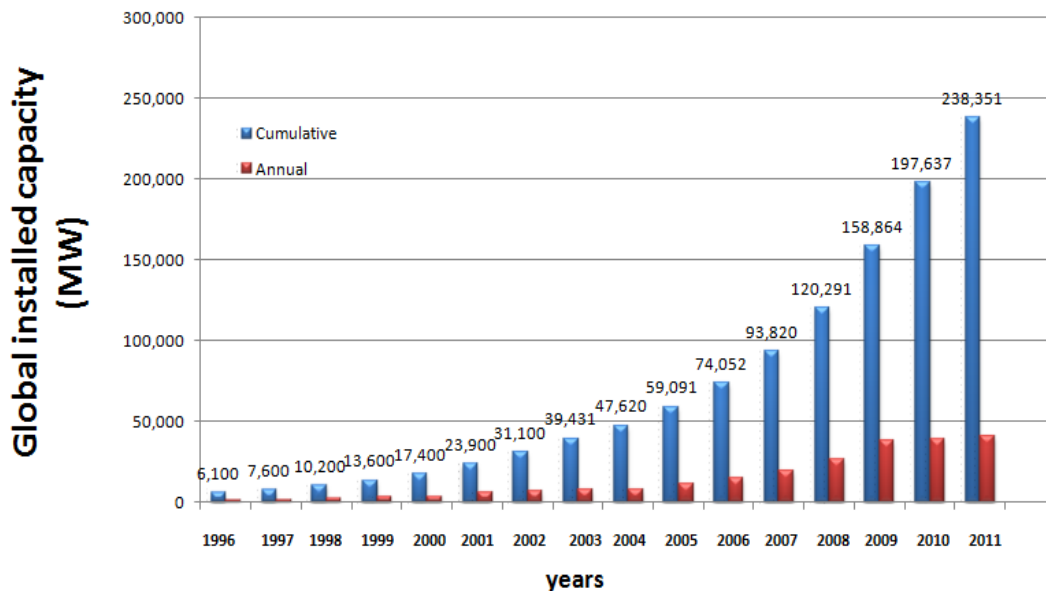


Figure (1.1): Global annual and cumulative installed wind power capacity

The value of world wind Generating capacity of power had become more than a quadrate number between 2000 and 2006 in the form of doubling the number every two years. China has been rapidly expanding its wind installations the late 2000s and passed the U.S. in 2010 to become the world leader. Germany held the top spot in Europe in terms of installed capacity, with a total of 29,060 MW as of 31 December 2011. Figure (1.2) shows the cumulative installed wind power capacity of the top ten countries in the world as of December 2011, where the total top 10 countries cumulative installed capacity is 205,905 MW i.e. 86.4% and the total countries in the world is 238,905 MW.

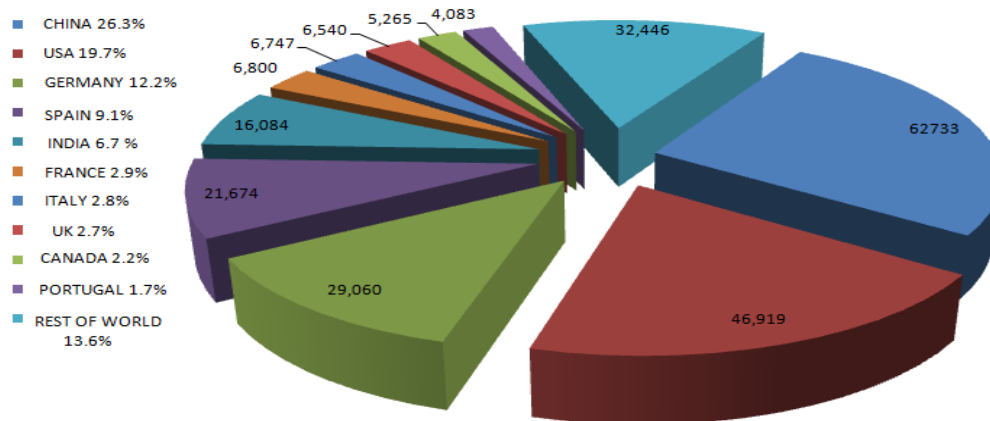


Figure (1.2): Top 10 Cumulative Capacity December 2011

1.2.2 Small and Large Wind turbines

Wind turbines range from a few kilowatts for residential or commercial use to several megawatts in large wind farms. Small-to-medium-size wind turbines are normally below 300 kW, and can be installed at homes, farms, and businesses to offset the consumption of utility power. Table (1.1) illustrates typical wind turbine ratings according to their application.

| Small (≤ 10 KW) | Intermediate (10 – 500 KW) | Large (500 – 5 MW) |
|--|----------------------------|---------------------------------------|
| Homes (grid connected) | Village power | Wind power plants |
| Farms | Hybrid systems | Distributed power |
| Autonomous remote applications (e.g. battery charging , water pumping , telecom sites) | Distributed power | Onshore and off shore wind generation |

Table (1.1): Wind turbine ratings and applications [5]

1.2.3 Sizes of Wind turbines

The evolution in turbine size can be clearly appreciated in figure (1.3) starting with a 50 kW power rating and a 15 m rotor radius in the early 1980s, wind turbines can be found today up to 7.5 MW with a rotor diameter of 126 m is made by (Enercon) company. It is expected that a 10 MW wind turbine will be developed in the future

with a turbine rotor diameter of 16 m, which is approximately twice the length of an Airbus A 380 airplane [6].

Larger wind turbines often result in reduced cost since their production, installation, and maintenance costs are lower than the sum of smaller wind turbines achieving the same power output.

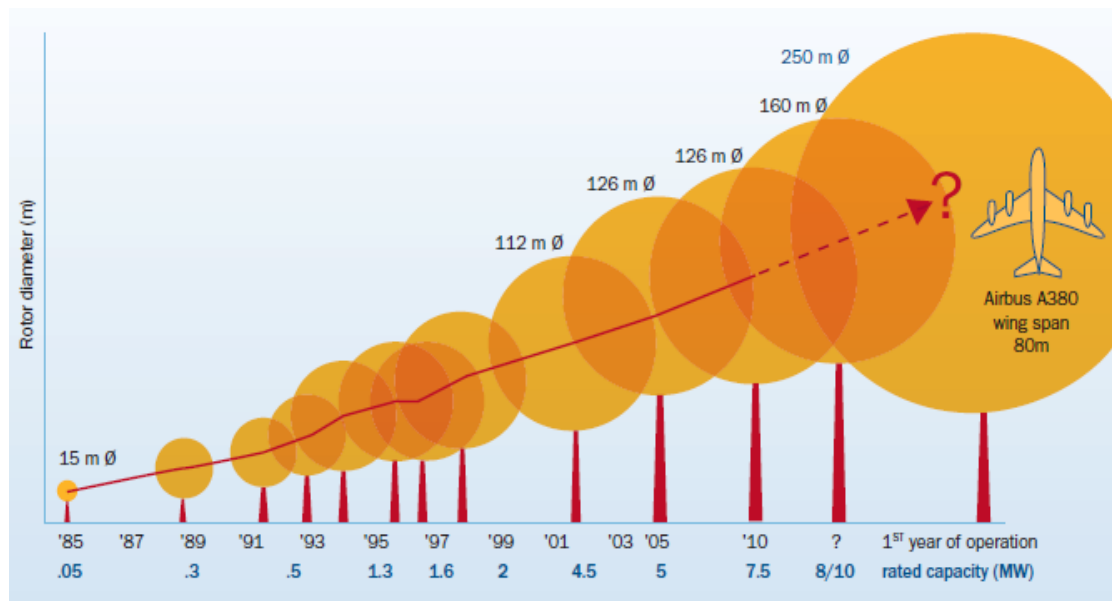


Figure (1.3): Evolution of wind turbine size (\varnothing = rotor diameter) [6]

1.3 LITERATURE REVIEW

L. Holdsworth, et al. (2003) [7] have discussed the dynamic modeling of large (MW) capacity fixed and variable speed induction generator wind turbines. A reduced order dynamic machine model is derived suitable for modeling fixed speed and doubly-fed asynchronous generator wind turbines, The operation of the models during power system disturbances such as network voltage sags and three-phase faults.

The work of Sigrid M. Bolik (2004) [8] presents the development of wind turbine technology. Several wind turbine types are discussed and the motivations for this project are stated. The main motivations are the challenges related to the grid connection of wind turbines. For the modeling the well known and widely used program Matlab/ Simulink has been chosen.

The Investigations by V. Salehi, et al. (2006) [9] of the impact of large wind farms on power system voltage stability, where one of the Iran's wind farms is

modeled in DIgSILENT software and the simulation results shows the effect of using FACTS devices including SVC and STATCOM on power system performance.

The study of increasing wind farm size that was done by N. Dinic, et.al (2006) [10] As the Wind-farm size is defined in terms of its rating relative to system fault level at the wind farm terminals. The voltage rise for a wind farm whose capacity is 20% of system fault rating is determined for various utility network reactance-to-resistance ratios (X/R). The focus is on a network with an X/R ratio of unity, typical of 33kV networks in the UK.

Kuperman and R. Rabinovici (2007) [11]. The output power and mechanical torque of a wind turbine driven induction generator, connected to a distributed system, change with the rotation speed. Simulation results are presented to prove the correctness of the mentioned assumptions.

In the paper of S.S. Murthy et al. (2007)[12], a comparative study of fixed and variable speed wind turbines incorporating squirrel cage induction generator take into consideration all realistic constraints has been presented. These two systems are modeled and simulated using Matlab. The variable speed induction generator system has been modeled using power electronic converters and vector control technology combined with peak power extraction technique (PPET).

The effect of electrical parameters that discussed by L. Dusonchet, et al. (2008) [13] of the induction generator on the transient voltage stability of a fixed speed wind turbine (FSWT) connected to a simple grid. The model of the FSWT has been developed in the simulation tool Simulink and described in.

The study of using a Static Synchronous Compensator (STATCOM) by Jayam, A.P., Chowdhury (2009) [14] near a wind farm to investigate the purpose of stabilizing the grid voltage after grid-side disturbance such as a three phase short circuit fault. The strategy focuses on a fundamental grid operational requirement to maintain proper voltages at the point of common coupling by regulating the voltage.

Researchers (A.D. Hansen, N. A. Cutululis, P. Sørensen, & F. Iov, 2009) [15] presents an overall perspective on contemporary issues like wind power plants and grid integration. Generally, this paper presents all these challenges involved and some possible solutions, with focus on power system and wind turbine technology development.

D. Dragomir et al. (2009) [16] present the technical requirements related to the connection of the wind power plants to the main grid. Grid connected wind turbines

may cause power quality problems, such as voltage variation and flicker, and therefore, the connection of wind farms requires new connecting rules to avoid negative effects on the existing electrical system. System operators usually issue these rules in the form of grid codes.

Researchers (Tohidi, S., Rabiee A., & Parniani M., 2010) [17] described modeling and small signal analysis of a grid connected fixed speed wind turbine generator FSWTG. A complete model of FSWTG is derived and some reduced-order models are deduced. The models are compared and the simplifying assumptions which have been considered in the literatures are evaluated.

H. J. Su, H. Y. Huang, & G. W. Chang, (2010) [18] found that the Voltage fluctuation produced by wind turbines are usually due to wind speed variations, power and voltage fluctuations. This paper presents simulations for numerical models of two wind turbine schemes, fixed and variable speed types, by using Matlab/Simulink.

In (2010) M. Jahangir et.al [19] presented the low-voltage ride-through (LVRT) capability of wind farms with fixed-speed induction generators in their paper. The nonlinear dynamics of the wind generator is represented as a linear system and a norm-bounded nonlinear uncertain term, derived from the Cauchy remainder of the Taylor series.

Omar Noureldeen, et.al (2011) [20], the investigation of the impact of the fault ride through on the stability of fixed speed wind farm interconnected grid. The effect of fault location and its duration time are studied for different fault types. The contribution of Static Synchronous Compensator STATCOM to support the fixed-speed wind farm interconnected electric grid during different fault locations and different fault duration times are investigated. Simulation test cases using MATLAB-Simulink are implemented on a 9 MW wind farm exports a power to 120 KV grid.

The search that was done by Omar Noureldeen (2011) [21] to analyzes the extent to which the LVRT capability of wind farms using squirrel cage generators can be enhanced by the use of a Static Synchronous Compensator STATCOM. The ability of wind farms to stay connected to grid during LVRT is investigated based on E-ONNETZ grid code. A simulation model of 9 MW wind farm interconnected grid is carried out using the MATLAB Sim.Power.Systems toolbox.

Researchers (Sanja Vitanova, Vlatko Stoilkov, and Vladimir Dimcev, 2011) [22] have made an overall observation of the most commonly used electrical machines, i.e. the squirrel cage induction generators (SCIG) and doubly fed induction

generators (DFIG) in the wind generation systems. Using the Matlab/Simulink, a simulation of wind farm with the two types of generators has been made in order to compare the results and to comment on the best option based on the output characteristics of the generator and wind turbine.

1.4 OBJECTIVES OF THE PRESENT WORK

The fixed speed wind turbine that using squirrel cage induction generator needs more studies about its performance when it is directly connected to the grid in single and multiple connections to discuss the issues that accompany its normal operation to get better performance of it, therefore the objectives of this work are to study the performance of the fixed speed SCIG wind turbine through the different changes in wind speeds, determination of its power curve, effects of transient switching, changing in grid voltage amplitude like (sag, swell and interruption), and to study the effects of all faults types and its impacts on the wind turbine operation with the capability of its ride through these faults and voltage dips without disconnection from the grid through the proper reactive power compensation in single and multiple connections of the wind turbines to the PCC point (common coupling point) and with a view of the effect of disconnection the wind turbine and then resume it by resetting the protection system.

1.5 ORGANIZATION OF THE THESIS

This thesis has been organized in five chapters where, chapter 1 includes an overview, installed capacities and growth rate and sizes of wind turbines, work that has been done by various researchers' Authorship and their contributions and a synopsis of this thesis. Chapter 2 gives an introduction to various WECS (wind energy conversion system) by giving some characteristics about wind energy, different technologies of extracting electric power from the wind and components of a wind turbine and speed control methods. Chapter 3 gives an introduction of performance of fixed speed wind turbine using SCIG and its operation principle with determination of the power curve of a (3 MW) wind turbine and giving a scope of effects of integration fixed speed wind turbines to the power system grid and at the last of this chapter there is a flowchart of studying the performance and issues of fixed speed wind turbines that using SCIG. Chapter 4 shows results and discussion in details of the performance of fixed speed wind turbine and study different effects of wind speed at starting and wind gust, effect of re-switching transient, changes of voltage at grid side, reactive

power compensation, performance during faults and LVRT, disconnection and re-connection of wind turbine to the grid, and way of connection of multiple wind turbines and their operation as a single wind farm. Chapter 5 is summarized conclusions of the studies of chapter 4 and it also includes a scope of future work.

WIND ENERGY CONVERSION SYSTEMS

2.1 INTRODUCTION

The Wind results from the movement of air due to atmospheric pressure gradients, and flows from regions of higher pressure to regions of lower pressure. The larger the atmospheric pressure gradient, the higher the wind speed and thus, the greater the wind power that can be captured from the wind by wind energy-converting machinery. Wind turbines are used to convert wind energy to electricity. The first automatically operated wind turbine in the world was designed and built by Charles F. Brush in 1887 – 1888, in Cleveland, Ohio. This wind turbine was equipped with 144 cedar blades having a rotating diameter of 17 m. It generated a peak power of 12 kW to charge batteries that supply DC current for lamps and electric motors. An invention design for modern wind turbines was the Gedser wind turbine that was built in Denmark in 1957 and was unveiled by Johannes Juul [23]. Today, modern wind turbines in wind farms have typically three blades, operating at relative high wind speeds for the power output up to several megawatts.

2.2 WIND ENERGY CHARACTERISTICS

Wind energy is a special form of kinetic energy in air as it flows. Wind energy can be converted into electrical energy by power converting machines. The wind turbine extracts kinetic energy from the swept area of the blades, figure (2.1). The power in the air flow is given by [5]:

$$P_{\text{air}} = \frac{1}{2} \rho A \bar{v}^3 \quad (2.1)$$

Where

ρ =air density (approximately 1.225 kgm^{-3})

A= swept area of rotor, m^2

\bar{v} = Upwind free mean wind speed, m/s

The power available in the wind the power transferred to the wind turbine rotor is reduced by the power coefficient, C_p :

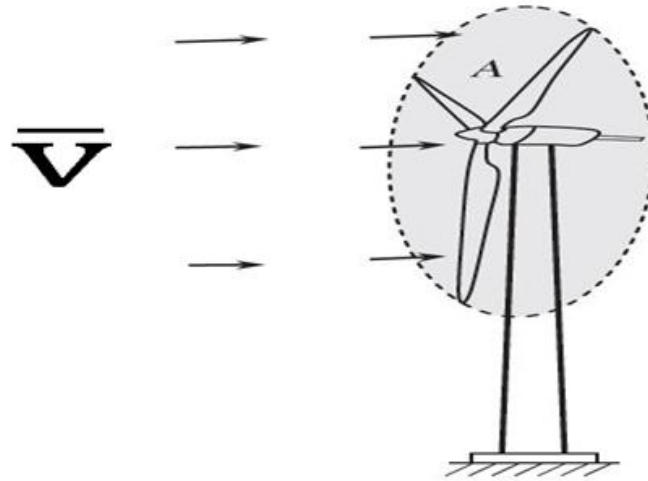


Figure (2.1): Swept area of wind turbine blades [26]

$$C_p = \frac{P_{\text{mechanical of wind turbine}}}{P_{\text{air}}} \quad (2.1)$$

The maximum value of C_p is called Betz limit. The theoretical maximum efficiency of an ideal wind turbine was derived by Lanchester in 1915 and Betz in 1920 [25]. It was indicated that (no wind turbo machines could convert more than 16/27 (59.26 %) of the kinetic energy of wind into mechanical energy). This is known as Lanchester–Betz limit (or Lanchester–Betz law).

Then

$$P_{\text{mechanical of wind turbine}} = C_p P_{\text{air}} = \frac{1}{2} \rho A \bar{V}^3 \quad (2.3)$$

An examination of equation (2.2), it reveals that in order to obtain a higher wind power, it requires a higher wind speed, a longer length of blades for getting a larger swept area, and a higher air density. Because the wind power output is proportional to the cubic power of the wind speed, a small variation in wind speed can result in a large change in wind power.

2.2.1 Tip speed ratio, λ

The tip speed ratio is an extremely important factor in wind turbine design, which is defined as the ratio of the tangential speed at the blade tip to the actual wind speed, i.e. [26]:

$$\lambda = \frac{(l+r) \omega}{\bar{v}} \quad (2.4)$$

Where l is the length of the blade, r is the radius of the hub, and ω is the angular speed of blades. If the blade angular speed ω is too small, most of the wind may pass undisturbed though the blade swept area making little useful work on the blades. On the contrary, if ω is too large, the fast rotating blades may block the wind flow and reducing the power extraction from the wind.

The tip-speed ratio, λ and the power coefficient C_p are dimensionless and so can be used to describe the performance of any size of wind turbine rotor [5]. Figure (2.2) shows that the maximum power coefficient is only achieved at a single tip-speed ratio and for a fixed rotational speed of the wind turbine this only occurs at a single wind speed. Hence, only one reason for operating a wind turbine at variable rotational speeds is that it is possible to operate at maximum C_p over a range of wind speeds.

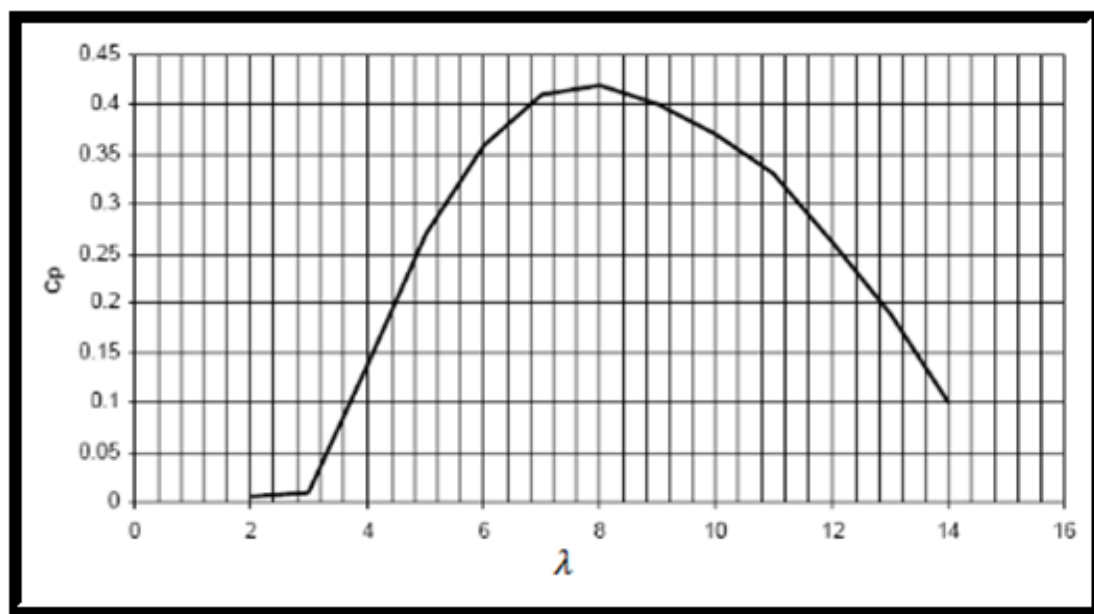


Figure (2.2) Illustration of power coefficient /speed ratio curve, C_p / λ [4]

2.3 POWER CURVE

The power curve of a wind turbine displays the power output in KW or MW ranges of the wind turbine as a function of the wind speeds in m/s. As shown in figure (2.3), the wind turbine starts to produce usable power at a low wind speed, defined as the cut-in

speed. The power output increases continuously with the increase of the wind speed until reaching a saturated point, to which the power output reaches its value that defined as the rated power output. The speed at this point is defined as the rated speed. At the rated speed, more increase in the wind speed will not increase the power output due to the activation of the power control. The last value of wind speed is called cut-out wind speed which is that maximum value of allowed value of wind speed for the normal operation of the wind turbine, more than it the turbine is stopped.

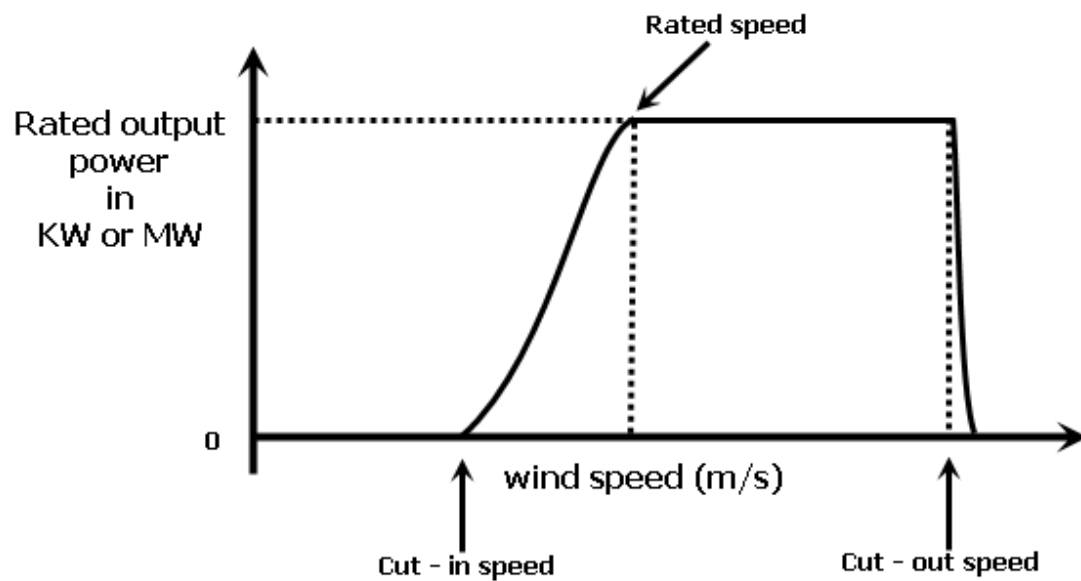


Figure (2.3): Typical wind turbine power curve

2.4 WIND TURBINE TECHNOLOGIES

2.4.1 Horizontal - and - Vertical - Axis Wind Turbines

Wind turbines can be categorized based on the direction of their spin axis into horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT), as shown in Figure (2.4) [27].

Most commercial wind turbines today belong to the horizontal-axis (HAWT) type, in which the rotating axis of blades is parallel to the wind stream. The advantages of this type of wind turbines include the high turbine efficiency, high power density, low-cut-in wind speeds, and low cost per unit power output.

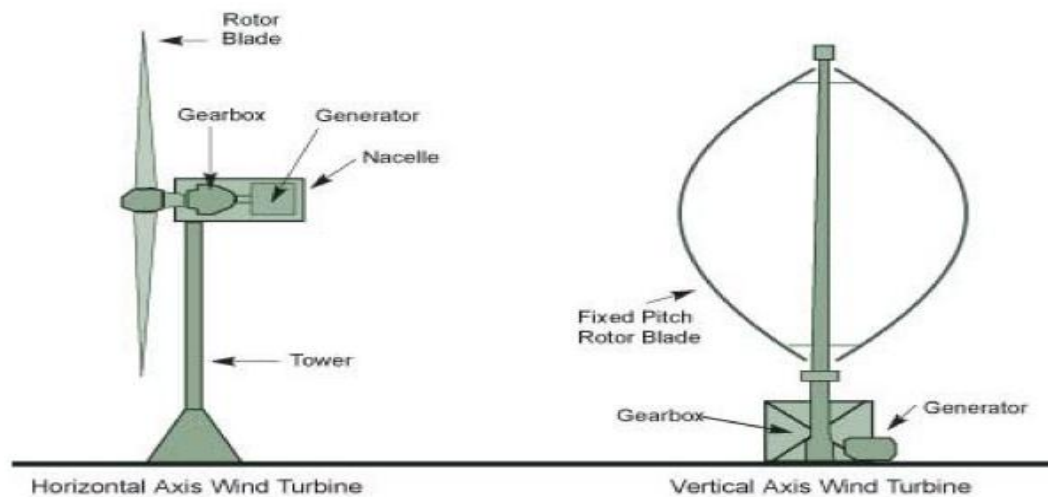


Figure (2.4) Horizontal and vertical wind turbines [27]

For the typical vertical-axis wind turbines (VAWTs), the blades of the vertical-axis wind turbines rotate with respect to their vertical axes that are perpendicular to the ground. A significant advantage of vertical-axis wind turbine is that the turbine can accept wind from any direction and thus no yaw control is needed. But the (VAWTs) must use an external energy source to rotate the blades during initialization. Because the axis of the wind turbine is supported only on one end at the ground, so its maximum practical height is limited.

2.4.2 Fixed and Variable Speed Wind Turbines

As the wind turbine contain an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and a generator. The fixed speed wind turbine is the type of wind turbines that its generator which is of asynchronous type generates electricity at a fixed rotational speed at different range of wind speeds. This type of wind turbines is directly connected to the grid through a transformer. The allowed range of change of rotational speed of the turbine's generator should not exceed (1-2 %).

Whereas in case of the variable speed wind turbine, the rotational speed of the turbine's generator which is of synchronous or asynchronous type is variable and the generator is allowed to generate electricity at different rotational speeds. The turbine is indirectly connected to the grid through power converters.

2.4.2.1 Generators systems for fixed and variable speed wind Turbine

The characteristic of fixed-speed wind turbines that they are equipped with an induction generator (squirrel cage or wound rotor) that is directly connected to the

grid, with a soft-starter and a capacitor bank for reducing reactive power compensation, as shown in figure (2.5.A).

The wound rotor induction generator with a variable resistor in series with the rotor circuit controlled by a high-frequency semiconductor switch as shown in Figure (2.5.B). Below rated wind speed and power, this acts just like a conventional fixed-speed induction generator. Above rated, however, control of the resistance effectively allows the air-gap torque to be controlled and the slip speed to vary, so that behavior is then similar to that of a variable-speed system. The speed control range is up to (10 %).

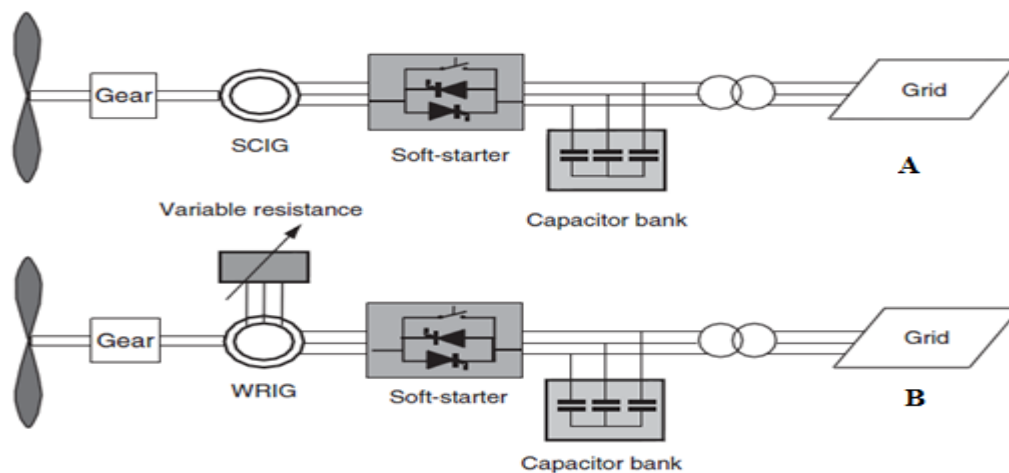


Figure (2.5): Generators systems for fixed speed wind Turbines [28]

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. The electrical system of a variable-speed wind turbine is more complicated than that of a fixed-speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter.

A doubly fed induction generator (DFIG) using a medium scale power converter is shown in Figure (2.6.A). Slip rings are making the electrical connection to the rotor. If the generator is running super-synchronously, electrical power is delivered to the grid through both the rotor and the stator. If the generator is running sub-synchronously, electrical power is delivered into the rotor from the grid. A speed variation of $\pm 30\%$ around synchronous speed can be obtained by the use of a power converter of 30% of nominal power. Furthermore, it is possible to control both active (P_{ref}) and reactive power (Q_{ref}), which gives a better grid performance [28].

The synchronous generator is much more expensive and mechanically more complicated than an induction generator of a similar size. However, it has one clear advantage compared with the induction generator, namely, that it does not need a reactive magnetizing current, as shown in figure (2.6. B, C). Two classical types of synchronous generators have often been used in the wind turbine industry:

- The wound rotor synchronous generator (WRSG)
- The permanent magnet synchronous generator (PMSG)

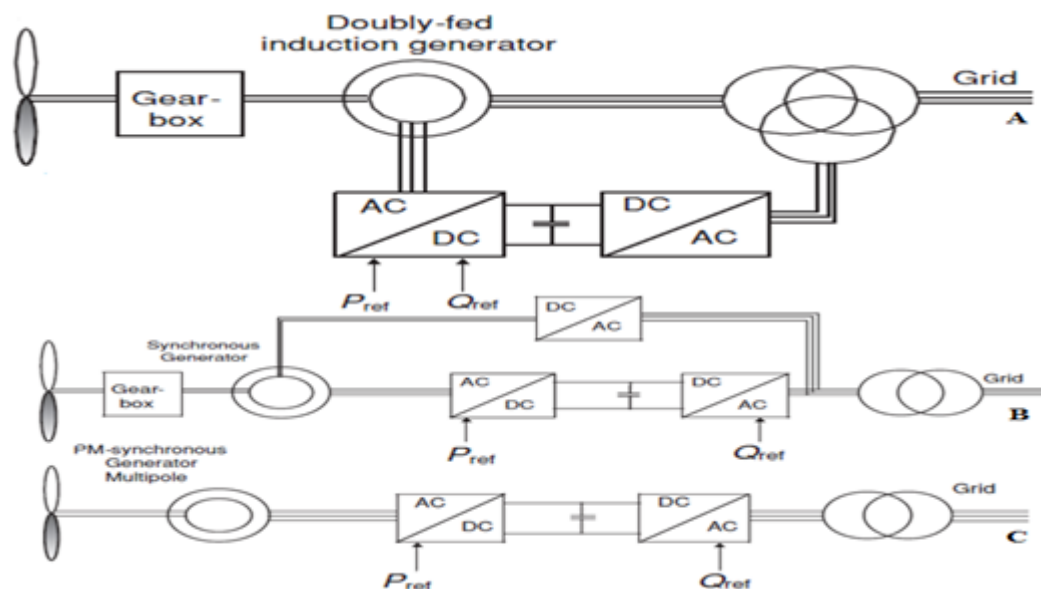


Figure (2.6): Generators systems for variable speed wind Turbines [28]

2.5 WIND TURBINE COMPONENTS

One of the first commercial wind turbines to generate electricity and feed it into the grid was the VESTAS V-15 with a rated power of 55 KW, as shown in figure (2.7). In the beginning of the 1980s, it was manufactured and installed in large numbers. It already had all essential components of grid-connected wind turbines [29]:

- Rotor: rotor blades, aerodynamic brake and hub
- Drive train: rotor shaft, bearings, brake, gearbox and generator
- Electrical components for control and grid connection.
- Yaw system between nacelle and tower: yaw bearing and yaw drive
- Supporting structure: tower and basis

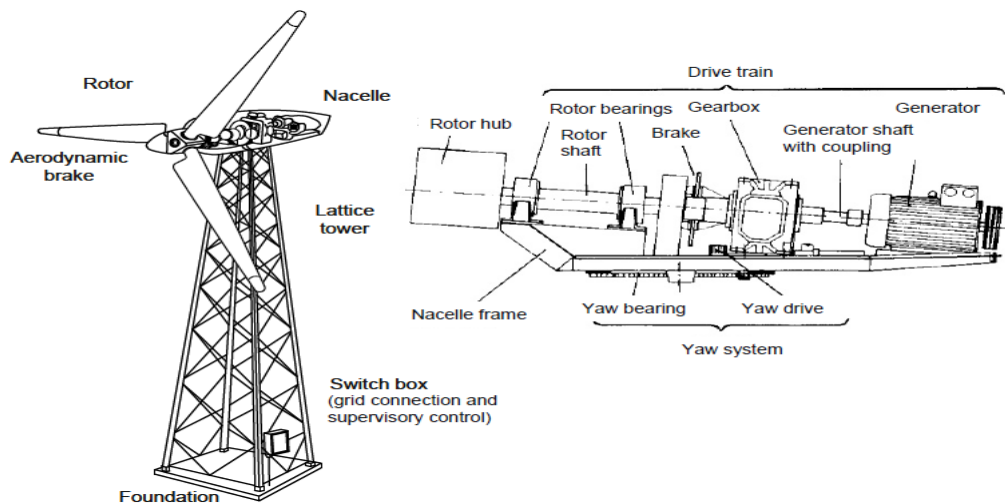


Figure (2.7) VESTAS V15, general view and nacelle section [29]

For 30 years in the working life of the wind turbines, the components of any typical horizontal type wind turbine that is shown in figure (2.7) did not change. The changes that was happened only in the size and rating of the generator, height of the tower, with or without Gearbox, and long of the blades.

2.6 SPEED CONTROL OF WIND TURBINES

There can be use of different control methods to either optimize or limit power output. The control of a wind turbines speed by controlling the generator speed by blade angle adjustment and rotation of the entire wind turbine. Blade angle adjustment and turbine nacelle rotation are also known as pitch and yaw control, respectively. The representation of pitch and yaw adjustment is shown in Figure (2.8).

The purpose of pitch angle control of the blades is to maintain the optimum blade angle to achieve certain rotor speeds or power output, i.e. a method of getting the maximum power at wind speeds more than rated value.

Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor swept area (A) and as a result, the output power. Because of wind direction can vary quickly, the turbine may miss Aligning with the oncoming wind and cause losses in power output.

2.6.1 Control Strategies [30]:

The following control strategies use pitch and generator speed control to manage turbine's mechanism throughout the power these types of control are fixed-

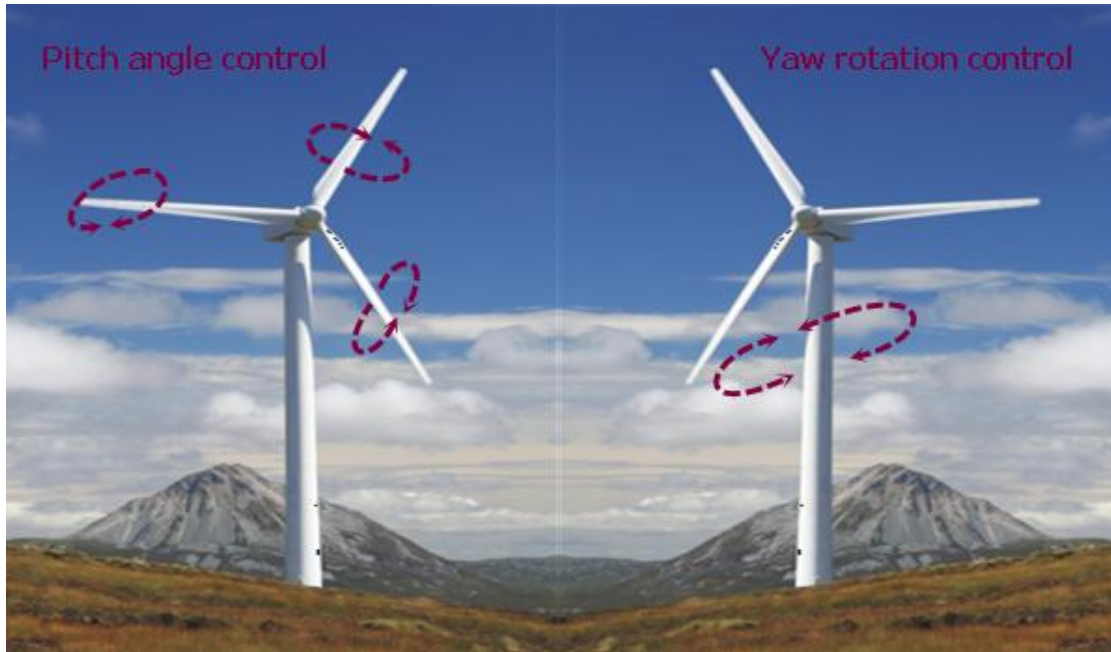


Figure (2.8): speed control methods of wind turbines

speed fixed-pitch, fixed-speed variable-pitch, variable-speed fixed-pitch, and variable-speed variable-pitch

Fixed-speed fixed-pitch (FS-FP):

In this design, the turbine's generator is directly coupled to the power grid, causing the generator speed to lock to the power line frequency and fix the rotational speed. The gearbox ratio selection is important for this passive control because it ensures that the rated power and wind speed are not exceeded.

Fixed-speed variable-pitch (FS-VP):

To explain fixed-speed operation implies a maximum output power at one wind speed. It can use both blade and stall pitch control methods in this configuration to limit power. Below the rated wind speed, the FS-VP turbine has a near optimum efficiency around Region II. Exceeding the rated wind speed, the pitch angles are continuously changed.

Variable-speed fixed-pitch (VS-FP):

This type of control assumes that the generator is indirect connected to the grid so that the generator's rotor and drive-train are free to rotate independently of grid frequency. Fixed-pitch relies heavily on the blade design to limit power through passive stalling.

Variable-speed variable-pitch (VS-VP):

Operating below the rated wind speed, variable speed and fixed pitch are used to maximize energy capture and increase power quality. Operating above the rated wind speed, fixed speed and variable pitch permit efficient power regulation at the rated power and wind speed.

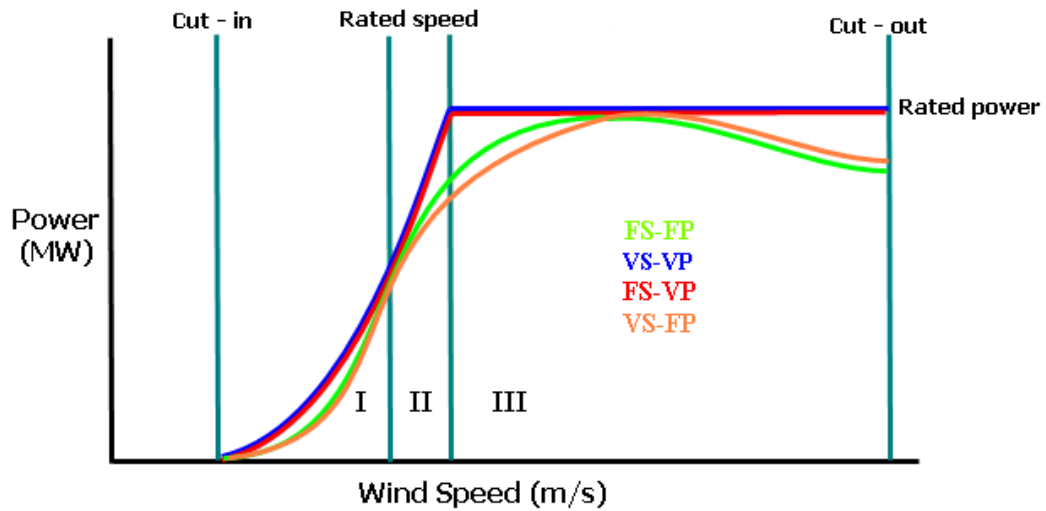


Figure (2.9): Power Curves for Different speed Control methods

PERFORMANCE OF FIXED SPEED WIND TURBINE

3.1 INTRODUCTION

One of the earliest wind turbine systems adopted by the industry and the simplest in its structure and control is the fixed-speed wind energy conversion systems WECS. Its simplicity and low costs compared to the variable-speed wind turbines made this configuration popular during the early years of the wind energy industry, particularly during the 1990s. This configuration is also known as the Danish concept since it was initially developed and successfully marketed by Danish companies [24].

In the fixed-speed WECS, a squirrel-cage induction generator SCIG is normally used, some of them are using wound rotor Induction generator WRIG. For SCIG, the generator's shaft is driven by the wind turbine and its stator is directly connected to the grid. Under normal operating conditions, the stator frequency is fixed to that of the grid and the speed change range is very low (1-2% for megawatt generators). The power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding. The pitch angle is controlled in order to limit the generator output power to its nominal value for high wind speeds. In order to generate power the induction generator speed must be slightly above the synchronous speed. But the speed variation is typically as small as mentioned above therefore, the wind turbine using SCIG is considered to be a fixed-speed wind generator, as shown in figure (3.1).

The reactive power which is absorbed by the induction generator is provided by the grid or by some devices like capacitor banks, SVC, or STATCOM and for smoother grid connection is also achieved by connection a soft-starter.

The well-known advantages of SCIG are it is robust, easy and relatively cheap for mass production. Some manufacturers, such as Micon (currently merged into Vestas), Bonus (currently Siemens), Made and Nordex, have products based on this concept.

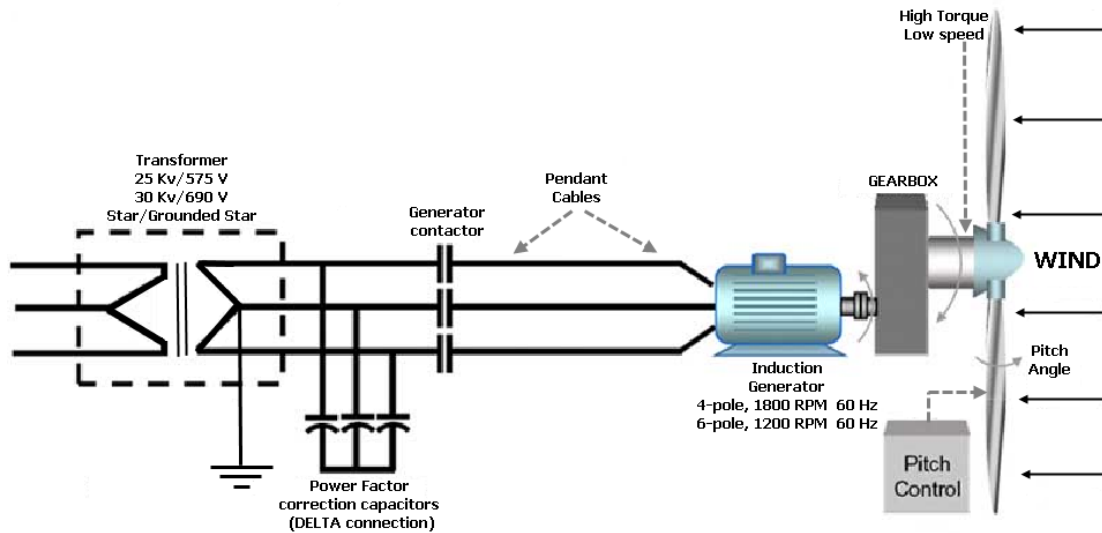


Figure (3.1): Configuration of fixed-speed SCIG wind energy conversion system

3.2 OPERATION PRINCIPLE OF FIXED SPEED WIND TURBINE USING SCIG

A typical wind turbine characteristic with the maximum power extraction speed curve plotted to intersect the C_p points for each wind speed is illustrated in figure (3.2)

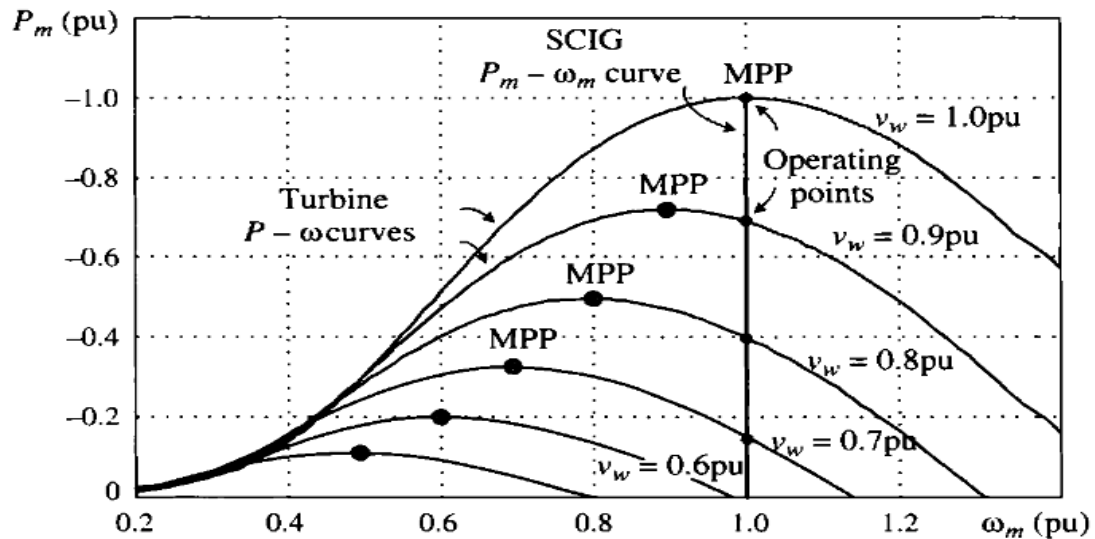


Figure (3.2): System operating points and maximum power points (MPP) at different wind speeds [31]

where, Y-axis represents the mechanical power of the wind turbine that is extracted from the wind power and X-axis represents the mechanical speed of the generator and

both of them are in per unit. Each wind turbine has a $P_m - \omega_m$ curve corresponds to a specific wind speed. Theoretically, the number of such curves is infinite, but only a few curves are plotted in figure (3.2) for analysis [31].

For a given wind speed, there is a corresponding maximum power point MPP on the turbine $P_m - \omega_m$ curve. For the fixed-speed WECS, the system can operate only at one MPP, which is at the rated wind speed of 1.0 pu in the example of figure (3.2). At the other wind speeds, the system operates at the points that are lower than MPP and, therefore, cannot capture the maximum power available from the wind, leading to lower power-conversion efficiency. Furthermore when the rotation speed increases above the value resulting in maximum output power at particular wind speed, the turbine output power reduces drastically [11]. Because of the operation range of wind speeds is very low, so to take the advantage from the more values of wind speed by fixing the mechanical power of the wind turbine at its rated value but up to some specific value of wind speed that make the wind turbine should not be exposed to a mechanical stress in case of high wind speeds. In this point a speed control methods should take place either by stall or pitch control of the wind turbines blades.

3.2.1 Pitch control of fixed speed wind turbine

By return to section 2.2.1, since the tip-speed ratio λ , and the power coefficient C_p are dimensionless and can be used to describe the performance of any size of wind turbine rotor. The power coefficient C_p is calculated using the strip theory for a certain rotor speed/wind speed ratio, i.e. a given tip speed ratio. Repeating this for a number of tip speed ratios yields the variation of the power coefficient with the tip speed ratio. This provides the rotor power coefficient for different wind speeds at a fixed rotor speed or for different rotor speeds at one wind speed. If the rotor is equipped with blade pitch control, the power coefficient curves must be calculated for every blade pitch angle β used in its operation. Figure (3.3) shows a power coefficient for different values of pitch angle and the maximum C_p is 0.48 at λ equals 8.1, the plotting code of the graph is available at Appendix B.

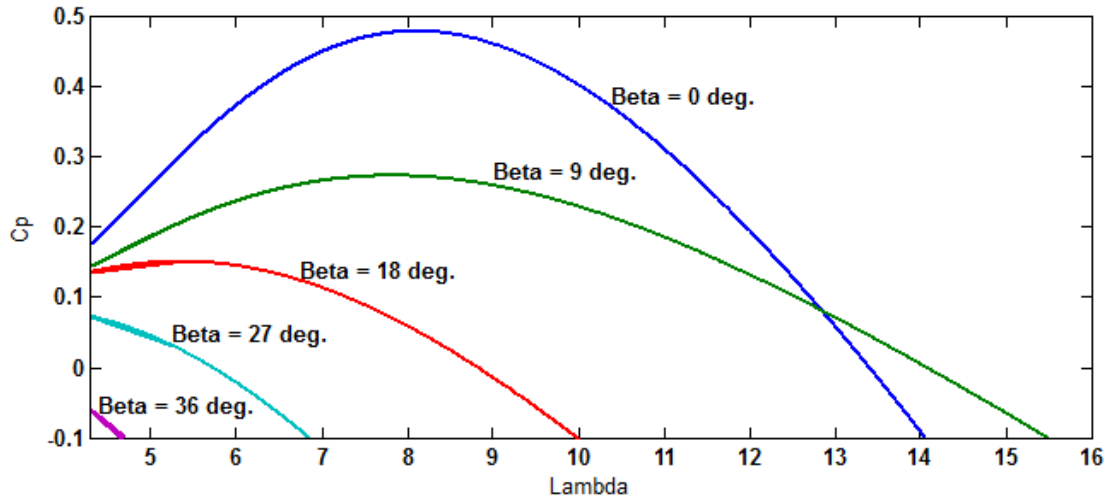


Figure (3.3): power coefficient versus tip speed ratio characteristics, for different values of the pitch angle

A generic equation is used to model $C_p(\lambda, \beta)$. This equation, based on the modeling turbine characteristics of [20], is:

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-0.0068}{\lambda_i}} + 0.0068\lambda \quad (3.1)$$

Where λ_i is given by:

$$\lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3.2)$$

This value of C_p is used to calculate the mechanical power of the wind turbine. In fact, when modeling the pitch control, it is very important to model the rate of change of this angle. The variation of the pitch should be limited. It is limited to about 10 degree/s during normal operation and 20 degree/s for emergencies. Regulation of the blade angle is modeled as shown in figure (3.4), by using PI controller. A Proportional-Integral (PI) controller is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value the PI controller increases the pitch angle to bring back the measured power to its nominal value, figure (3.5). The minimum value of β is zero and the higher operation value of it is 45 degree while the maximum value is 90 degree which is used for emergency stop and parking mode.

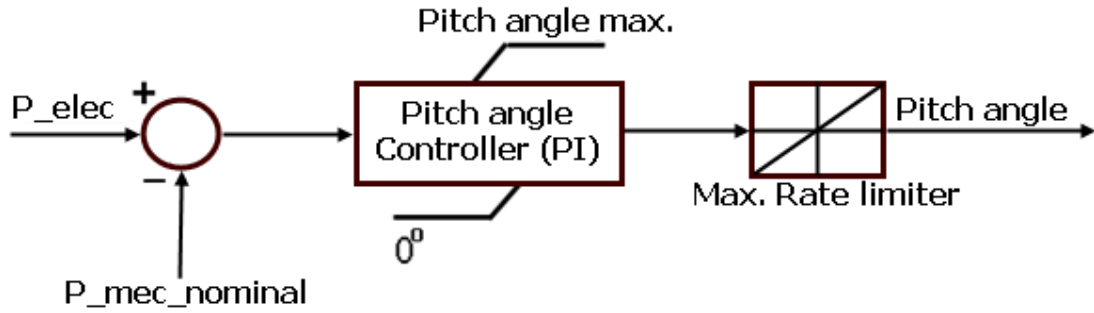


Figure (3.4): control system of pitch angle

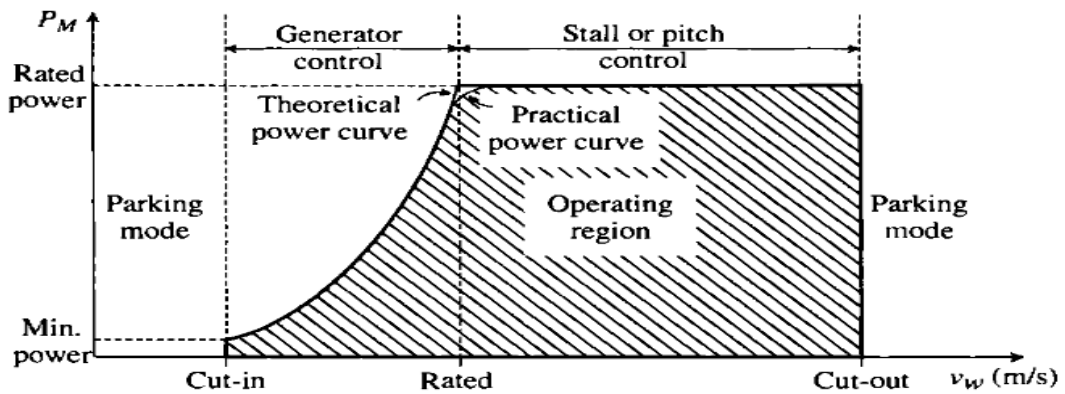


Figure (3.5): Qualitative turbine mechanical power versus wind speed curve [31]

3.3 DETERMINATION OF THE POWER CURVE OF A 3 MW FIXED SPEED S.C.I.G. WIND TURBINE

The data of the 3 MW fixed speed SCIG wind turbine is available in appendix - A and it is taken from [21]. To determine the power curve of a single wind turbine, there are three types of wind speeds should be known and these types are (cut-in wind speed, rated wind speed and cut-out wind speed). As the rated wind speed is known as 9 m/s that generates the nominal mechanical power at zero pitch angle β , as shown in figure (3.6), which is calculated by using equations (3.1) and (3.2). To know the value of cut-in wind speed, the wind turbine should be started at lower value of wind speed that can generate useful electricity and without a disconnection from the grid due to its protection system. The lower value of wind speed that can generate electricity is 5.6 m/s and the active power and the voltage are 50.28 KW and 0.9975 pu or 573.56 Volt respectively. Typical cut-out wind speeds is 25 m/s.

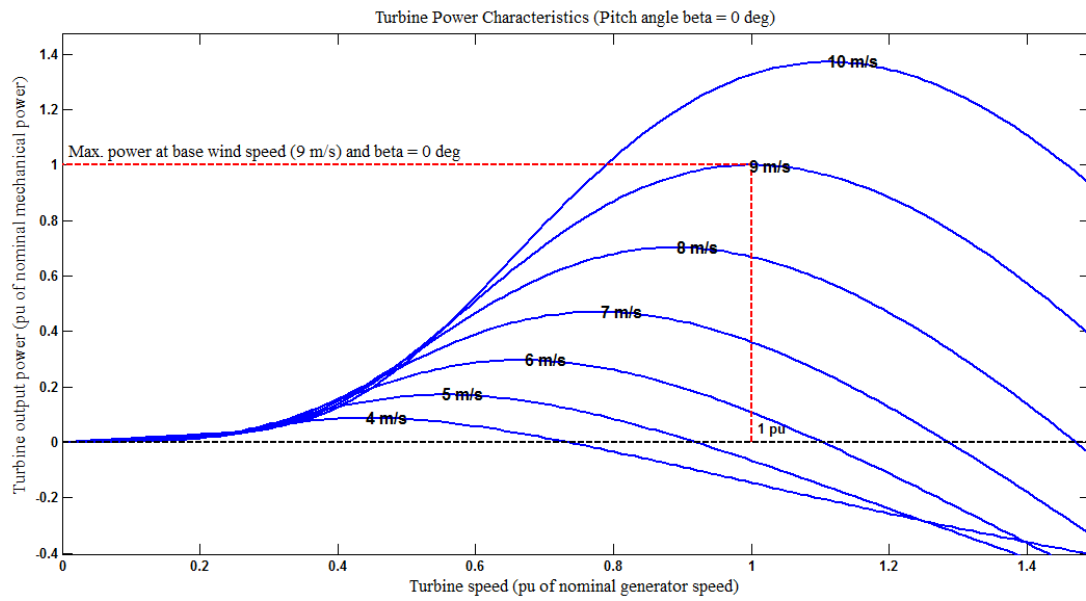


Figure (3.6): wind turbine power characteristics

The power curve working areas of the (3 MW) wind turbine is defined as:

- Cut – in wind speed is 5.6 m/s
- Rated wind speed is 9 m/s
- Cut – out wind speed is 25 m/s

The power curve of the 3 MW wind turbine is shown in figure (3.7):

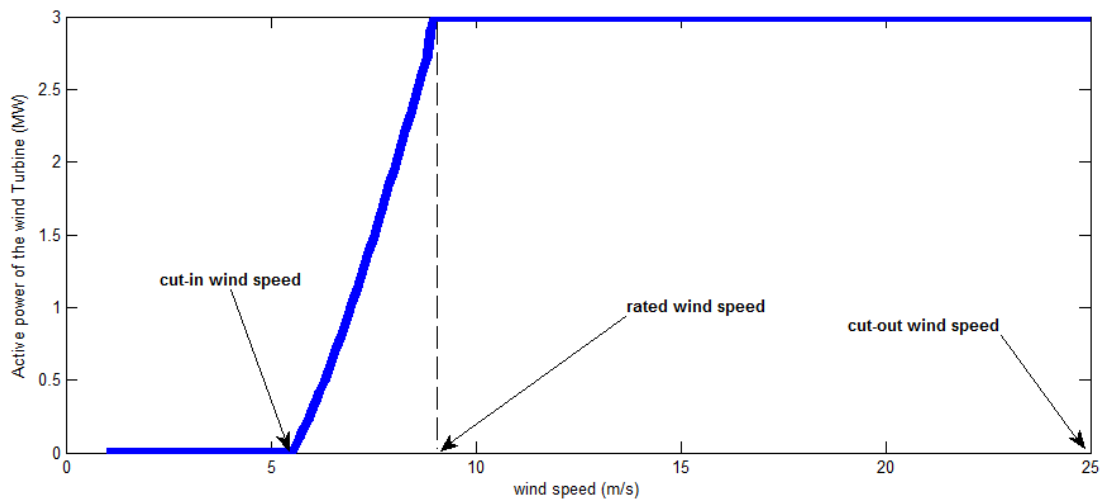


Figure (3.7): Power curve for the (3 MW) wind turbine

| Wind speed (m/s) | Active power (MW) | Voltage (volt) | Pitch angle (deg) |
|------------------|-------------------|----------------|-------------------|
| 1 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 |
| 5.6 | 0.05028 | 573.56 | 0 |
| 6 | 0.2898 | 574.48 | 0 |
| 7 | 1.041 | 576.15 | 0 |
| 8 | 1.943 | 574.25 | 0 |
| 9 | 3 | 567.06 | 0 |
| 10 | 3 | 565.915 | 2.1 |
| 11 | 3 | 565.915 | 7.78 |
| 12 | 3 | 565.915 | 12.77 |
| 13 | 3 | 565.915 | 16.7 |
| 14 | 3 | 565.915 | 19.92 |
| 15 | 3 | 565.915 | 22.61 |
| 16 | 3 | 565.915 | 24.9 |
| 17 | 3 | 565.915 | 26.88 |
| 18 | 3 | 565.915 | 28.61 |
| 19 | 3 | 565.915 | 30.13 |
| 20 | 3 | 565.915 | 31.49 |
| 21 | 3 | 565.915 | 32.7 |
| 22 | 3 | 565.915 | 33.8 |
| 23 | 3 | 565.915 | 34.78 |
| 24 | 3 | 565.915 | 35.68 |
| 25 | 3 | 565.915 | 36.51 |

Table (3.1): active power, terminal voltage and pitch angle of the (3 MW, 575 Volt) fixed speed - induction generator wind turbine at different wind speeds

For the values of wind speeds below 5.6 m/s and higher than 25 m/s the wind turbine is stopped of working by applying of a tripping signal from the protection system of the wind turbine.

3.4 EFFECTS OF INTEGRATION OF FIXED SPEED SCIG WIND TURBINE TO POWER SYSTEM GRID

3.4.1 Direct grid connection of fixed speed SCIG wind turbine

The fixed speed wind turbine is provided with a classical squirrel cage induction generator, directly connected to the grid, and the turbulence of the wind will result in power variations, and thus it can affect the power quality of the grid. The low rotational speed of the turbine rotor is translated into the generator rotational ω_m speed by a gearbox with the transmission ratio R . The generator speed depends on the number of pole pairs p and the frequency of the grid f [16].

$$n_{rotor} = \frac{n_{generator}}{R} \quad (3.3)$$

$$n_{generator} = \frac{f}{p} \quad (3.4)$$

$$n_{rotor} = \frac{f}{R \cdot p} \quad (3.5)$$

The disadvantages of induction generators are high starting currents and their demand for reactive power. Having in view the grid connection requirements, a specific rule should be applied for classical induction generators their reactive power needs and the possibly required additional reactive power generation are provided by capacitor banks connected either to the producer's installation or to the High Voltage/Medium Voltage substation.

3.4.2 Performance during grid voltage changes

Voltage variations caused by fluctuating loads and/or production is the most common cause of complaints over the voltage quality. A variation in the voltage of the network to which the fixed speed induction generator wind turbine is connected has a significant impact on the performance of the generator and even transient failures may be incidentally due to system voltage collapse, which causes induction generators runaway. These types of voltage variation could be voltage sag, voltage swell, flickers and voltage interruption. With the increasing time of the effect of any of these types of voltage changes may lead to disturb the operation or to damage of the fixed speed wind turbine.

3.4.3 Performance during network faults

During short circuit faults, it is critical to supply enough reactive power to reduce the magnitude of voltage sag and provide sufficient short circuit current to allow

protection relays to detect and isolate the fault. Power systems are designed to operate under short circuit conditions for short periods of time without damaging any equipment or de-stabilizing power system operation. Protection relays are employed to detect short circuit faults and act to isolate faults in an effective and responsive manner to reduce impact of the fault. The occurrence and removal of short circuit faults will result in momentary voltage sag experienced across the entire power system. The ability of a power system to supply enough reactive power to reduce the magnitude of voltage sag and supply enough short circuit current to allow protection relays to operate correctly can be measured by the availability of short circuit power at the point of fault. The collapse of dynamic voltage performance as a direct result of wind generation can severely affect the ability of generation (including wind generation) to remain connected to the power system.

3.4.4 Re-switching transients

In grid codes requirements are taken up which distributed generations have to meet when connected to the power system. These requirements can affect the normal operation of the fixed speed SCIG wind turbines.

One of those requirements is the immediate disconnection of wind turbines during disturbances. In order to prevent malfunction of the protection system, where a severe transient current can flow in the system if the induction generator operating in a steady state and suddenly gets disconnected due to a system fault or some other reason, and then gets reconnected by automatic re-switching. The magnitude of the current depends on the phase angle of the voltage wave when the generator gets reconnected to the grid. Frequent faults like this nature can cause shaft breakage due to fatigue stresses, particularly at the coupling with the wind turbine [4].

3.4.5 Low-Voltage-Ride-Through LVRT

Wind turbines in the past were designed to be disconnected in the event of major system disturbances such as lightning strikes, equipment failures, or downed power lines. However, this loss of generation impact stability and can lead to cascaded trip and loss of revenue. Today many utilities are requiring wind turbines ride through grid disturbances while remaining online to continue supporting the system. With recent advances in power electronics, the LVRT capability that enables wind turbines to stay connected to the grid during system disturbances is among the technologies introduced in the market during 2003 by many manufactures. With this new feature wind turbines remain online and feed reactive power to electric grid ride through

major system disturbances. This meet the transmission reliability standards similar to those demanded on thermal power plants [4]. A number of grid operators already require voltage-dip ride-through capability, especially in places, where wind turbines provide for a significant part of the total power supply. The squirrel cage induction generator wind turbine needs the support of an external device FACTS in order to remain connected during voltage dips. Flexible AC Transmission Systems which abbreviated by FACTS forms a new domain in power system control engineering [21]. They can be connected to transmission line in series or shunt. The shunt FACTS devices are used for controlling transmission line voltage, power flow, reducing reactive losses, and damping of power system oscillations for high power system stability and reliability The STATCOM is one of these types, as shown in figure (3.8).

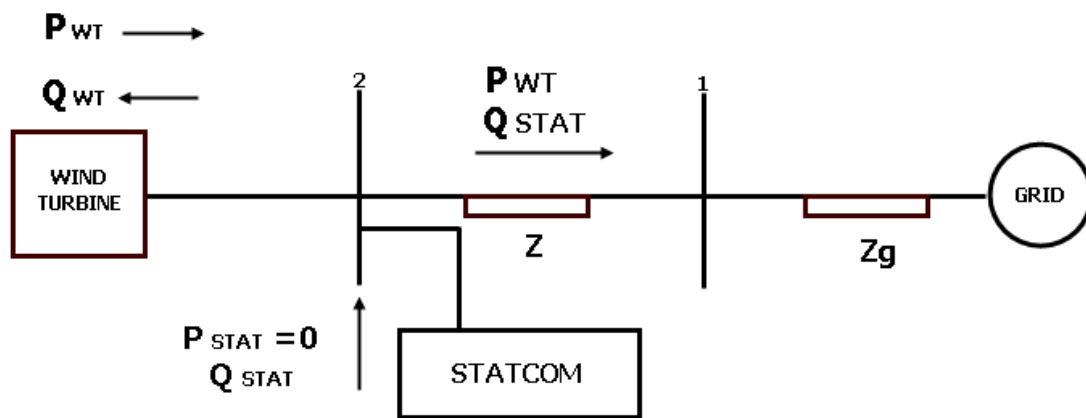


Figure (3.8): STATCOM and a wind turbine in the system for Voltage quality and LVRT

3.4.6 Increasing wind farm capacity

Wind-farm size is defined in terms of its rating relative to system fault level at the wind farm terminals. There are number of options which can extend the capacity limit. These depend on the wind turbine generator technology used. With fixed-speed wind turbines, power factor correction PFC capacitance can be selected to maximize the connected capacity. One suggested process is to reduce the wind farm power factor aim from say unity to 0.98, then reducing the local voltage and hence enabling wind-farm expansion but the main problem is that there will be an increase in losses [10]. If dynamic in addition to steady-state voltage control is required, then the switched capacitor banks could be replaced by static VAR compensation or a STATCOM for regulate the voltage and reactive power compensation, where

according to figures (3.8) and (3.9) the STATCOM only generate reactive power and its active power is zero.

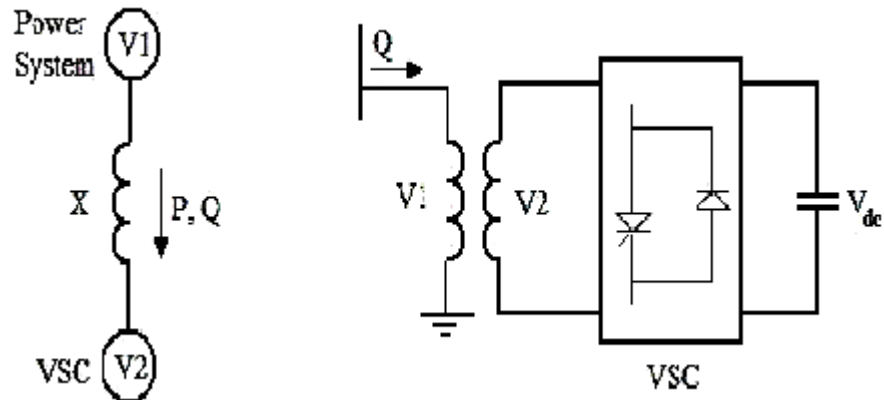


Figure (3.9): STATCOM configuration and principle of operation [21]

$$p = \frac{V_1 V_2}{x} \sin \delta \quad (3.6)$$

$$Q = \frac{V_1 V_2}{x} \cos \delta - \frac{V_1^2}{x} \quad (3.7)$$

Where:

P & Q are active and reactive power of the VSC respectively

δ = the phase difference between V1 and V2

As the angle δ is equal to zero, then $P = 0$. If AC voltage that generated by VSC is higher or (lower) than system voltage V1, then the STATCOM generate or absorbs reactive power.

3.5 FLOWCHART OF STUDYING THE PERFORMANCE AND ISSUES OF THE FIXED SPEED S.C.I.G WIND TURBINE

Figure (3.10) specifies the way of study the performance of the 3 MW fixed speed SCIG wind turbine and the issues that may happen during its normal operation, and define the working limits of the wind turbine at these issues, the way to ride through some of them, the way of protection of the wind turbine and how to resume its work after disconnection from the Grid.

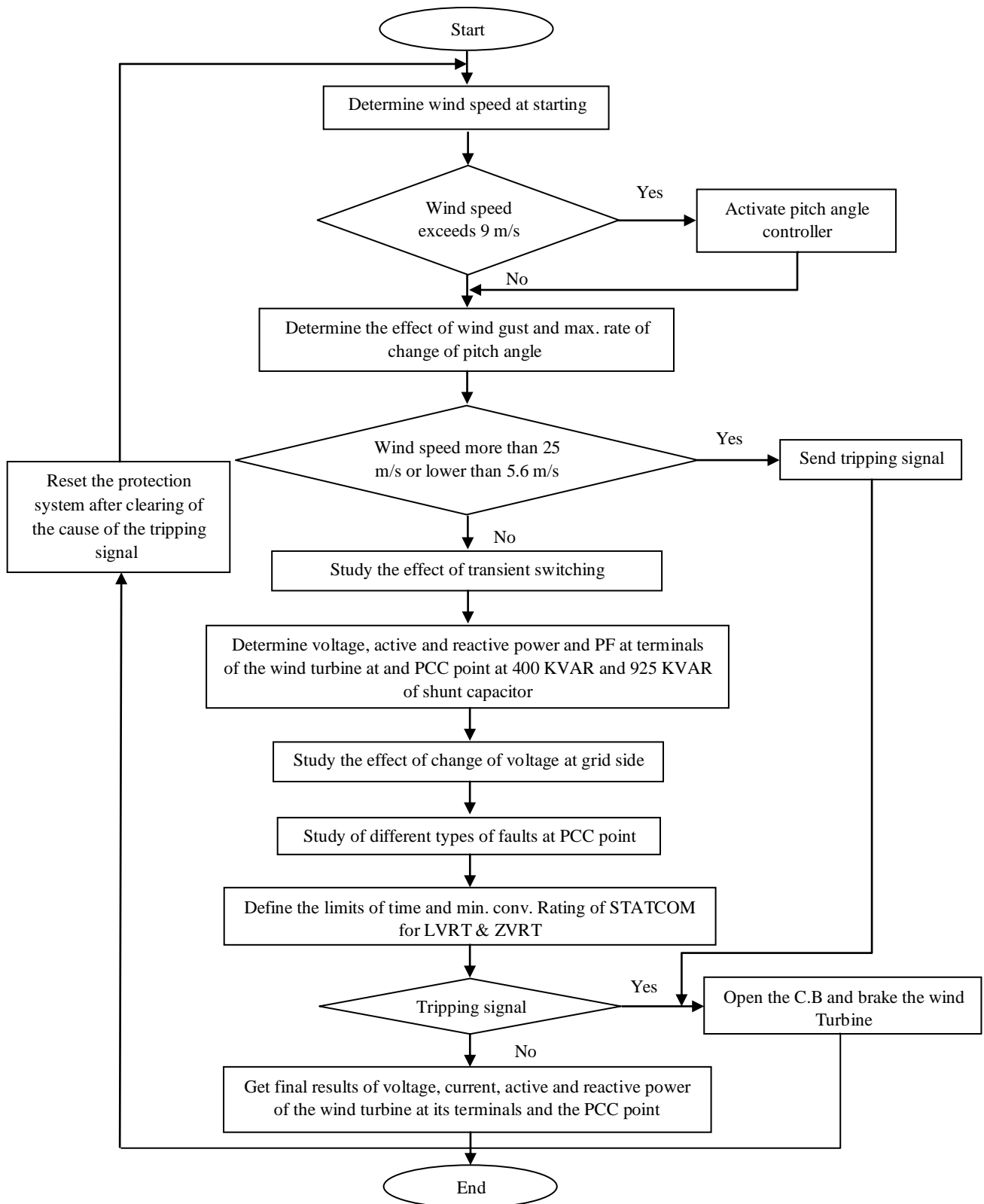


Figure (3.10): flowchart of operation of the fixed speed SCIG wind turbine

RESULTS AND DISCUSSIONS

The Figure (4.1) shows a single line diagram of a typical fixed speed wind turbine using SCIG. The parameters of a single wind turbine and its generator are available in appendix-A. The single wind turbine which is available in MATLAB SimPowerSystems toolbox is 3 MW, 575 Volts and 60 Hz rated frequency. In this system there will be using for each wind turbine a protection system for stopping each of the turbines individually whenever there are any exceeding of the predefined values of currents, voltages, voltage sequences, the rotational speed of the generator of the wind turbine, and cut-in and cut-out wind speed values. These predefined values also available in appendix-A [21]. A simulation model of a wind turbine consisting of 3 MW wind turbine is connected to a 25 kV distribution system exports power to a 120 kv grid through a 25 kV feeder. The stator winding of SCIG is connected directly to the 60 Hz grid and the rotor is driven by a variable pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the rated wind speed 9 m/s. Fixed capacitor banks in delta connection are connected at low voltage bus of each wind turbine 400 KVAR for 3 MW turbines which supplies the constant no load demand of reactive power. A STATCOM is connected at the main bus B_25 to provide the reactive power and voltage control capability.

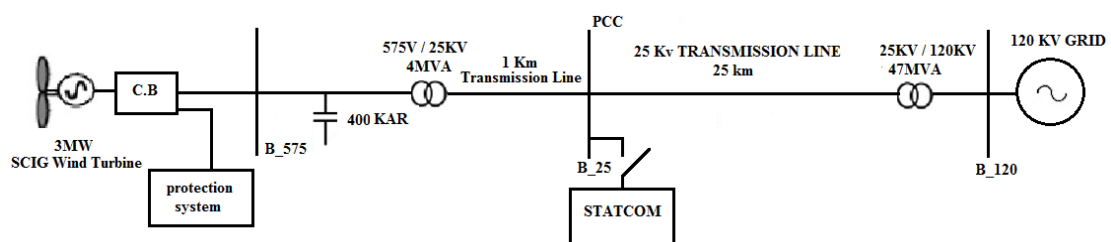


Figure (4.1): Single line diagram of 3MW wind turbine connected to the 120 Kv grid

4.1 DYNAMIC PERFORMANCE OF WIND TURBINE USING SCIG WITH DIRECT GRID CONNECTION DURING SYSTEM START-UP

This case study investigates the dynamic performance of a 3 MW SCIG wind energy conversion system during system start-up. As the wind turbine is initially in a

parking mode. When the wind speed reaches cut-in speed level, the blades are pitched into the wind slightly, and wind turbine starts to rotate slowly. When the generator is accelerated to the synchronous speed, 1200 rpm 1 pu, the circuit breaker is closed and the generator is directly connected to the grid. The simulated waveforms for the generator are illustrated in figure (4.2), where the system is simulated at the rated wind speed for the turbine which is 9 m/s.

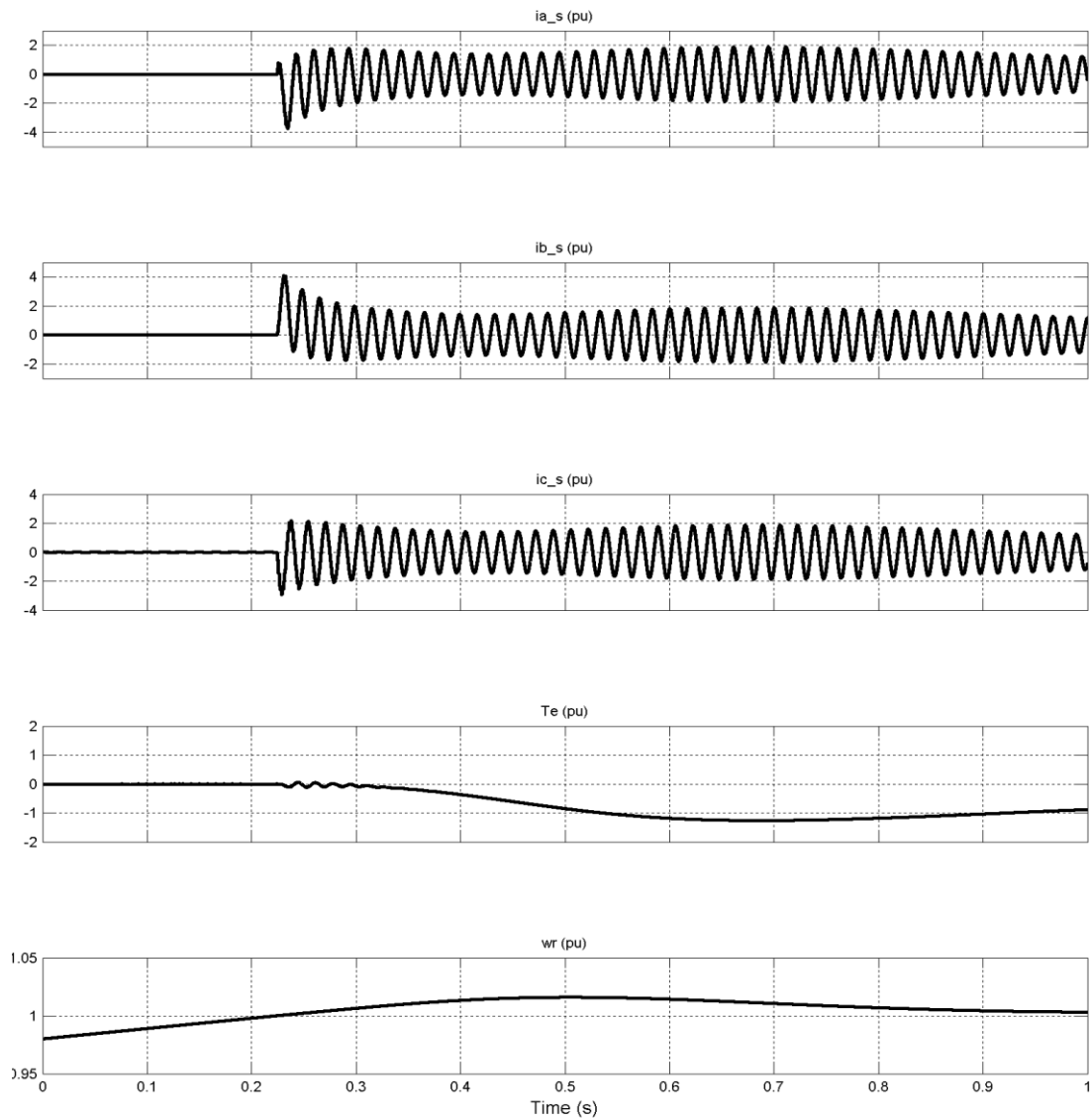


Figure (4.2): Dynamic response of SCIG with direct grid connection

This is a simulation of discrete trapezoidal model SCIG wind turbine, it can be noticed that when the time is zero (s), the speed $w_r = 0.98$ pu, and when the time = 0.224 s the circuit breaker of the wind turbine is closed since the induction generator generates electricity when its rotational speed is more than synchronous speed 1200 rpm , or 1 pu. During the system transients, a high inrush current flows into the generator and a DC offset current appears in each of the stator currents i_{a_s} , i_{b_s} , and i_{c_s} , but the sum of these offset currents is zero due to a three-phase balanced system. As a rotating magnetic field is being built and generator core is being magnetized by the stator current, an electromagnetic torque T_e is produced. The direct connection of the generator to the grid during the system start-up causes excessive inrush currents with peak values of 4 per unit (pu) i.e. 4.08 times of its rated value, as well as some of torque oscillations. This simulation should be done without connection the STATCOM.

In figure (4.3), the wind turbine work is simulated at rated wind speed in phasor model, it can be noticed that after the direct connection to the grid, the active power will exceed its nominal value and reach its maximum value after starting 4 MW, so in this case the pitch angle controller as in figure (3.4) is activated to reduce the active power to its nominal value,. When this is happened the pitch angle is returned back to be zero at simulation time = 1.95 s, because at normal operation of any wind turbine at rated wind speed the pitch angle is zero. The wind turbine generates active power at steady state 2.915 MW, reactive power of 1.381 MVAR and voltage of 0.9861 pu, or 567 Volt. It reached the steady state after 2.466 s from the time of direct connection to the grid.

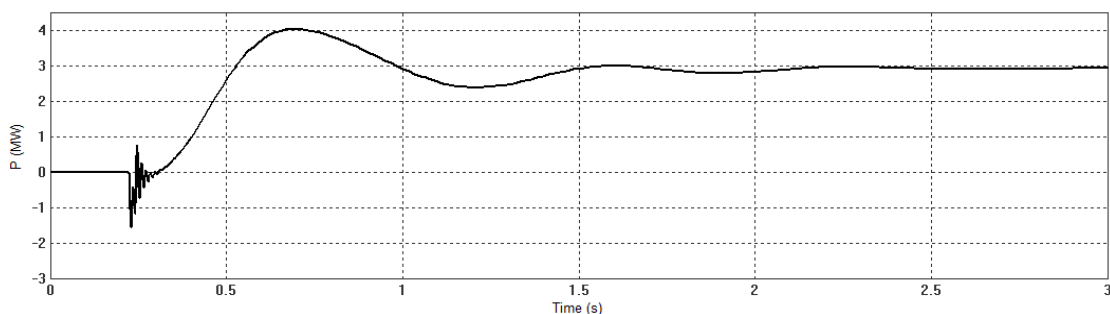


Figure (4.3.A): operation of wind turbine at rated wind speed

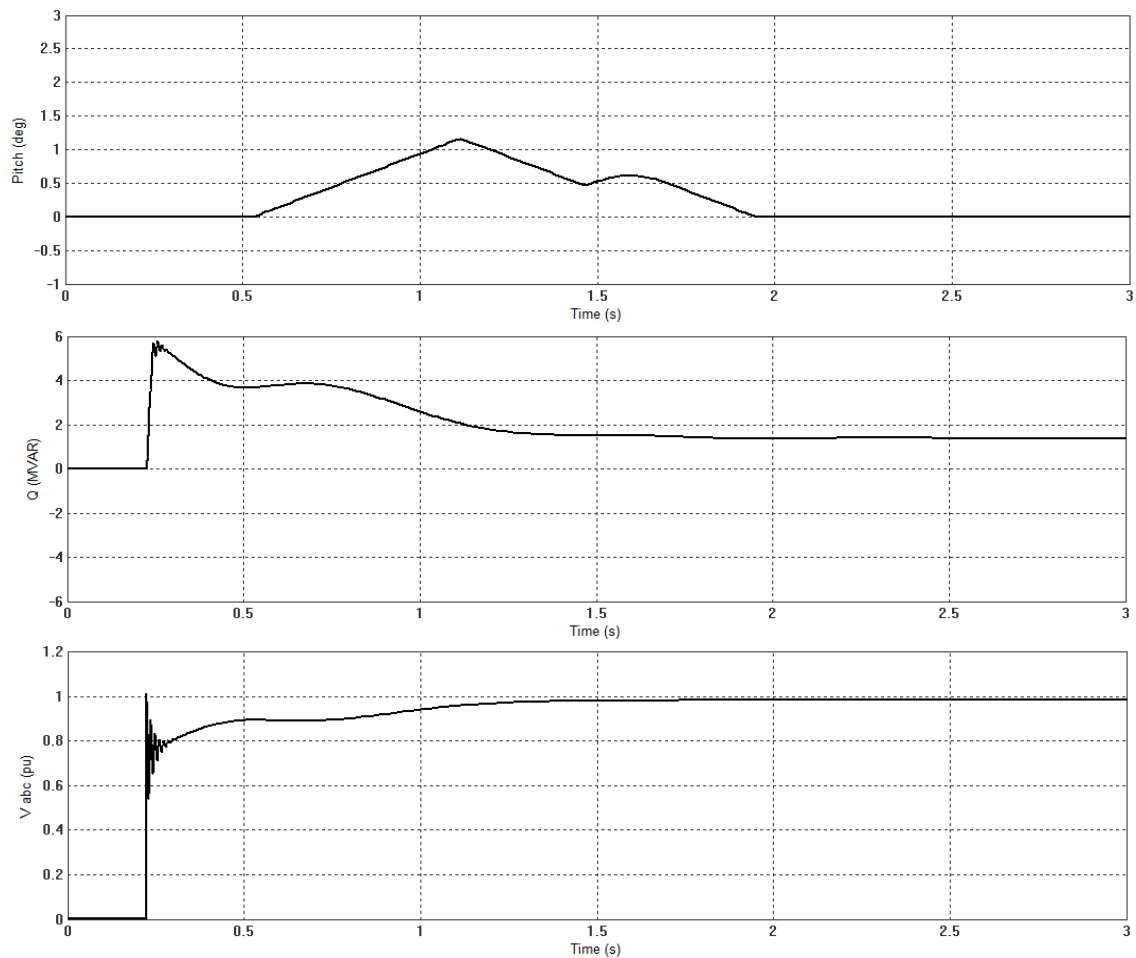


Figure (4.3.B): operation of wind turbine at rated wind speed

4.2 EFFECTS OF WIND SPEED AT STARTING AND WIND GUST

The lower value of wind speed that can generate electricity is 5.6 m/s and the active power and the voltage are 50.28 KW and 0.9975 pu or 573.56 Volt respectively. As shown in figure (4.4). The maximum constant value of wind speed at starting is 10.5 m/s, and more than this value the wind turbine will suffer from a drop in voltage below 0.75 pu of rated voltage and increasing on current 2.42 times of its rated value and the generated power is -203.4 KW,6.04 MVAR. See figure (4.5).

As there are changes in wind speed, and it is not constant all the time in one value, but it is changing continuously. For example the change from 10 to 18 m/s, this state is called wind gust and the wind turbine is exposed to drop in its active power,

and with the using of the protection system, the wind turbine is disconnected at time = 9.56 s. See figure (4.6).

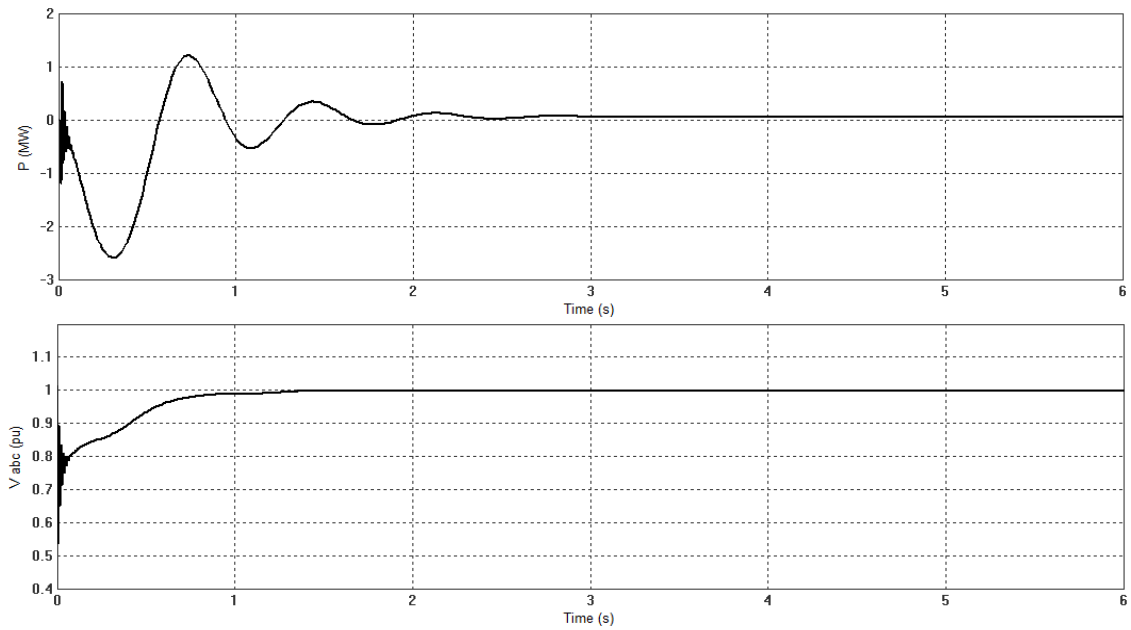


Figure (4.4): active power and voltage of the SCIG at 5.6 m/s of wind speed

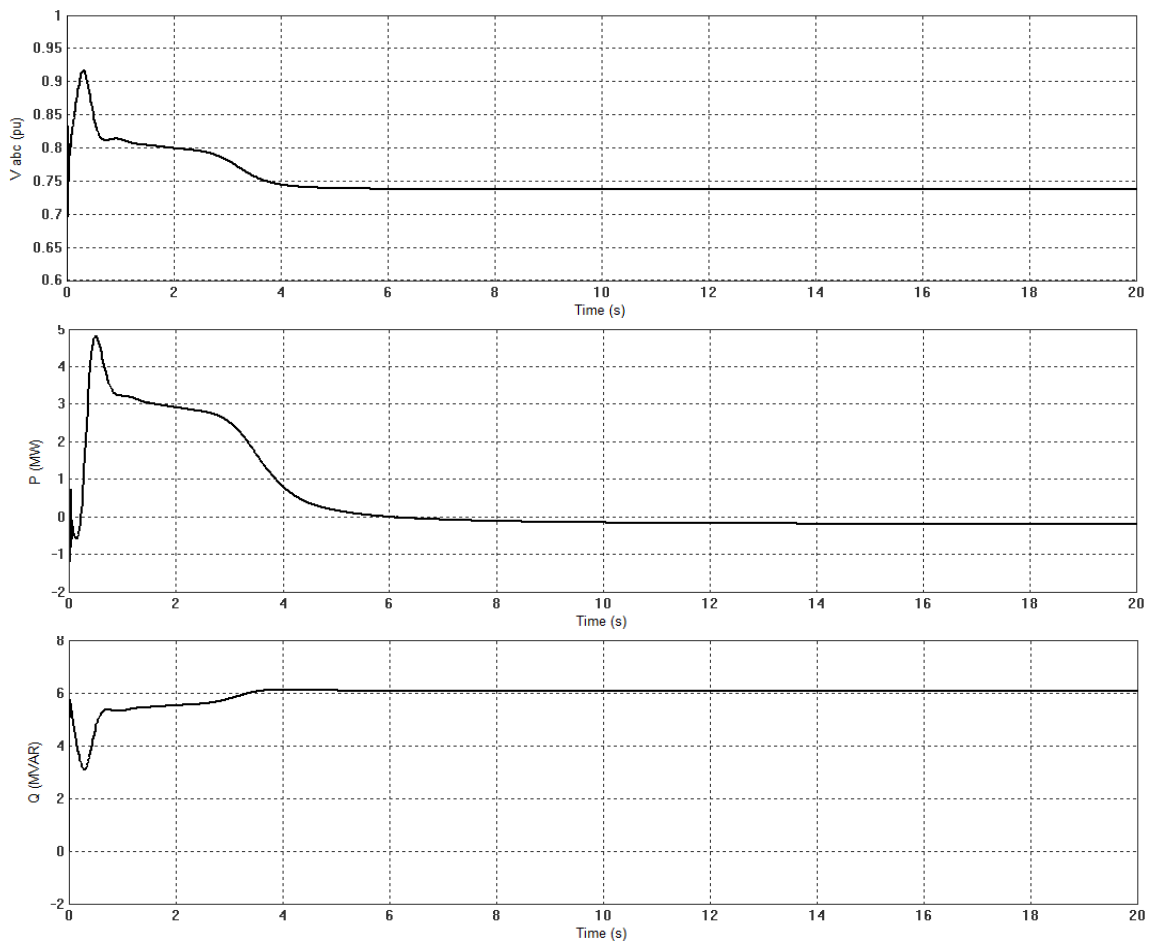


Figure (4.5): voltage, active and reactive power of the turbine at 10.6 m/s of wind speed

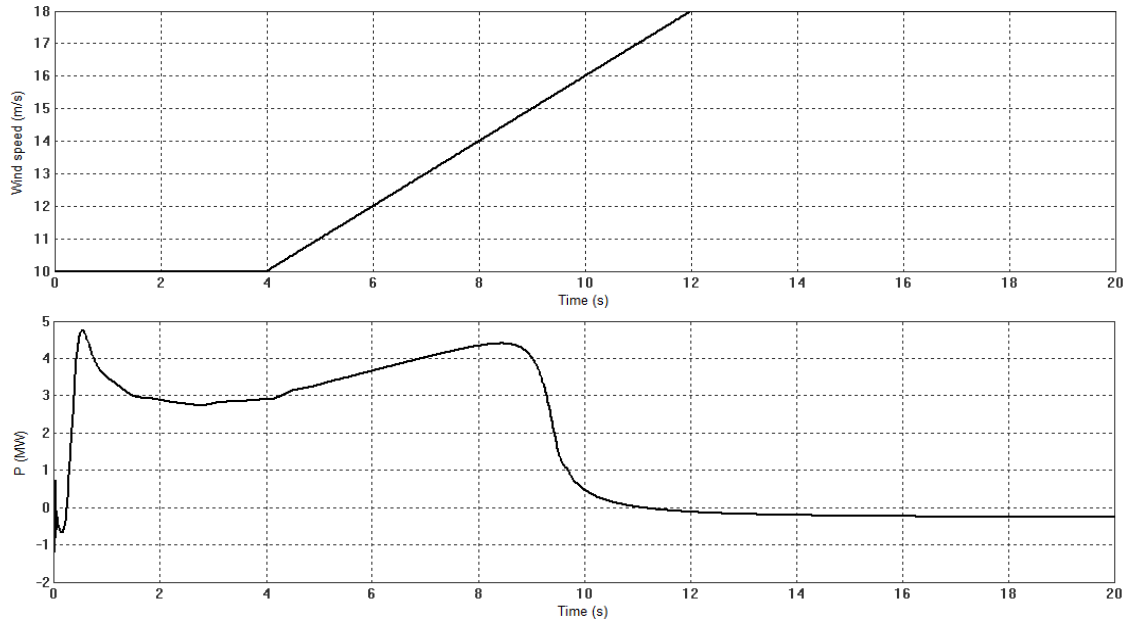


Figure (4.6): active power of wind turbine at change of wind speed from 10 to 18 m/s

It can be noticed that when the wind speed increases as some of a wind gust for several m/s of speeds, the pitch angle could not follow this high change in wind speed to limit the power and voltage and currents. As the pitch angle controller is limited by the maximum rate of change of pitch angle deg/s, and the default value of the wind turbine block is 2 deg/s. It can be noticed that this value is very small and by making some tuning to this value to get the optimum results for the maximum value of wind speed is allowed at starting and for the change in wind speed as wind gust, for example 10 to 18 m/s.

Now after some tuning, the best value of maximum rate of change of pitch angle should be 11 deg/s, and by this value the maximum allowed value of wind speed at starting of the wind turbine is 11.2 m/s and for the change of wind speed as instantaneous wind gust. See figure (4.7)

4.3 EFFECT OF RE-SWITCHING TRANSIENT

Suppose the circuit breaker in the figure (4.1) is exposed to an immediate opening and closing at the steady state operation of the wind turbine, maybe due to fault occurrence or any other reason, after the re-switching the SCIG of the wind turbine is exposed to high current, voltage and electromagnetic torque values, where the current increasing is 6.60 times and the voltage is 8.93 times and electromagnetic torque is

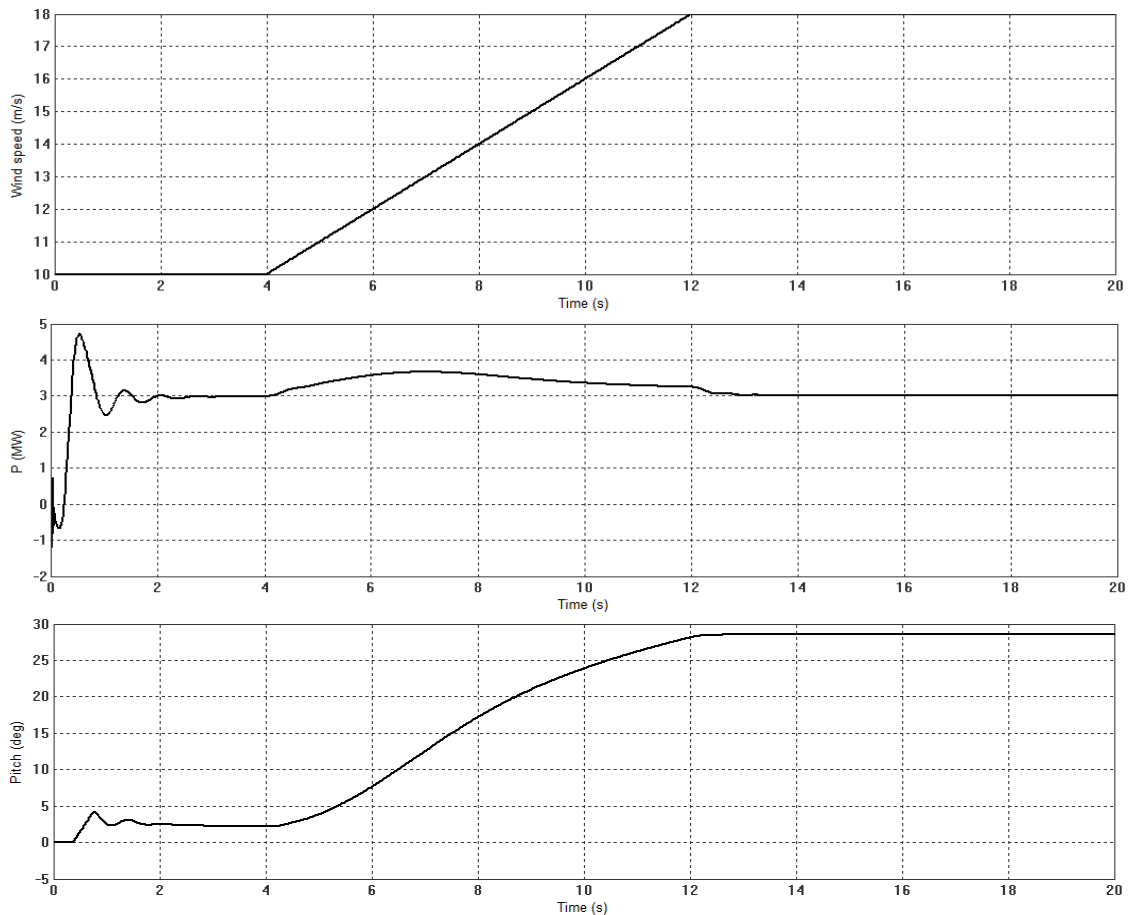


Figure (4.7): active power and pitch angle at change of wind speed (10 to 18 m/s) when the maximum change of pitch angle is (11 deg/s)

5.64 times to their steady state rated values. The duration of disconnection is an important factor, where if the time of the circuit breaker disconnection is more than 260 ms, the SCIG will not be able to build its own power and it will collapse. See figure (4.8).

The maximum time of the disconnection should not increased more than 260 ms if in case there was no fault occurrence, but if some fault happened then the maximum time for the re-switching transient should not be more than 170 ms or the power of the SCIG wind turbine will collapse. See figure (4.9). The immediate disconnection for figure (4.8) was due to a false tripping signal from the protection system, while in figure (4.9) was due to double line to ground fault for 100 ms.

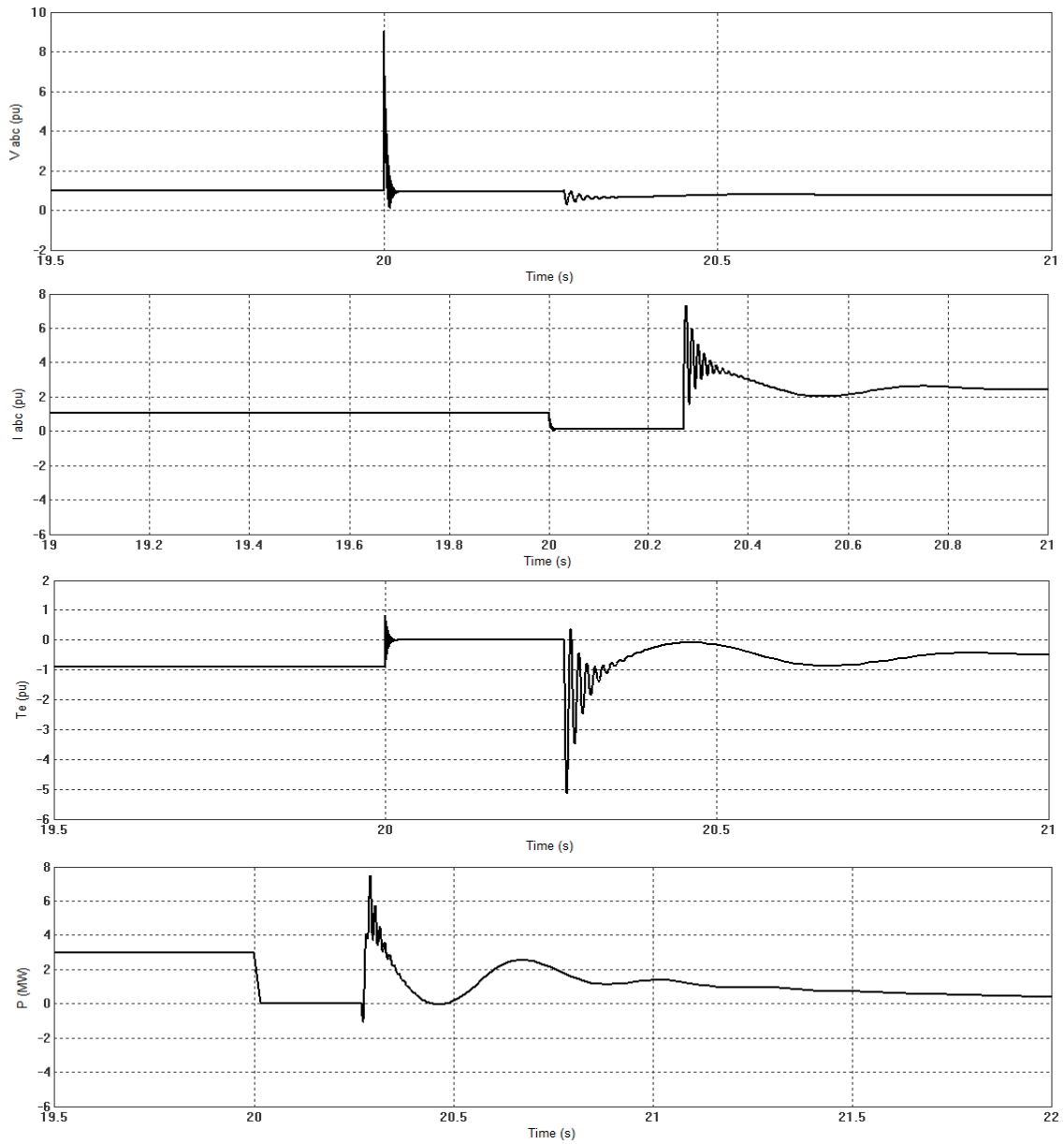


Figure (4.8): effect of re-switching transient in 270 ms from the disconnection

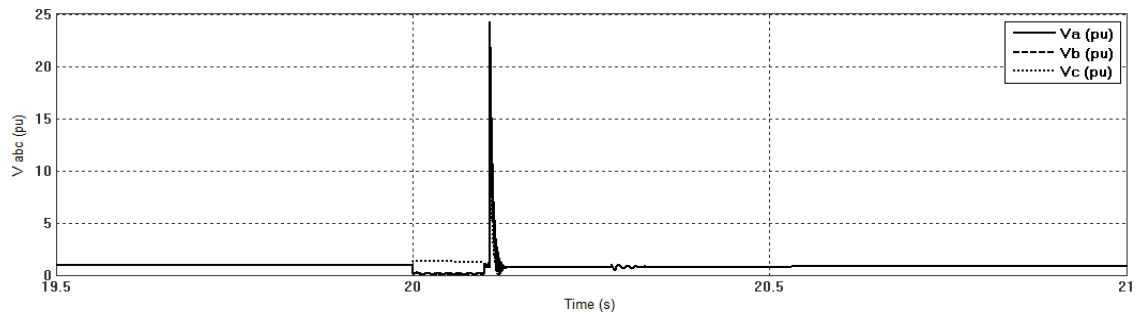


Figure (4.9.A): effect of re-switching transient at fault occurrence and after 170 ms from the protection tripping signal

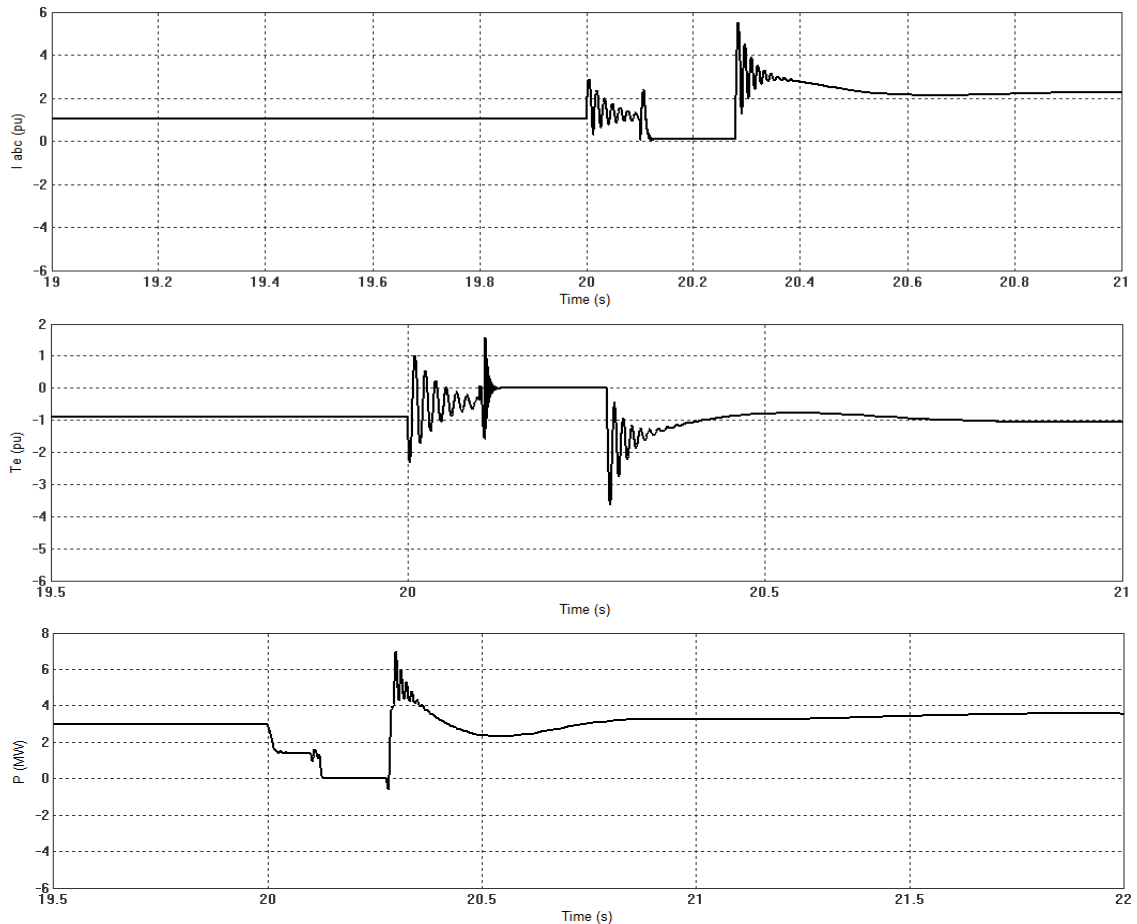


Figure (4.9.B): effect of re-switching transient at fault occurrence and after 170 ms from the protection tripping signal

4.4 EFFECT OF VOLTAGE SAG, SWELL AND INTERRUPTION AT 120 KV GRID SIDE ON THE WIND TURBINE

4.4.1 Effect of voltage Sag

As the voltage sag is defined as the temporary reduction in the R.M.S. voltage value lasting from half cycle to several seconds, and also called as voltage dip. When this voltage dip is occurred at 120 Kv grid side, the voltage of the wind turbine and also its power will decrease with an increasing of its current value. By using the protection system, It will send a trip signal if the 120 Kv voltage grid becomes less than 0.46 pu for 100 ms of simulation time or 6 cycles. The operation of the wind turbine during the voltage sag is simulated at different values of the reduction in the grid side voltage. The wind turbine will lose its voltage and active power if the voltage sag lasts

for 500 ms or more and with voltage amplitude less than 0.45 pu as shown in figure (4.10).

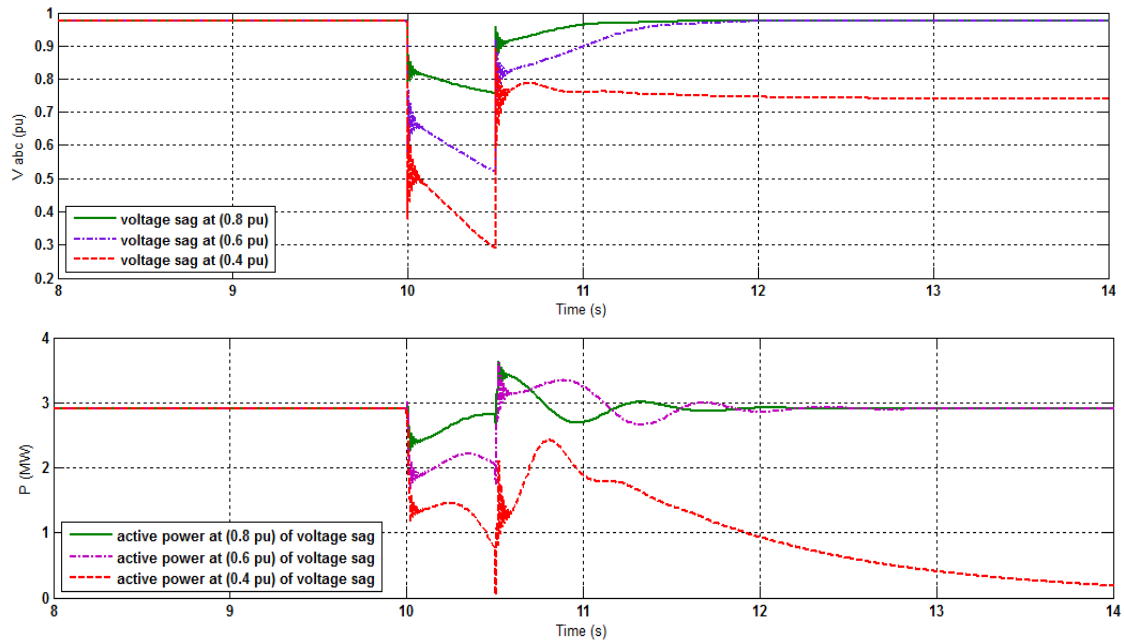


Figure (4.10): simulation of the wind turbine at different voltage sag values for 500 ms

4.4.2 Effect of voltage Swell

The voltage swell is the increasing in the value of R.M.S. voltage lasting from half cycle to several seconds. As it is the opposite of the voltage sag, the wind turbine in this case will be exposed to increase in its terminals voltage and reduction in its current, electromagnetic and mechanic torques also, while the active and reactive power will be at their maximum values at the moment of the voltage swell starting, where they will be 3.9 MW and 4.7 MVAR for active and reactive power respectively. If the voltage swell becomes more than 1.9 pu for 100 ms or 6 cycles, the protection system will disconnect the wind turbine from the grid. See figure (4.11).

4.4.3 Effect of voltage interruption

As the interruption symptom is defined as the loss of power. The duration of this loss of power is affecting the operation of the SCIG wind turbine system. When the power interruption last for more than 90 ms or 5.4 cycles the protection system will trip the wind turbine circuit breaker. The maximum time for the power loss or power

interruption should not exceed more than 240 ms or 14.4 cycles, as shown in figure (4.12).

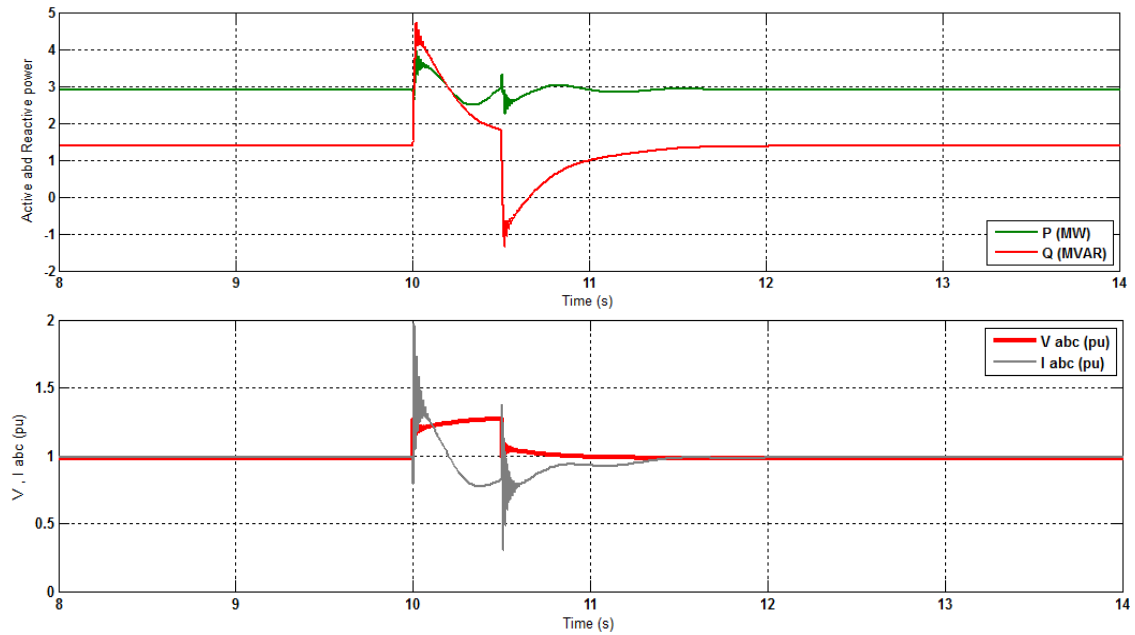


Figure (4.11): simulation of the wind turbine operation at 1.29 pu voltage swell in 120 Kv grid side for 500 ms

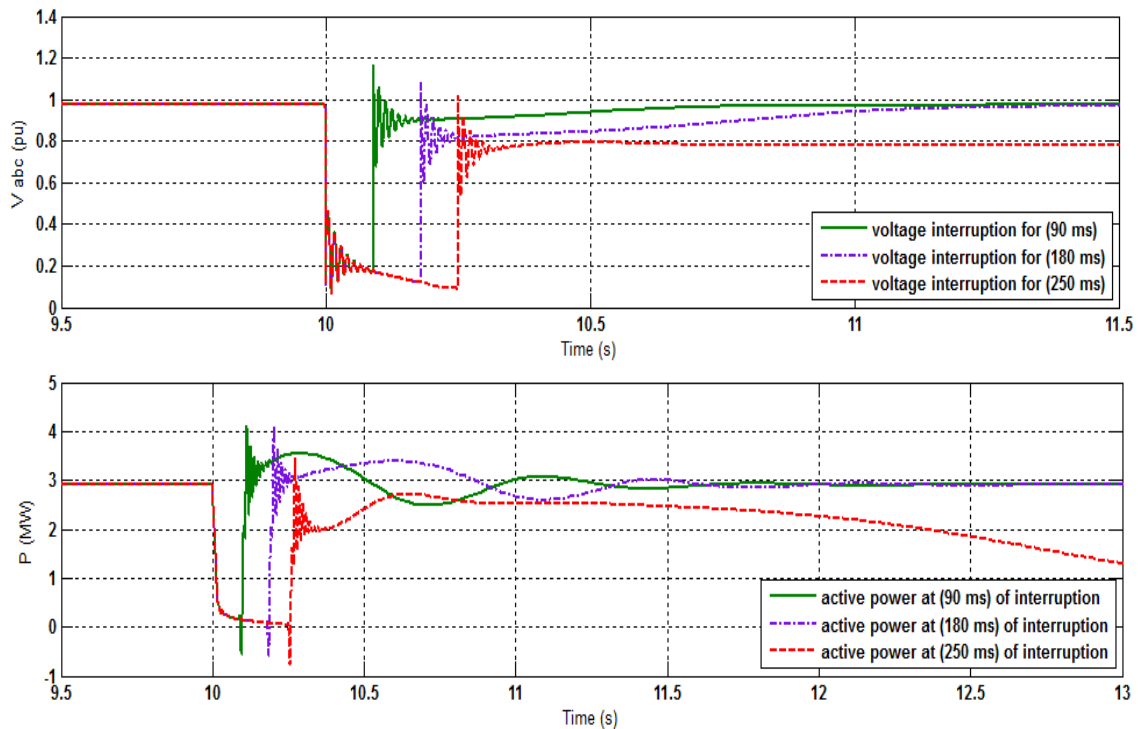


Figure (4.12): simulation of the wind turbine operation at different interruptions of power at 120 Kv grid

As both of the transient switching and the interruption symptoms represent the loss of power in some duration of time, but there is a differences in the effect of them, where

the re-switching transient is more severe than the interruption even if it was due to a false tripping signal, because after the reconnection to the grid, the wind turbine is exposed to higher current of the SCIG stator, higher torque and reactive power demand from the grid. Where this will affect the operation of the wind turbine and will lead to a mechanical stress on it. See figure (4.13).

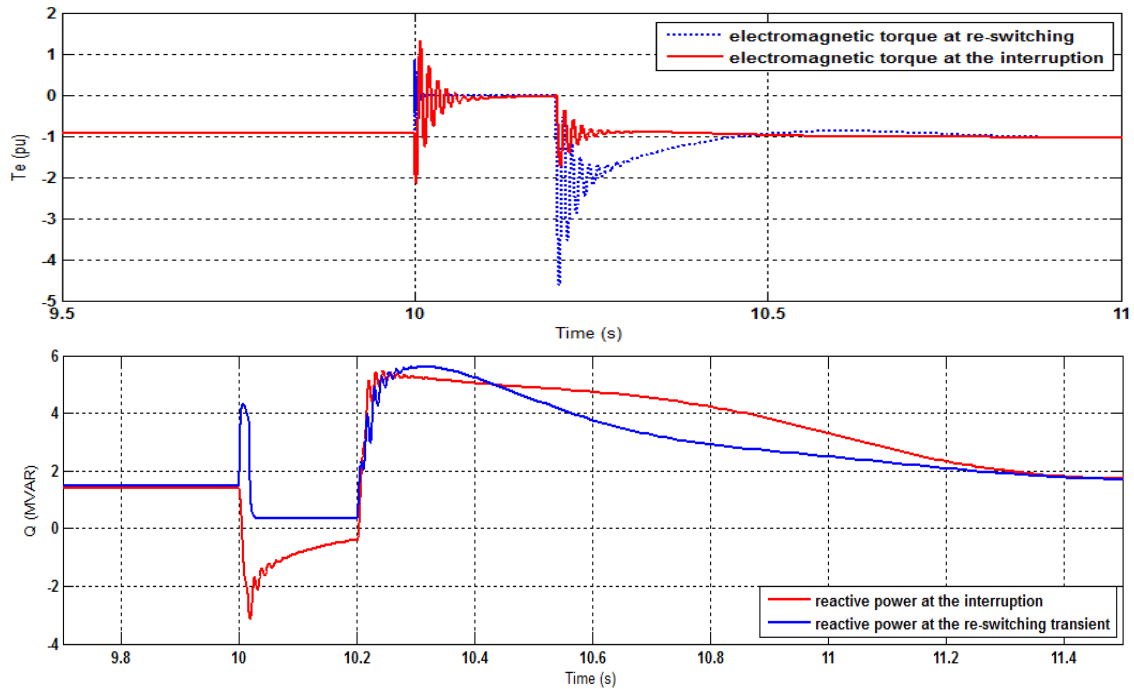


Figure (4.13): the difference in the torque and reactive power for the 3 MW SCIG at the re-switching transient and power interruption for 200 ms

Also at the duration of power loss due to the interruption, the SCIG of the wind turbine generated a negative VAR and its voltage decreased while in case of the re-switching transient it was generating a positive VAR and its terminal voltage increased. As it was shown in the figures (4.8), (4.9) and (4.12).

4.5 REACTIVE POWER COMPENSATION OF THE S.C.I.G. FIXED SPEED WIND TURBINE

By studying the different values of the active, reactive and voltage at the buses B_575 and B_25, the bus B_25 is the sender of the electric power from the wind turbine to the grid, when the value of the capacitive reactive power for the shunt capacitor of the wind turbine at bus B_575 is 400 KVAR, then the wind turbine voltage, active and reactive power at steady state are 0.9862 pu, 3 MW and 1.378 MVAR respectively, while in the bus B_25 these values are 0.9896 pu, 2.8627 MW and 1.113

MVAR. As the voltage in the bus B_25 is less than 1 pu and the reactive power that demanded by the wind turbine is high and the power factor is 0.932 as shown in figure (4.14).

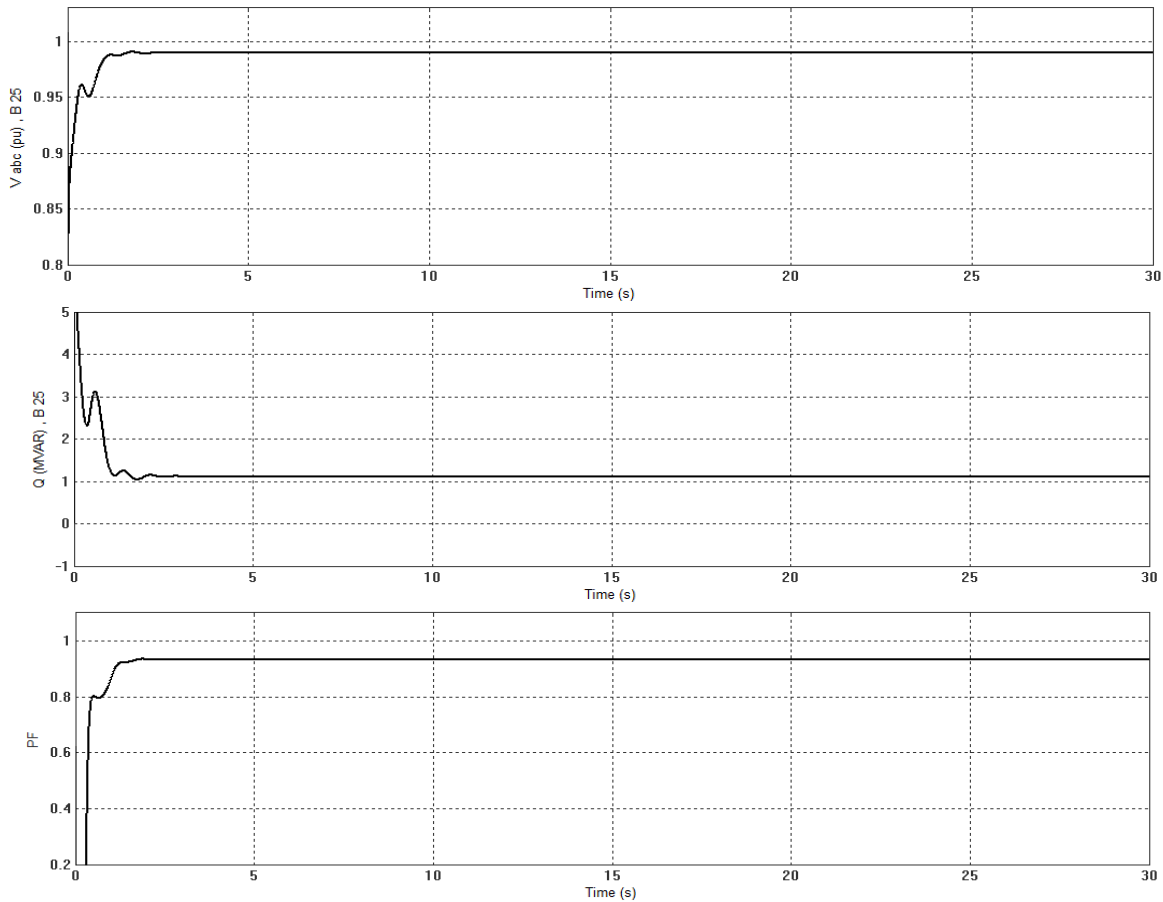


Figure (4.14): voltage, reactive power and power factor at bus B_25 when the capacitive VAR of capacitor is (400 MVAR)

By adjusting the value of the capacitive reactive power of the shunt connected capacitor to 925 KVAR to get the voltage at but B_25 1.001 pu, and to reduce the reactive power at bus B_25 to 0.5312 MVAR and to improve the power factor to 0.9833, as shown in figure (4.15), where this type of compensation is without using the STATCOM. For wind speeds more than 9 m/s the voltage will be 1 pu. See how this value of 925 KVAR of the capacitor is more important in the section (4.7).

4.6 PERFORMANCE OF THE 3 MW FIXED SPEED WIND TURBINE DURING FAULTS

The weakest point for faults is the PCC point (common coupling point), because at this point where the wind turbine is connected to transmission line that connected to

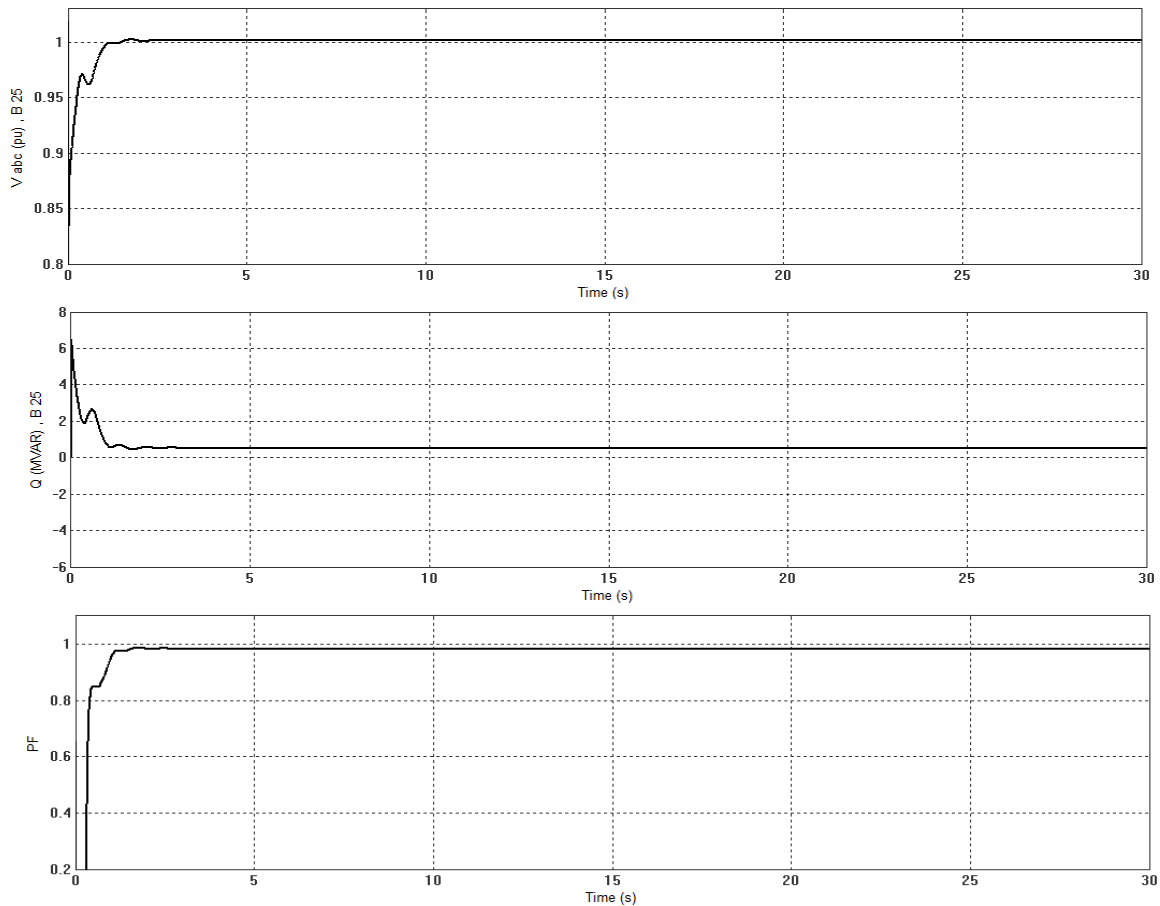


Figure (4.15): voltage, reactive power and power factor at bus B_25 when the capacitive VAR of capacitor is 925 KVAR

the grid, and from this point another wind turbine can be connected and also from this point the wind turbine takes its reactive power and send its generated power to the grid, so all the faults types will be studied at this point.

4.6.1 Single line to ground fault type

For the single line to ground fault at the PCC point, the wind turbine can ride through this type of fault, but the protection system will trip the wind turbine at time more than 180 ms. Without the protection system the wind turbine is able to work but with an unbalanced voltage at zero sequence and the fault current exceeds 1000 A at the first moment of the fault. The SCIG of the wind turbine generated zero VAR in the beginning of fault, later it is able to generate positive VAR. By this type of fault the wind turbine can generate electricity but the voltage is unbalanced, so the wind turbine should be disconnected and stopped. See figure (4.16).

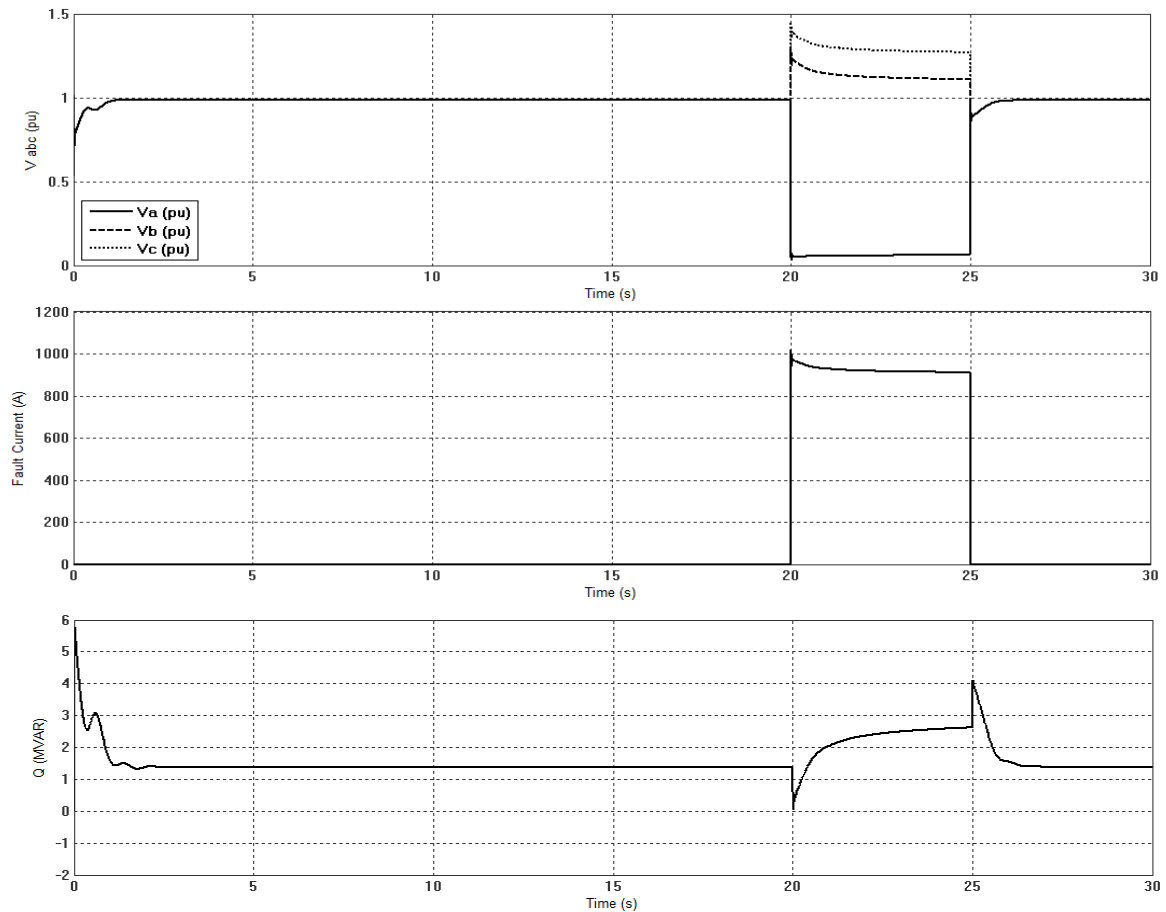


Figure (4.16): operation of the wind turbine during single line to ground fault lasted for (5) seconds

4.6.2 Double lines to ground fault type

For this type of fault, the protection system will disconnect the wind turbine exceeds 90 ms, while if without the protection the maximum time should not exceeds 480 ms or the wind turbine will be exposed to a voltage and power collapse. This type of collapse means the damage that can happen to the SCIG of the wind turbine. With using the adjusted value of the capacitance VAR of the capacitor which was 925 KVAR, the wind turbine can ride through more than 480 ms. See figure (4.17).

4.6.3 Line to line fault type

With this type of fault the protection system will trip the circuit breaker if the duration of this type of fault lasts for more than 90 ms. Without using the protection and at 400 KVAR of the capacitor the maximum time before the power collapses of the wind turbine should be less than 530 ms but also for the 925 KVAR of the capacitor value it can ride through it. See figure (4.18).

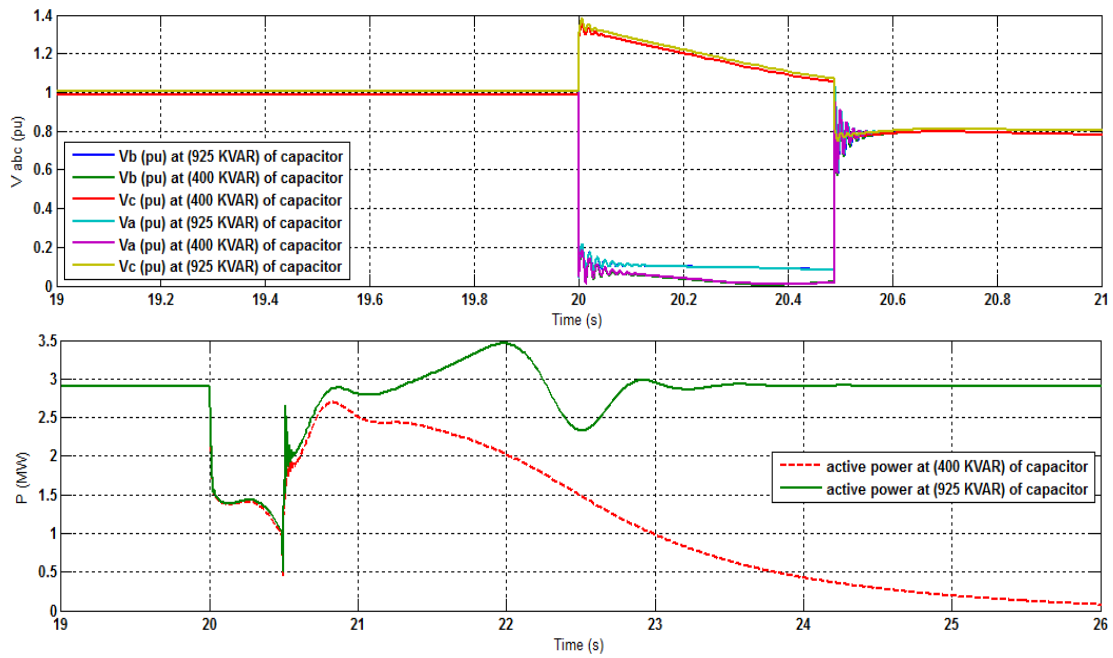


Figure (4.17): performance of the wind turbine at double lines to ground fault for 490 ms and different types of VAR values of the capacitor

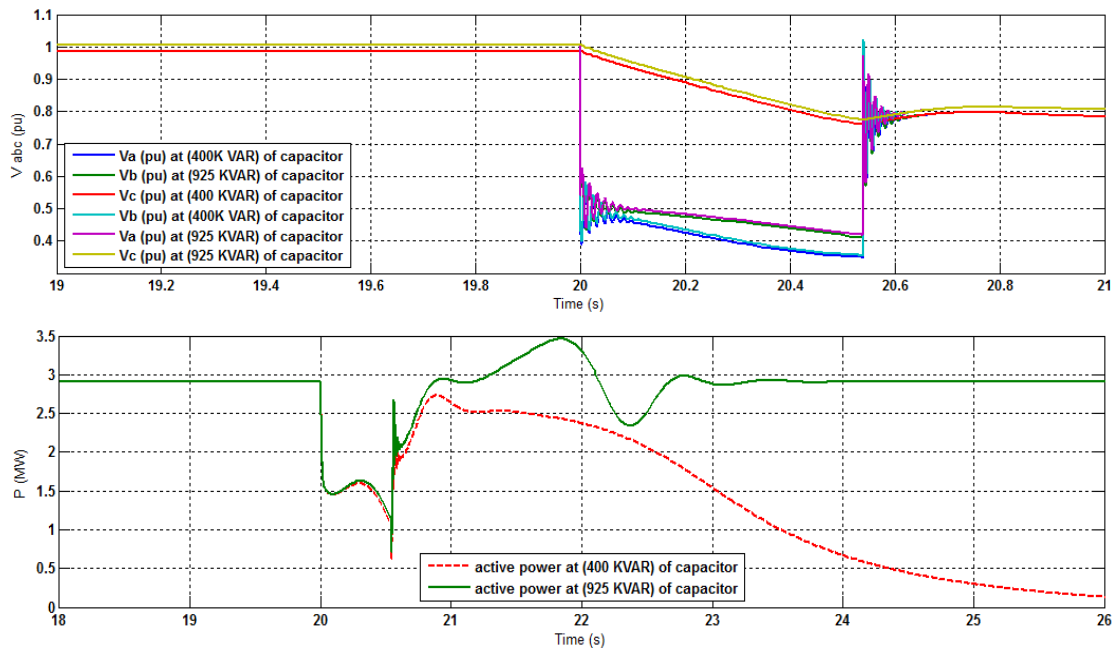


Figure (4.18): performance of the wind turbine at lines to line fault for 490 ms

4.6.4 Three phases symmetrical fault type

With this type of fault, the protection system will make trip to the circuit breaker if this type of fault lasts for more than 90 ms. The protection system send this signal since the minimum value of the voltage at bus B_575 should not be less than 0.75 pu for 100 ms, and in this type of fault all the phases have voltage near zero value.

Without using the protection, the maximum time of this type of fault duration should not be more than 250 ms for 400 KVAR of capacitor. See figure (4.19).

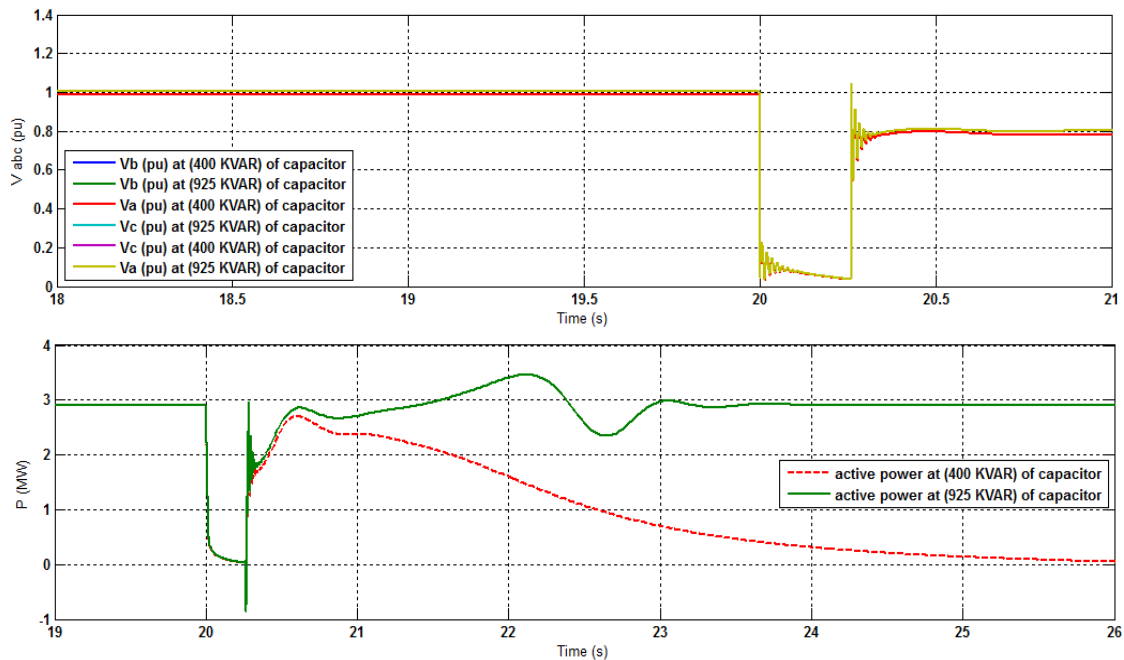


Figure (4.19): performance of the wind turbine at 3 phases symmetrical fault for 260 ms

4.7 LOW VOLTAGE RIDE THROUGH (LVRT) OF THE 3 MW FIXED SPEED S.C.I.G. WIND TURBINE

In all the previous sections all the simulations were done without using of the STATCOM, since the function of it is to control the voltage amplitude and the reactive power compensation, so the idea was to make small improvements to the system without using the STATCOM, then using it to improve the performance of the system. The reference voltage of the STATCOM is kept at 1 pu to let the voltage at the PCC point 1 pu. The fixed speed SCIG wind turbine can ride through the fault that happen for 100 ms by using the STATCOM, without a tripping signal from the protection system to make the wind turbine in serve even during network faults. But when this duration is increased more than 100 ms the protection system will trip the circuit breaker of the wind turbine due to its setting to the voltage dips. For the three phases symmetrical fault the STATCOM do not have the ability to let the wind turbine ride through this type of fault because the voltage on its terminal will be zero. See figure (4.20).

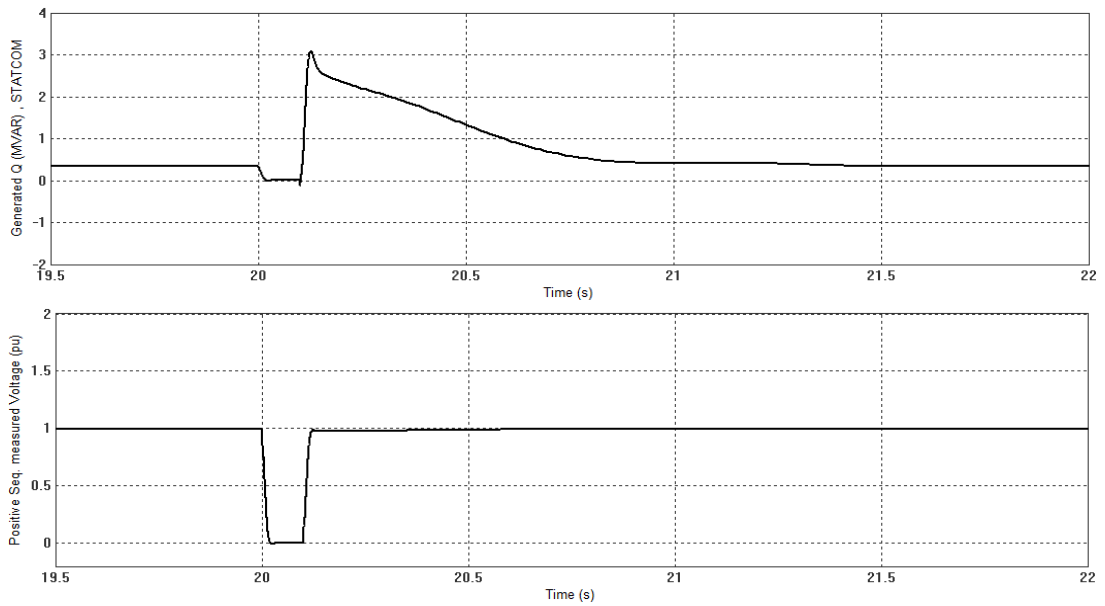


Figure (4.20): generated VAR and voltage of the STATCOM at three phase symmetrical fault for 100 ms

The other types of faults (line to line and double lines to ground) are simulated at PCC point and with the 400 KVAR capacitive VAR of the capacitor for 100 ms. The STATCOM MVA rating at the 400 KVAR of shunt connected capacitor should be at least 7.2 MVA to let the 3 MW wind turbine ride through the fault without tripping signal from the protection system, while its rating should be at least 4.7 MVA for the 925 KVAR of the capacitor, as shown in the following figures.

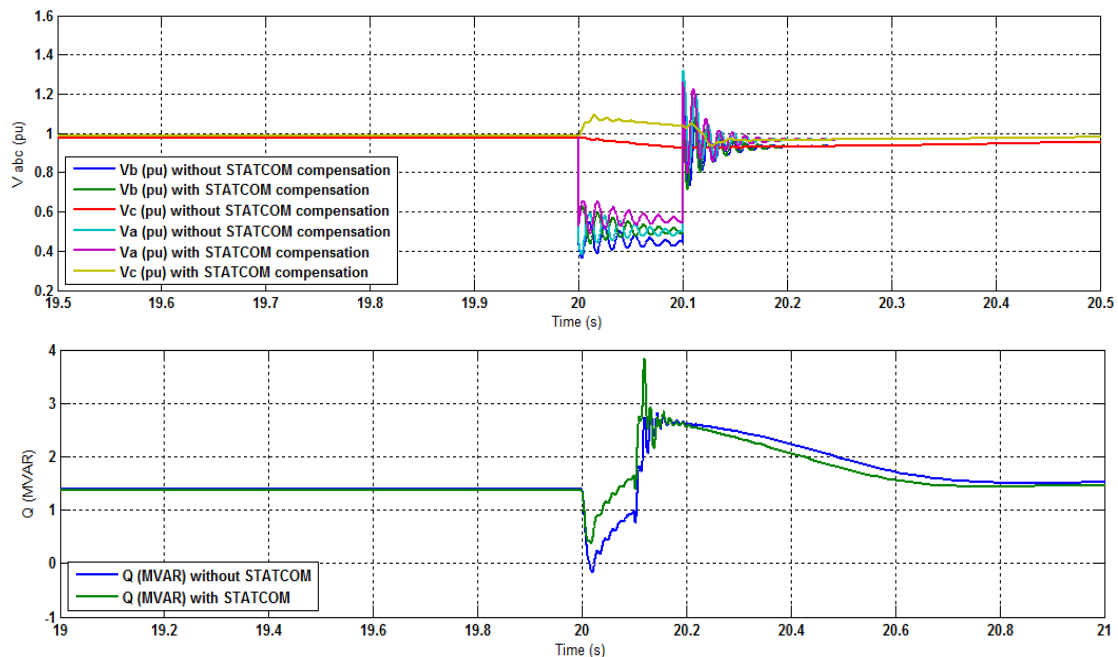


Figure (4.21): simulation of wind turbine voltage and reactive power with 7.2 MVA STATCOM and without it at (line to line fault) with 400 KVAR of capacitor

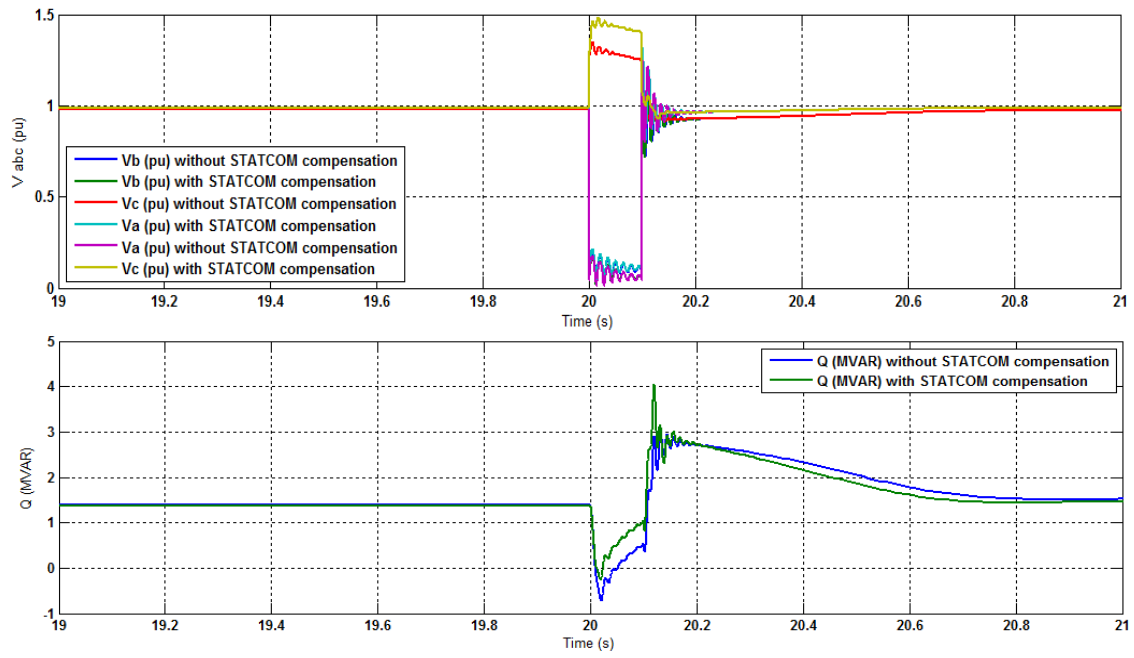


Figure (4.22): simulation of wind turbine voltage and reactive power with 7.2 MVA STATCOM and without it at (double lines to ground fault) with 400 KVAR of the capacitor

And with the 925 KVAR of capacitor and 4.7MVAR STATCOM rating

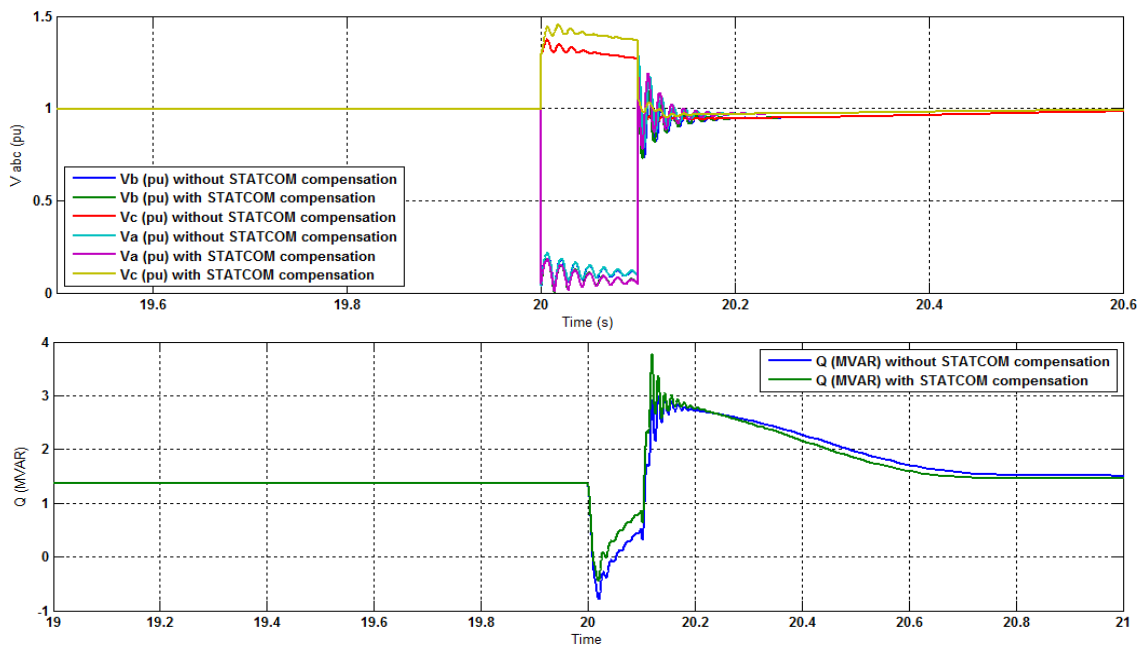


Figure (4.23): simulation of wind turbine voltage and reactive power with 4.7 MVA STATCOM and without it at (double lines to ground fault) with 925 KVAR of the capacitor

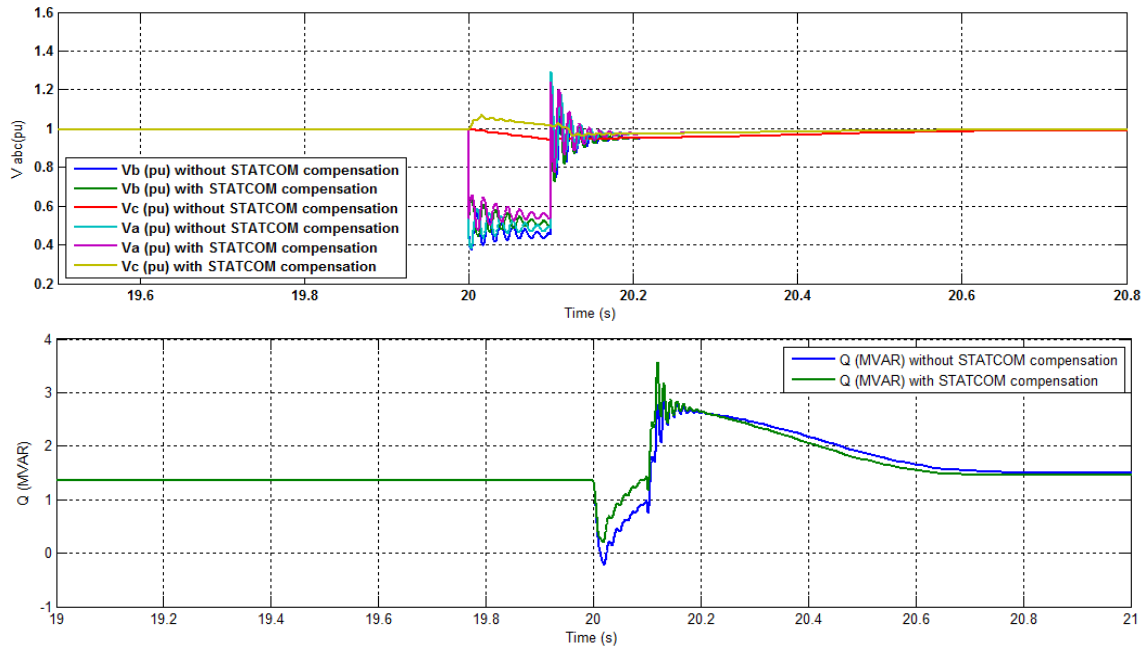


Figure (4.24): simulation of wind turbine voltage and reactive power with 4.7 MVA STATCOM and without it at (line to line fault) with 925 KVAR of the capacitor

The idea of this studying was to increase the value of the capacitive VAR of the capacitor from 400 KVAR to 925 KVAR to let the voltage at the point PCC at bus B_25 1.001 pu and to improve the power factor at this point and without using the STATCOM, now and after using it the voltage of the point PCC is becoming 1 pu and is fixed at this level and with the ability of the wind turbine to ride through (double lines to ground and line to line) faults with 4.7 MVA rating of the converter of the STATCOM. The reducing of the value of the converter rating of the STATCOM makes the ability to maximize the wind turbines of the wind farm.

4.8 RESETTING THE PROTECTION SYSTEM AFTER CLEARING THE CAUSE OF THE TRIPPING SIGNAL

Suppose there is a interruption in voltage at 120 Kv grid side for 2 seconds. In this case and as the limiting values of voltage interruption for the wind turbine operation is stted in section (4.4.3), the protection system sends a tripping signal to the circuit breaker to disconnect the wind turbine from the grid. After the opening of the circuit breaker, there should be a force act as a brake to the shaft of the generator to reduce the rotational speed of the SCIG up to zero.

If there was a clearing to the cause of voltage interruption and after some duration of time for delay say 8 seconds, the protection system is reseted and the

circuit breaker is closed and the wind turbine is reconnected again to the grid, as shown in figure (4.25).

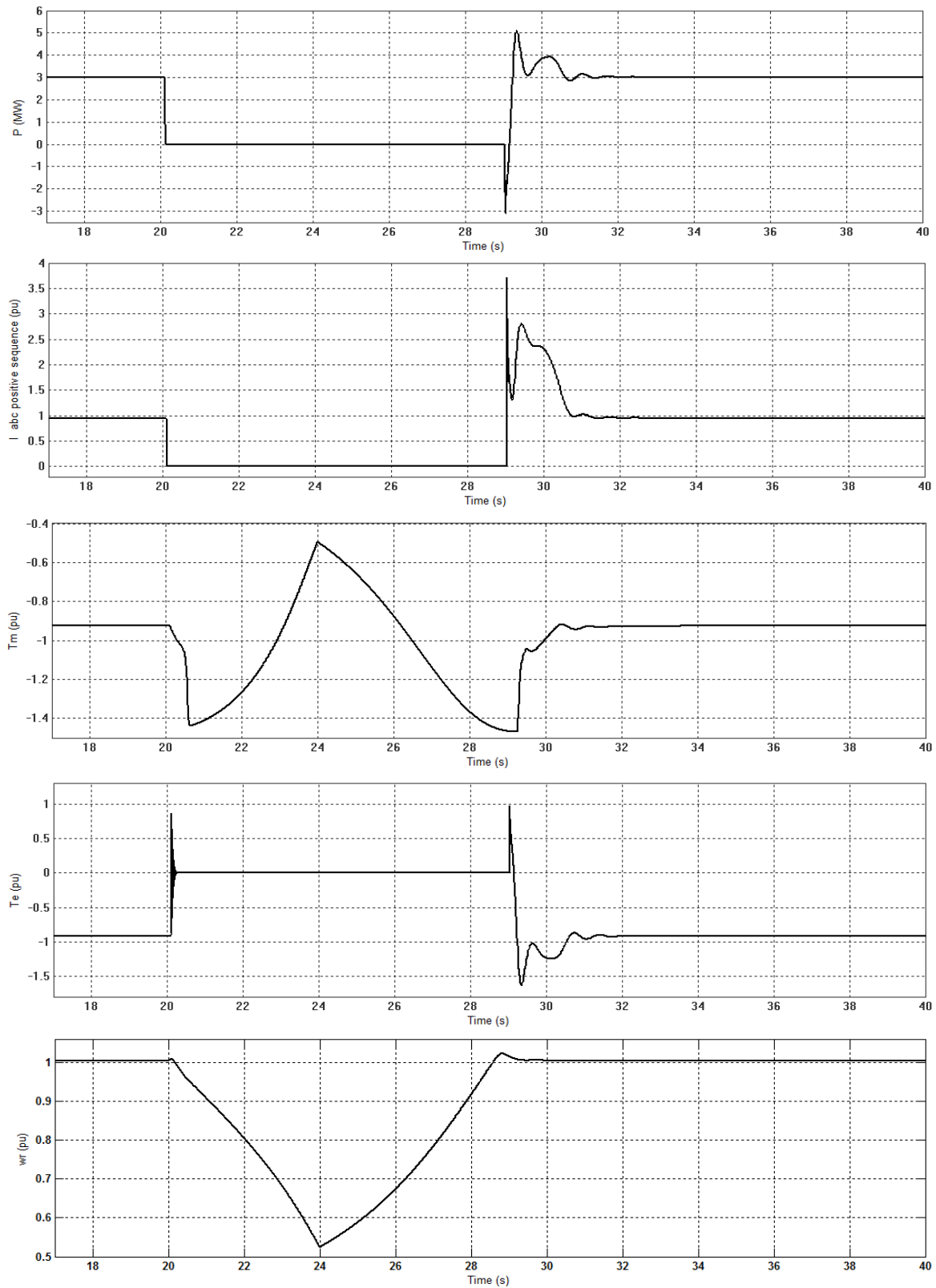


Figure (4.25): effect of tripping signal, resetting the protection system and resume the generation operation of the fixed speed wind turbine

The effect of stopping the operation of the fixed speed wind turbine is studied only at one issue which is the interruption in voltage at grid side, only to show the effect of disconnection and re-connection to the grid, and the assistances of this operation. As the wind turbine needs a protection system, from this study it can be noticed that the wind turbine also needs another system for reset the wind turbine after clearing of the obstacles of its normal operation. This system will be as a future work.

4.9 INCREASING WIND FARM GENERATING CAPACITY

4.9.1 Connection of multi wind turbines in a single wind farm, 12 MW

By connection of four units of fixed speed wind turbines of 3 MW capacity to make a 12 MW wind farm with the capacitance VAR of the capacitor is 400 KVAR and without using the STATCOM, all the units will be disconnected from the grid by the protection system when simulation time reaches 11.23 s due to the high reactive power demanded from the grid to the wind turbines, and this will reduce the voltage and increase the current at the PCC point at bus B_25, see figure (4.26), Whereas with using of the 925 KVAR of capacitor and without the STATCOM compensation all the units can work and generate electricity and without a disconnection from the grid. See figure (4.27).

According to the advantage that taken from the new value of capacitor VAR rating 925 KVAR, so it will be used for the simulations of the wind turbines performance in this section.

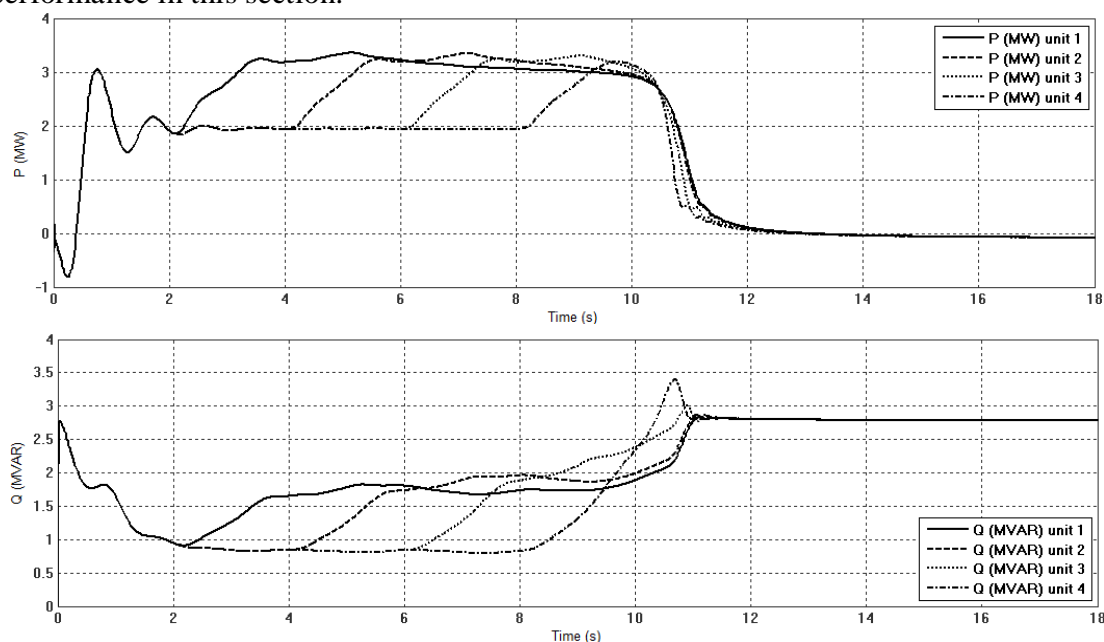


Figure (4.26.A): operation of 4 units of 3 MW wind turbine without STATCOM

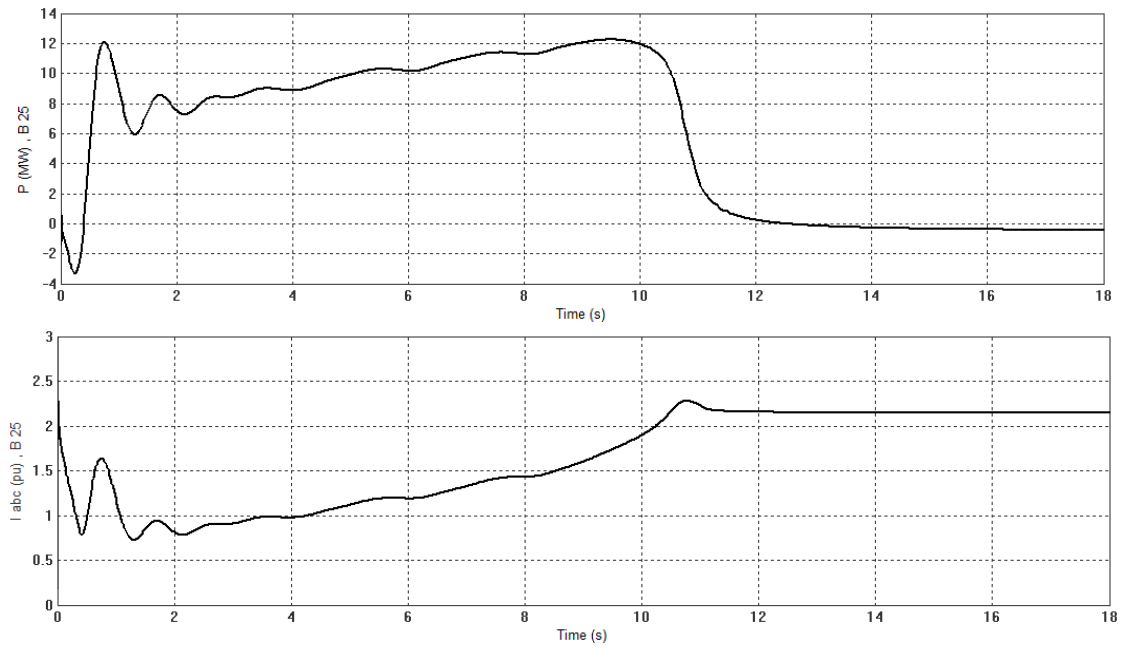


Figure (4.26.B): operation of 4 units of 3 MW wind turbine without STATCOM compensation and with 400 KVAR of capacitor

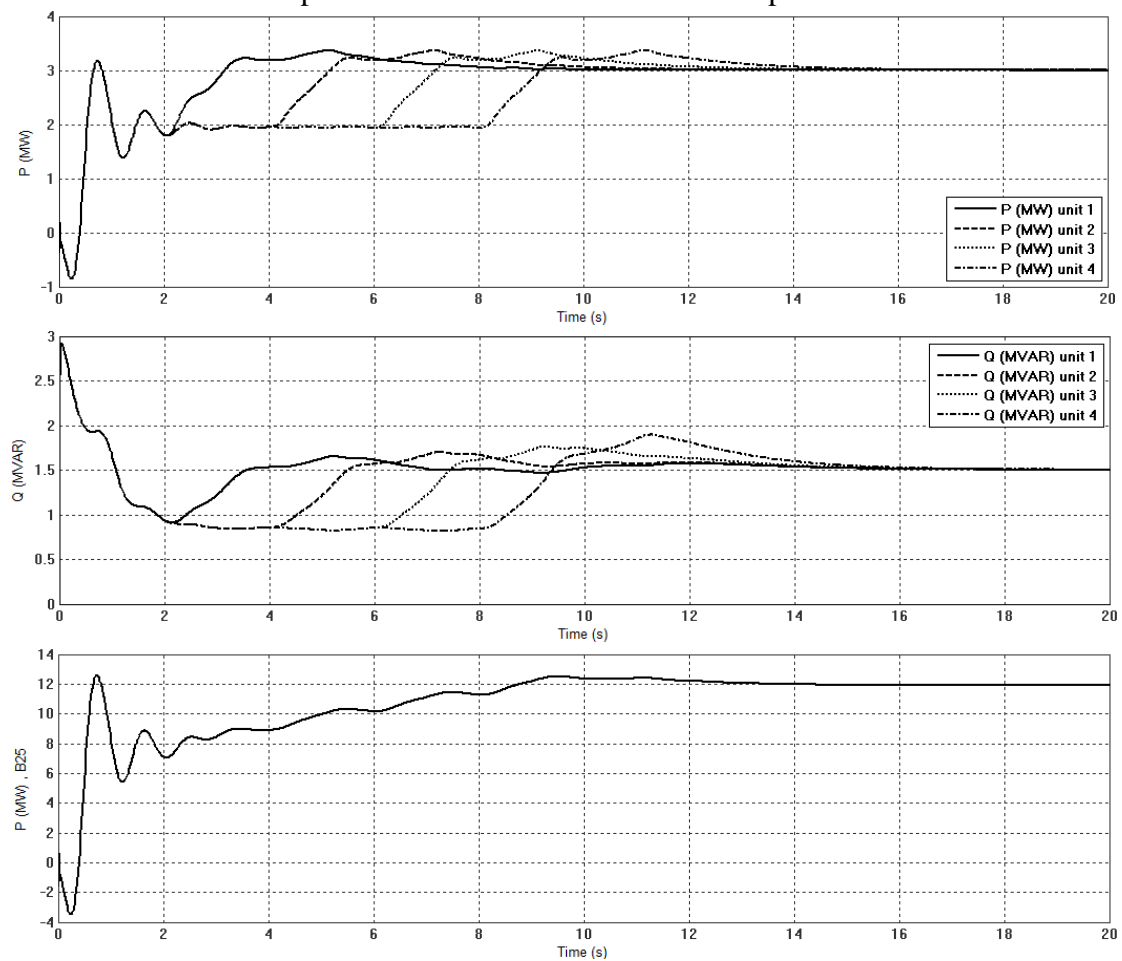


Figure (4.27.A): operation of 4 units of 3 MW wind turbine without STATCOM compensation and with 925 KVAR of capacitor

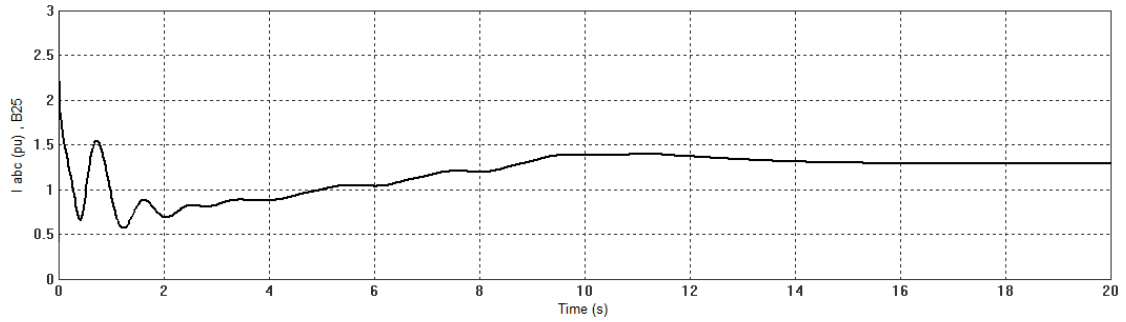


Figure (4.27.B): operation of 4 units of 3 MW wind turbine without STATCOM compensation and with 925 KVAR of capacitor

4.9.2 Different wind speeds at multi wind turbines in a single wind farm (12 MW)

As the wind speed is not uniformly distributed at all the wind turbines at the same time, but there is some differences in its values at all wind turbines blades in the wind farm, and this changing is happening continuously. See figure (4.28).

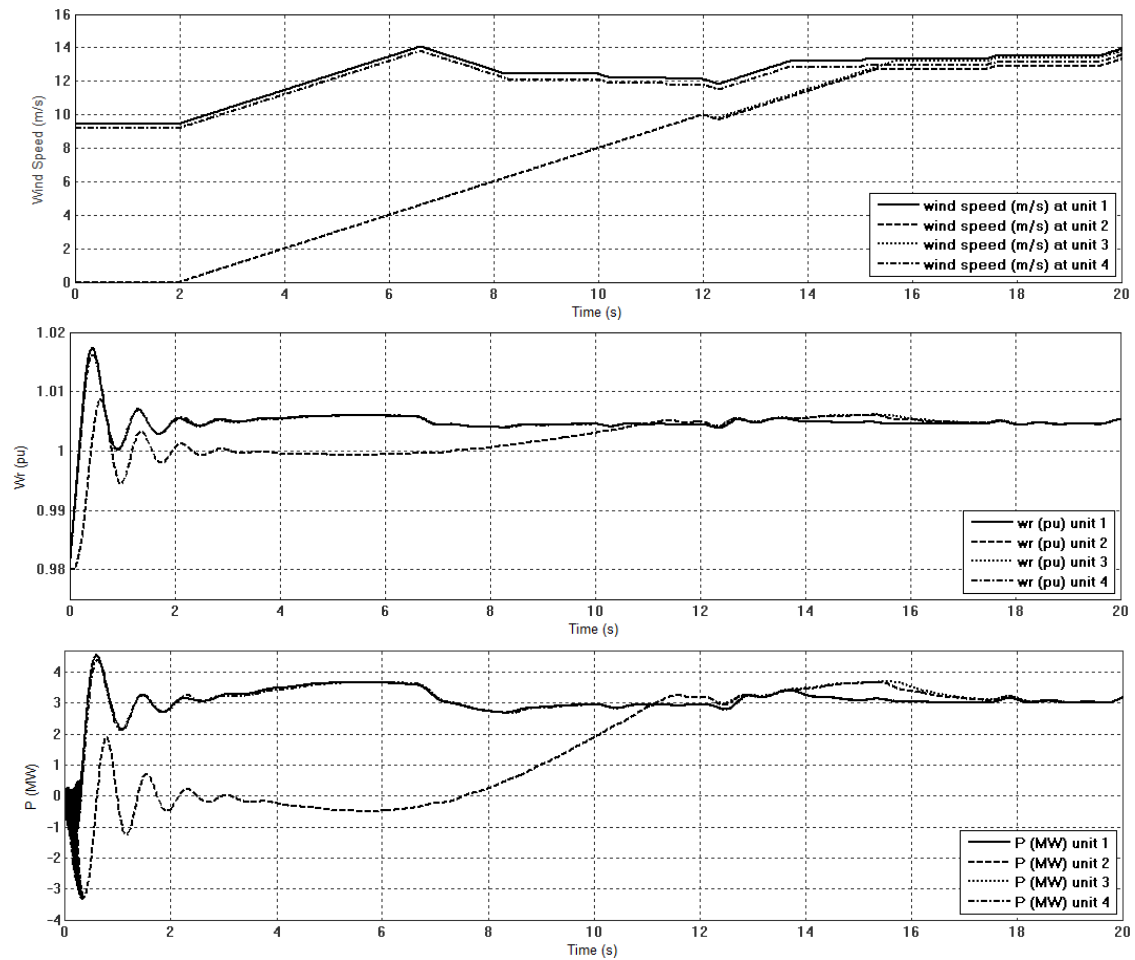


Figure (4.28.A): changing in wind speeds at 12 MW of wind turbines

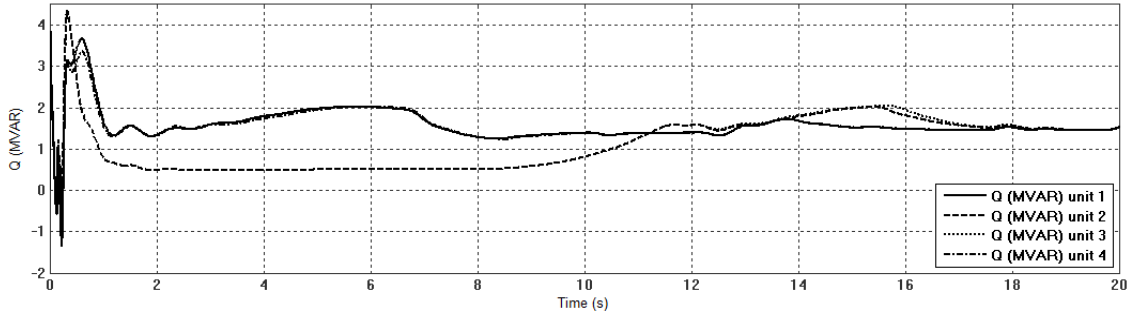


Figure (4.28.B): changing in wind speeds at (12 MW) of wind turbines

While at the PCC point the active power and current are fluctuating but with constant voltage as shown in figure (4.29)

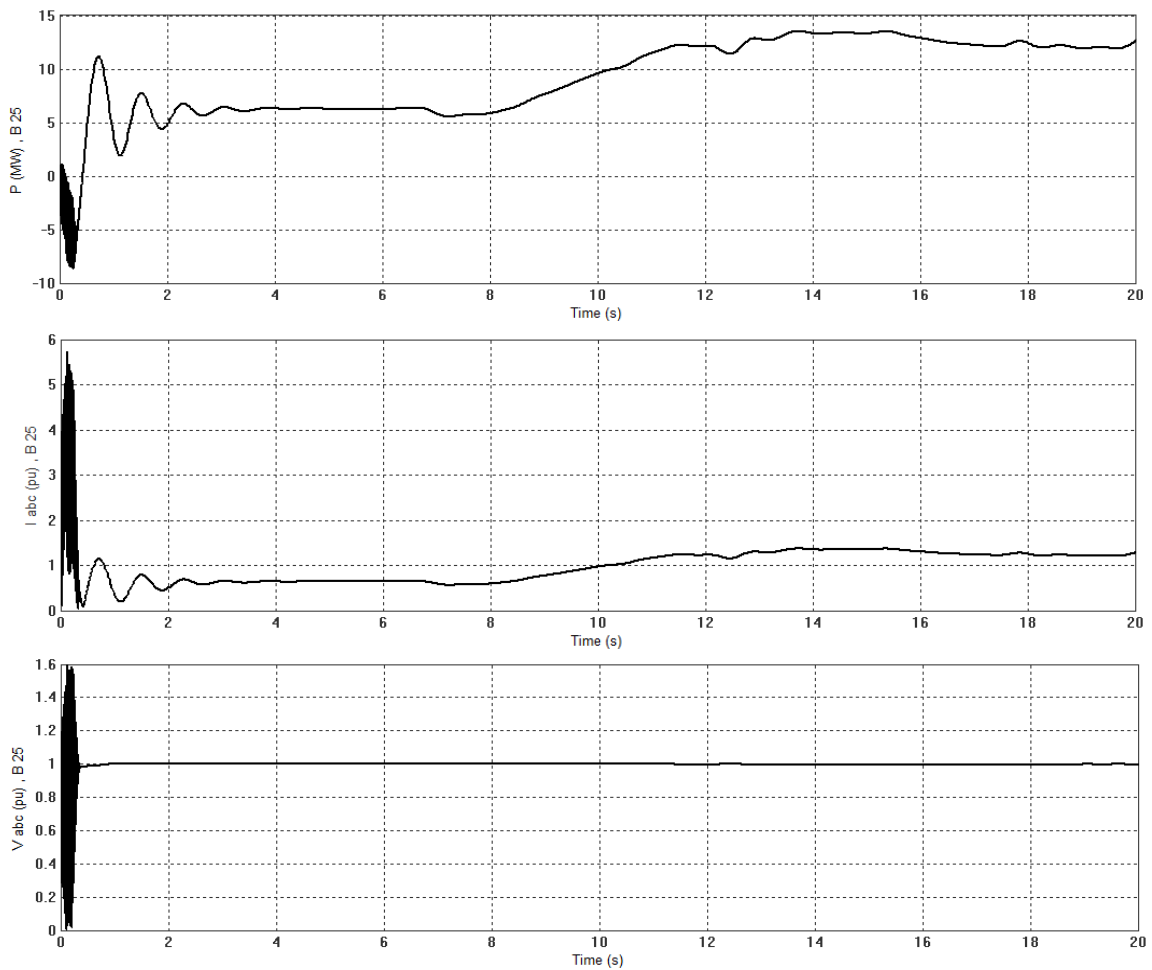


Figure (4.29): Active power, current and voltage in PCC point during the changing in wind speeds at 12 MW of wind turbines

4.9.3 Connection of multi wind turbines in a single wind farm, 36 MW

The starting of operation of the wind turbines in a wind farm should be in cascade style, suppose that a 36 MW wind farm contains 12 units of 3 MW, connected at the same time to the grid, it can be seen that for short duration of time no one of these

turbines can wake up to generate the power due to the high reactive power that taken from the grid and even if with the using of a 20 MVAR of STATCOM. See figure (4.30).

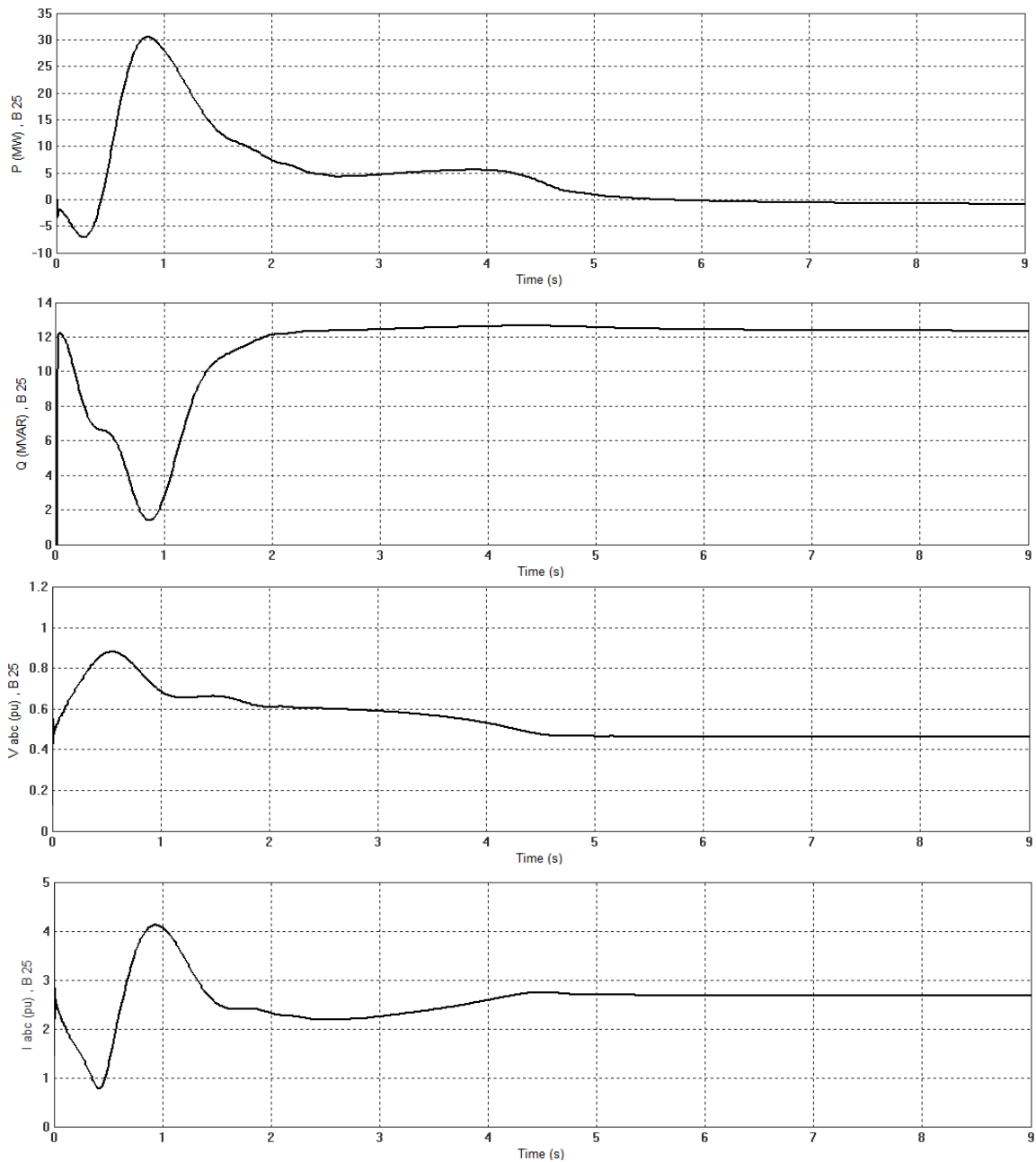


Figure (4.30): simulation of 12 wind turbines of capacities of 3 MW to make 36 MW wind farm, all units started at the same time

Whereas with a cascade way to make each 4 units start work together, see figure (4.31).

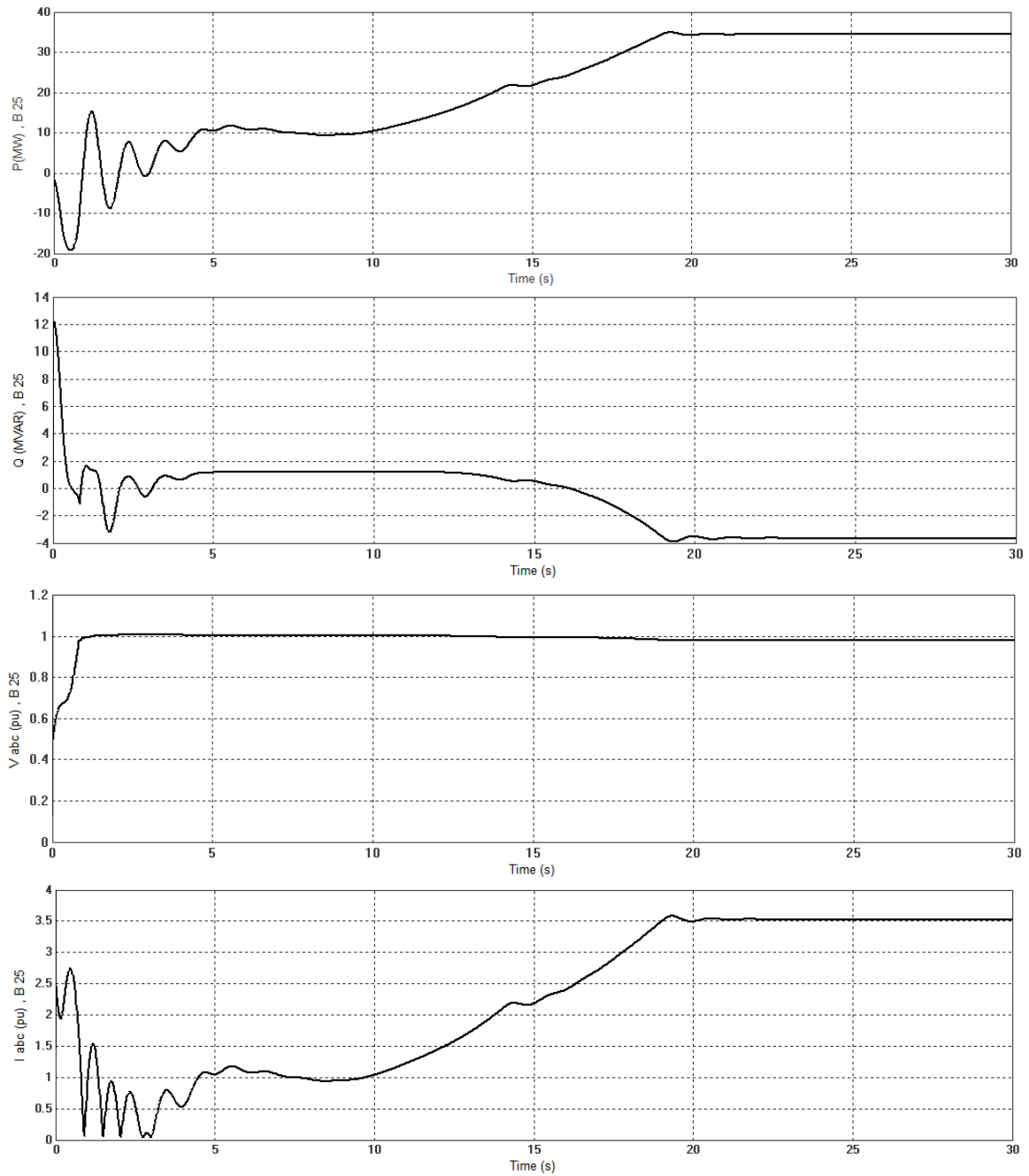


Figure (4.31): simulation of 12 wind turbines of capacities of 3 MW to make 36 MW wind farm, each 4 units started after 5 s in cascade style

4.9.3.1 LVRT of 36 MW wind farm

The whole 36 MW wind farm can ride through faults of (single line to ground , double lines to ground, and line to line) and also in case of voltage sag at grid side up to 0.2 pu for duration of 100 ms and the converter rating of the STATCOM is 35 MVA. See figure (4.32).

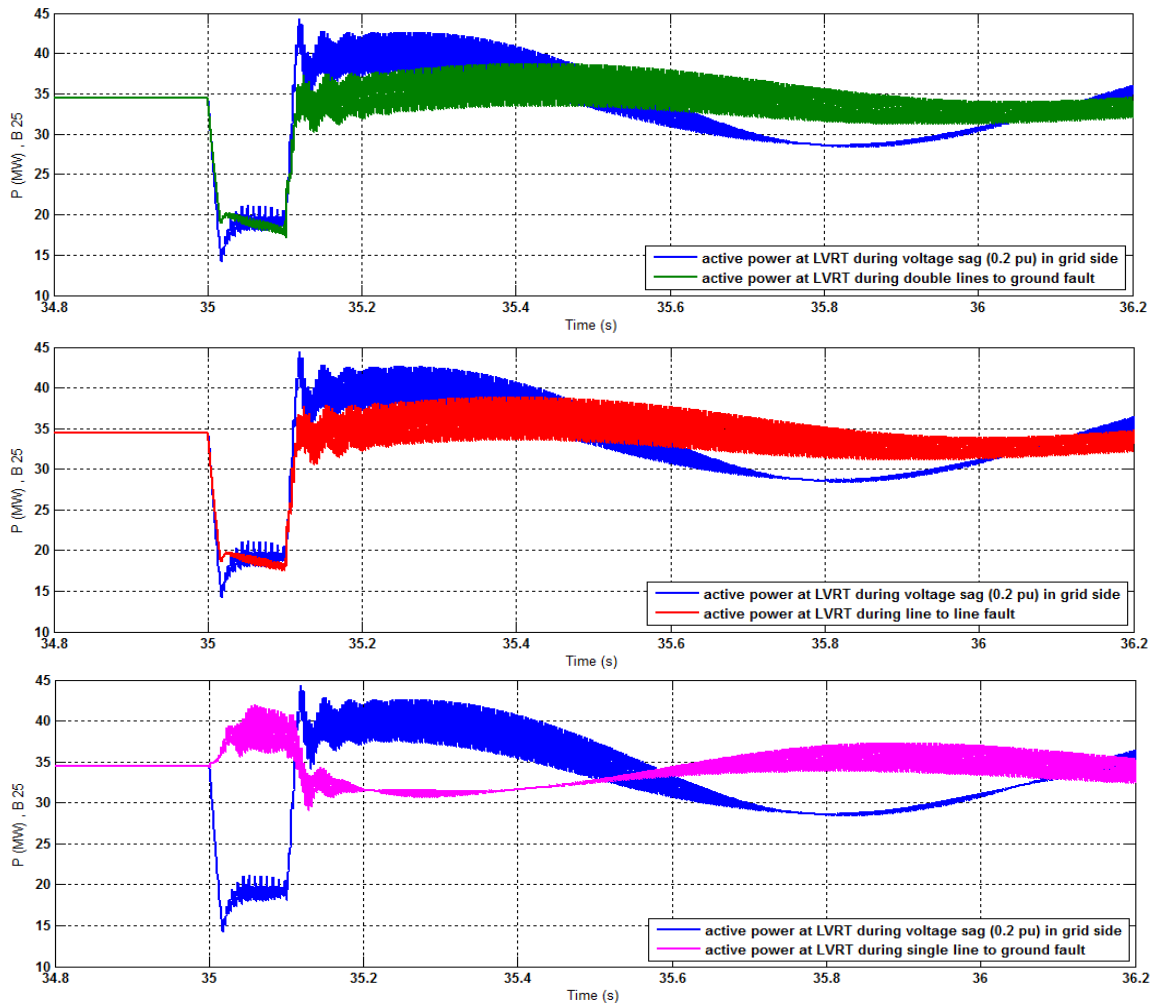


Figure (4.32): LVRT of (36 MW) wind farm with (35 MVA) rating of STATCOM

The thick line of active power at the PCC point is due to the power fluctuations and after removing the effects of fault or voltage dip in the simulation the curve will return to be as a straight line. These fluctuations are in range of 34 to 37 MW lasting for few seconds and then the system is gone to the steady state.

It can be noticed that at the faults of (line to line and double line to ground) durations, the power is reduced up to 17 MW, while it was reducing up to 15 MW during voltage sag at grid side but in case of single line to ground fault the active power is increased up to 42 MW due to increasing of the zero and negative sequences of current and voltage at PCC point.

4.10 SUMMARY

In the study of the performance of the fixed speed SCIG wind turbine WECS, there were some improvements were added to get the best results of performance of the fixed speed wind turbine. These types of improvements were in:

- Through the maximum rate of change of pitch angle to improve the performance of the wind turbine at different wind speeds and to get its (0 – 25 m/s, 0 – 3 MW) power curve.
- Through the Q_c (reactive power) of the capacitor that was connected to the wind turbine terminals to get the voltage at the PCC point equal 1 pu and the power factor equal 0.98, and the assistance of this value to reduce the VA ratings of the converter of the STATCOM that used for dynamic compensation of reactive power and voltage control at the PCC point with its advantages in the LVRT and ZVRT.
- The last improvement was in starting of multiple connections of wind turbines in the wind farm and the way of their starting.

The studies of the faults that happening at the PCC point are to Simulates the fact that is in the real ground, where the wind farm may have capacity more than 100 MW of wind turbines, so the study cases that happened in this chapter for LVRT at the PCC point where the wind turbines in the wind farm are gathered and connected as groups and if the faults are happened, some of the wind turbines are still in generating mode and the others which are affected by the fault are disconnected.

CONCLUSIONS AND SCOPE OF FUTURE WORK

5.1 CONCLUSIONS

In this search, the performance of the fixed speed SCIG wind turbine WECS are studied at different types of operation during system start-up and at steady state with a view of its operation at different issues that may happen to any WECS with single and multiple connections of wind turbines to power system grid. The conclusions of this work are summarized in the following points:

- According to the cut-in wind speed value this type of wind turbine is better for working in offshore sites.
- The wind turbine should not be started at the wind speeds equal or greater than rated wind speed, because this may lead to expose it to a mechanical stress or defect in the insulator of the SCIG stator windings of the wind turbine due to high starting currents. For these reason there must be an existence of mechanical brakes that open gradually at starting and also with using of soft starters.
- The value of maximum change of pitch angle is an important factor for the operation of pitch angle controller of the wind turbine blades, which through it the wind turbine can follow the fast changes of wind speeds that above rated wind speed value.
- The wind turbine should not exposed to a re-switching transient case in sudden form during its normal operation, since this leads to increasing in the current and mechanical and electrical torques for several times to their rated values, which may lead to expose the wind turbine to a mechanical stress, And high currents that may damage the SCIG stator windings of the wind turbine.
- The value of provided reactive power of the capacitor which is connected to the wind turbine terminals for reactive power compensation at no load should be selected to make the value of the voltage at the PCC point is near (1 pu) and with high power factor.
- The wind turbine has the ability for ZVRT (zero voltage rides through), that may happen due to symmetrical faults at the PCC point up to (90 ms) to still

running without disconnection due to protection system but with its terminal voltage is zero and power also is zero.

- The wind turbine has the ability for ZVRT (zero voltage rides through), that may happen due to voltage interruption without a tripping signal from the protection system and to serve power up to (90 ms).
- The wind turbine has the ability for LVRT due to happening of the faults of (line to line and double lines to ground) for (100 ms) and for (180 ms) for the (single line to ground) fault.
- The voltage sag leads to drop of voltage at the terminals of the wind turbine and also drop in its active power that supplied from it. The wind turbine can ride through the voltage sag at minimum value of (0.46 pu) for (100 ms).
- All the operations of ZVRT and LVRT of the wind turbine are done with assistance of a STATCOM.
- The effect of voltage swell is the rise of the voltage at the terminals of the wind turbine with decrease of its current. The STATCOM can absorb this increasing in the voltage and reactive power also but partially and without tripping signal from the protection system.
- By connection of multiple wind turbines and with their different changes with their respective rotational speeds, it can be noticed that the power and the current at their clustering point or PCC point are in change but with constant voltage. This makes the possibility to regard that the wind farm can be considered as big single wind turbine at different of power capacities and current values but with a constant voltage. This is useful for simulation a wind farm as a single or few equivalent wind turbines for some particular studies.
- For the connection of multiple wind turbines inside the wind farm and their integration with power system grid, each few numbers of wind turbines should be connected in one node in the PCC point through a circuit breaker for their starting and stopping in cascade manner.
- The cascade starting of the wind turbines groups inside the wind farm is for simplifying the operation of starting all of the wind turbines to avoid the drop of voltage and the high reactive power at the PCC point. This principle of operation leads to stability of operation of whole the system and to avoid

opening of the circuit breakers of the individual wind turbine protection system due to the voltage drop at the PCC point.

5.2 SCOPE OF FUTURE WORKS

As the direct connection of fixed speed SCIG wind turbine is studied, the future work is to:

- Study the performance and issues of FRC (fully rated converter) variable speed SCIG wind turbine WECS that used in offshore wind farm connection.
- Make a system for stopping the wind turbine after applying a tripping signal and to resume its work again after clearing of the causes of the tripping.

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APPENDIX A

GENERIC PARAMETERS OF THE SYSTEM NETWORK

According to the system of figure (4.1), the fixed speed wind turbine ratings are:

| | |
|---|-------------|
| Nominal mechanical output power | 3 MW |
| Base wind speed | 9 m/s |
| Maximum power at base wind speed (pu of mechanical power) | 1 |
| Pitch angle controller [K _p K _i] | [5 25] |
| Maximum pitch angle | 45 degree |
| Maximum rate of change of pitch angle | 11 deg./sec |

Table (A.1): parameters of fixed speed wind turbine

The SCIG data parameters are:

| | |
|-------------------------------|--------------|
| Nominal electric power | 3 MW |
| Apparent power | 3.3333 MVA |
| Nominal voltage and frequency | 575 V, 60 Hz |
| Power factor | 0.9 |
| Stator resistance | 0.004843 pu |
| Rotor resistance | 0.004377 pu |
| Stator leakage inductance | 0.1248 pu |
| Rotor leakage inductance | 0.1791 pu |
| Mutual inductance | 6.77 pu |
| Inertia constant | 5.04 sec. |
| Viscous Friction factor | 0.01 pu |
| No. of poles | 6 |
| Initial slip | 0.02 |

Table (A.2): parameters SCIG of fixed speed wind turbine

Parameters of Three-Phase PI Section transmission Line

| | |
|--|-------------|
| Frequency used for R L C specification | 60 |
| Positive sequence resistance | 0.1153 Ω/Km |
| Zero sequence resistance | 0.413 Ω/Km |

| | |
|-------------------------------|-----------------------------|
| Positive sequence inductance | 1.05×10^{-3} H/Km |
| Zero sequence inductance | 3.32×10^{-3} H/Km |
| Positive sequence capacitance | 11.33×10^{-9} F/Km |
| Zero sequence capacitance | 5.01×10^{-9} F/Km |

Table (A.3): parameters of Three-Phase PI Section transmission Line

Parameters of 25 KV/575 V Transformer (star / grounded star)

| | |
|-------------------------------|-------------|
| Nominal rating power | 4 MVA |
| Frequency | 60 Hz |
| Primary windings resistance | 0.025/30 pu |
| Secondary windings resistance | 0.025/30 pu |
| Primary windings inductance | 0.025 pu |
| Secondary windings inductance | 0.025 pu |
| Magnetization resistance | 500 pu |
| Magnetization inductance | infinity |

Table (A.4): parameters of 25 KV/575 V Transformer

Parameters of 120 KV/25 KV Transformer (grounded star / delta)

| | |
|-------------------------------|------------|
| Nominal rating power | 47 MVA |
| Frequency | 60 Hz |
| Primary windings resistance | 0.08/30 pu |
| Secondary windings resistance | 0.08/30 pu |
| Primary windings inductance | 0.08 pu |
| Secondary windings inductance | 0.08 pu |
| Magnetization resistance | 500 pu |
| Magnetization inductance | 500 pu |

Table (A.5): parameters of 120 KV/25 KV Transformer

The calculation of capacitance value at the terminals of wind turbine as the relations that is taken from [31]:

$$Q_c = 3 V_c I_c = 3 (V_s)^2 \omega_s C \quad (\text{A.1})$$

$$C = \frac{Q_c}{3 (V_s)^2 \omega_s} \quad (\text{A.2})$$

so for capacitor of (400 KVAR)) the three phase capacitance is:

$$C = 1.0967 \times 10^{-3} \text{ farad}$$

And for capacitor of (925 KVAR) the three phase capacitance is:

$$C = 2.4737 \times 10^{-3} \text{ farad}$$

This shunt capacitor should be connected to the terminals of the fixed speed SCIG wind turbine in (Delta) connection.

Protection system setting parameters:

| | |
|--|------------------------------|
| Fundamental frequency | 60 Hz |
| Instantaneous Ac over current (positive-sequence) | 10 pu |
| Maximum Ac current [I max, Delay] | [1.1 pu, 10 sec.] |
| Maximum Ac current unbalance [I_2/I_1 max , Delay] | [0.4 pu, 0.2 sec.] |
| Ac under/over voltage [V_1 min, V_1 max, Delay] | [0.75 pu, 1.1pu, 0.1 sec.] |
| Maximum Voltage Unbalance [V_2/V_1 max, V_0/V_1 max, Delay] | [0.05 pu, 0.05 pu, 0.2 sec.] |
| Under/Over rotational Speed [Speed_min, Speed_max, Delay] | [1 pu, 1.05 pu, 5 sec.] |
| Under/Over wind Speed [wind Speed_min, wind Speed_max, Delay] | [5.6 m/s, 25 m/s, 5 sec.] |
| Start time for protection system | 5 sec. |

Table (A.6): setting parameters of the protection system of each wind turbine

$C_p(\lambda, \beta)$ GRAPH PLOTTING CODE IN MATLAB

```

% In this system of wind turbine where the maximum power coefficient
% is 0.48 at 0 pitch angle and lambda =8.1
% % cp(lambda,pitchangle)=c1*(c2/lambda_i-c3*pitch_angle-c4)*exp(-
% c5/lambda_i)+c6*lambda
% and
% lambda_i=1/(1/(lambda+0.08*pitch_angle)-0.035/(pitch_angle^3+1))
% the constants are c2=116,c3=0.4,c4=5,c5=21.
% to calculate the constants c1& c6 is as follows:
% c1=cp_max/((c2/lambda_i_nom-c4)*exp(-
% c5/lambda_i_nom)+k_nom*lambda_nom)
% c6=k_nom*c1;
clc
c2=116;c3=0.4;c4=5;c5=21;
lambda_nom=8.1;
    cp_max=0.48;
    cp_nom=cp_max;
    lambda_i_nom=1/(1/lambda_nom-0.035);
    k_nom=-((c2*c5/lambda_i_nom-c4*c5-c2)*exp(-
c5/lambda_i_nom)/lambda_nom^2);
    c1=cp_max/((c2/lambda_i_nom-c4)*exp(-
c5/lambda_i_nom)+k_nom*lambda_nom);
    c6=k_nom*c1;
    P_wind_base=1;
    wind_base=9;
    speed_nom=1;
    wr_elec_pu=1e-3:0.02:1.5;
    pitch_angle=0:9:45
    wr_mec_pu=wr_elec_pu/speed_nom;
    wind_max=9:.01:25;
    wind_min=1:.002:9;
        wind_pu=[wind_min wind_max]/wind_base;
        for k=1:length(wind_pu)
            for i=1:length(wr_mec_pu);
                for m=1:length(pitch_angle)
lambda_pu(k)=wr_mec_pu(i)/wind_pu(k);
                lambda=lambda_nom*lambda_pu;
                lambda_i(k)=1/(1/(lambda(k)+0.08*pitch_angle(m))-
0.035/(pitch_angle(m)^3+1));

                    cp(k,m)=c1*(c2/lambda_i(k)-c3*pitch_angle(m)-c4)*exp(-
c5/lambda_i(k))+c6*lambda(k);
                    cp_pu(k,m)=cp(k,m)/cp_nom;
                end
            end
        end
    end
plot(lambda,cp)

```