# A STATCOM BASED PMSG WIND ENERGY SYSTEM

By

Anil Thapa
22171004

A project submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Masters of Engineering

Department of Electrical and Electronic Engineering
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## Declaration

It is hereby declared that

1. The project submitted is my own original work while completing degree at BRAC University.
2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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# Approval

The project titled “A STATCOM BASED PMSG WIND ENERGY SYSTEM” submitted by Anil Thapa has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Masters of Engineering in Electrical and Electronic Engineering.

**Examining Committee:**

Supervisor:
(Member)

___________________________________
Dr. Abu Hamed M. Abdur Rahim
Professor, Electrical and Electronic Engineering
Brac University

Internal Expert Examiner:
(Member)

___________________________________
Dr. A.S. Nazmul Huda
Assistant Professor, Electrical and Electronic Engineering
Brac University

Departmental Head:
(Chair)

___________________________________
Dr. Md. Mosaddequr Rahman
Professor and Chairperson, Electrical and Electronic Engineering
Brac University

## Ethics Statement

This is to certify that this thesis titled "A STATCOM BASED PMSG WIND ENERGY SYSTEM" is the result of my study for partial fulfillment of Master of Science in Electrical and Electronic Engineering degree under supervision of Dr. Abu Hamed M. Abdur Rahim, Professor, Department of Electrical and Electronic Engineering, Brac University and no part of this work has been submitted elsewhere partially or fully for the award of any other degree or diploma.

# Abstract

With ever increasing growth of the wind power, the large penetration of wind energy has brought opportunities along with challenges integrating it in the existing power system grid. A power system network is complex and the contingencies are inevitable. The energy generated from the wind is intermittent and need proper Maximum Power Point Tracking (MPPT) Algorithm with appropriate power electronics device. The situation is more difficult for variable speed PMSG system connected to weak grid. The grid codes are necessary to strictly comply with a set of rules that address reactive power control, power quality, voltage ride through to minimize the grid instability and power quality issues.

STATCOM is one of the promising FACTS devices extensively used in solving power quality issues. This project studies the role of permanent magnet synchronous generator (PMSG) wind turbine system with STATCOM controller for reactive power compensation. A detailed model of the PMSG along with the dynamics of the converters have been included. DC link capacitor voltage of the back-to-back converter needs to be maintained within strict limits for smooth power transfer in the system. The STATCOM is placed at the terminal of the grid side converter. An independent P-Q controller is designed for STATCOM to provide the necessary reactive power to regulate DC link capacitor voltage and maintain stability. The simulation studies have shown that the proposed controller provides good damping and settles the transients satisfactorily following the disturbances.

**Keywords:** Wind energy, permanent magnet synchronous generator, STATCOM, independent P-Q control, MPPT

*Dedicated to*

*My Dearest Mother and Father*

*My loving Brother and Sister*

*And*

*My Respected Teachers*

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## Table of Contents

# List of Figures

# List of Tables

## List of Acronyms

| | |
|---|---|
| BESS | Battery Energy Storage System |
| DFIG | Doubly Fed Induction Generator |
| ECS | Energy Capacitor System |
| EESG | Electrically Excited Synchronous Generator |
| ESS | Energy Storage System |
| FACT | Flexible AC Transmission System Device |
| FRT | Fault Ride Through |
| LVRT | Low Voltage Ride Through |
| HVAC | High voltage AC |
| HVDC | High voltage DC |
| IGBT | Insulated Gate Bipolar Transistor |
| MPPT | Maximum Power Point Tracking |
| MVAR | Mega Volt Ampere Reactive |
| MW | Megawatt |
| MWh | Megawatt hour |
| PI | Proportional plus Integral |
| PID | Proportional plus Integral plus Differential |
| PMSG | Permanent Magnet Synchronous Generator |
| PSS | Power System Stabilizer |

| | |
|---|---|
| SCIG | Squirrel Cage Induction Generator |
| STATCOM | Static Synchronous Compensator |
| SVC | Static Var Compensator |
| TW | Terawatt |
| TWh | Terawatt hour |
| VFC | Variable Frequency Converter |
| VSC | Voltage Source Converter |
| VSWT | Variable Speed Wind Turbine |
| WECS | Wind Energy Conversion System |
| WEPP | Wind Energy Power Plant |
| WRIG | Wound Rotor Induction Generator |
| WT | Wind Turbine |
| WTGS | Wind Turbine Generating System |

# Chapter 1

# INTRODUCTION

## 1.1 Renewables and wind energy

Global warming and environmental concerns are drawing attention on renewable alternatives. The whole world is heavily reliant on fossils fuels Renewable energy sources include generation of electricity from the perpetual natural resources like wind, water, bio mass, tides etc. The energy from such resources can be generated on the site only and distributed to the people around the vicinity. This looks even promising for the geographically constrained area where the distribution line is difficult to extend because the resources are freely available in locality. Out of all the renewable resources, the power from wind energy has achieved increased attention [1-3]. In 2014, the energy supported by wind energy surpassed more than gas and coal combined with installation of 11,791 MW [3]. An increased effort has been put in the renewable energy technologies, of them are solar PV and wind turbine system.

Wind power has proved to be the cheaper source of renewable energy. Besides, it is also environment friendly and doesn’t affect the ecosystem like fossil fuels. According to data obtained from US energy website [4], the countries with the largest total installed capacity are China (288 320 MW), US (121 985 MW), Germany (62 850 MW), India (38 625 MW) and Denmark (3136 MW). As the covid 19 pandemic hit the world miserably, the production and development in the wind turbine system has taken some break but still progressing. In accordance with global wind energy council report, 93.6 GW wind power capacity was added worldwide in 2021 [1,4]. These data substantiated that electrical power produced by wind turbine generators has been increasing steadily, which promises that the wind technology will be in many different parts of the countries across the globe.

## 1.2 Wind Turbine Systems

The historical data on wind turbine reveals that the modernizations and technological innovation wind of energy technology dates back to 1972s. The global market for the electricity production from wind turbine system has been ascending gradually. This trend shows participation of clean energy production in the world dominated by the fossil. A number of studies has been carried out in the wind turbine system to ensure its operation effectively from different perspective regarding the fixed or variable speed or nature of constructions. Two most generally established and tested wind turbine generator are: fixed speed wind turbine generator and variable wind turbine generator systems. The generator employed in the fixed speed wind turbine system is the induction type generator directly connected to the grid. In early prototype, synchronous generators have been used but the induction generator is mostly preferred because of low cost and flexibility for mechanical adjustment with rapid wind fluctuations. The generators utilized in the variable speed generators are either variable speed doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) [5].

Wind turbine systems are being explored these days with PMSG by employing double mass drive train system that includes gear box. This step can lead to larger number of smaller wind turbine systems that could produce an output as close to DFIG.

A variable wind speed turbine utilizes optimal tip speed ratio method that determines the rotor speed related to the current wind speed. This is one of the Maximum Power Point Tracking (MPPT)techniques in order to obtain maximum power [7]. The method requires use of the anemometer to measure the wind speed. This method is suitable only at very low or medium speeds in the normal operating zone between cut in and cut off speed. The pitch control system along with the wind speed measurement requires the extra sensors in the mechanical design and increase the cost of the system.

Variable speed wind turbines have certain merits like reduced mechanical stress, decoupling of the torque oscillation. The reduced mechanical stress means the system is not heavy and cost of the system is also low. Decoupling of torque oscillation means that the oscillation in generation sites least affect the grid side.

The overall efficiency of the modern variable speed wind generators is enhanced by the configuration of the electronic power converters such as cycloconverter and voltage-controlled inverter. The difference between these two converters is due to the mode of their transmission of the power. Cycloconverters are the power electronics converter that is like amplifier that amplifies the ac power to new value with required frequency at the grid. Voltage source inverter converts AC power to DC power and again back to AC power at a fixed system frequency for the transmission in the grid.

There are two configurations in variable wind speed wind turbine that have gained wide recognition in the research field of wind energy technology. They are doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG). They are different in the mode of operation that DFIG transfers around 30% of the total power generated to the grid side while the PMSG transfers whole the power generated at the generator to the grid. The PMSGs are known as direct driven PMSG with full scale power converter [10]. The salient features of this configuration are that PMSG doesn’t require gear box, known as direct driven, which reduces cost and weight. Additionally, the designed configuration coupled with the advanced power electronics can yield higher efficiency over wide range of speed [9,11]. The full-scale converter constitutes of the electronic converters at the generation side called generator side converter and the converter at the transmission side called the grid side converter. There exists a dc link capacitor in between these two converters to transfer the power. The grid side converter converts the ac voltage obtained from turbine system to acceptable dc voltage which means to regulate the dc bus voltage. Then dc link capacitor is responsible for transferring power from generator to grid side. The full-scale converter requires well designed system for the uninterrupted power supply maintaining the power quality at desired frequency. The converter is also resilient to the contingencies like faults and grid failures for defined period of time.

There has been rapid development in the field of power electronic based devices to utilize in the power system. FACTS devices power electronic based device which are very essential in wind energy system to maintain the power quality at a desired level. The wind speed is random, there will be much of the fluctuations arising from the generation side and also from the load side due to unbalanced load and various faults. FACTS device can support the system during such contingencies by providing the active and reactive power to the grid.

FACTS devices are flexible alternating current transmission system devices. They are mostly power electronic based device. There are different types of FACTS device depending upon their arrangement either series or shunt, static or dynamic. Static VAR Compensator (SVC) is one of the most popular FACTS devices. It is a shunt device capable of providing instant reactive power control at the point of common coupling (PCC) on bus. STATCOM is another popular device similar to SVC, but it utilizes a voltage source converter (VSC) based technology to provide fast reactive power/voltage control [16,17,18]. A voltage converter that mimics the behavior of PWM technique incorporating STATCOM is proposed to stabilize the PMSG based variable speed wind turbine connected to the grid.

Interconnection of number of electronically interfaced power sources with rapid variation hinders the power system stability. The stability can be improved by implementing STATCOM which can operate as main controller for the variable speed wind turbine PMSG.

## 1.3 Variable Speed Wind Turbine PMSG Control Systems

As much wind power seems promising renewable energy source, more the challenges and technical constraints are. This is because of the fact that the wind power gets fluctuated due to change in wind speed causing a nightmare to the power grid institution and their owners. It is to smoothening of wind power fluctuation up to certain range by pitch angle control of the wind turbine. The controls at the load side are generally voltage source converter or energy storage device. STATCOM is integrated with supercapacitor to deal with the power quality issues arising in the system [47]. In [22], the battery energy storage system (BESS) is implemented in the dc link capacitor side. Implementing supercapacitor instead of battery is implemented in this research [23].

## 1.4 Problem Statement

The prominent issue with variable speed wind turbine systems is the inadequacy of the system to maintain power quality during faults, fluctuation in power supply and unbalanced load conditions. As the grid codes have been introduced strictly to assure the power quality problems, low voltage ride through (LVRT) has become the important requirement in power grid operators. In this project, the disturbances are simulated as short wind gust and torque pulse. Maintaining the DC link capacitor voltage to strict limit for stability of system is of paramount importance. Out of all the FACTS devices. STATCOM has been showing promising performance while managing the power quality issues like supplying reactive power. The DC link capacitor voltage is also kept in permissible range avoiding instability [16-18].

## 1.5 Problem Objective

A major objective of this research is to design independent P-Q controller for the PMSG attached with STATCOM at grid side and control the transient behavior during the presence of disturbance relating to short wind gust and torque pulse. The controller design should be robust to maintain DC link capacitor voltage constant and adequately controlling the transients. The suggested processes are performed to achieve objective of this project are as follows:

1. Performing literature survey for variable speed WECS and use of STATCOM in this operation.
2. Developing a non – linear model of dual mass system PMSG with STATCOM for a single machine infinite bus system.
3. Designing the independent P-Q controller.
4. Performing the transient response study.

## 1.6 Project Organization

The organization of the report is as it follows:

**Chapter 2: Literature review**

Wind turbine generator system, variable speed operation methods and the prospects of STATCOM in Wind Energy Conversion System. The recent research, study, application and implementation of STATCOM in WECs along with their contribution on power quality and transient issues.

**Chapter 3: System model**

Modelling of the PMSG wind along with its converter and STATCOM with local load and the relevant mathematical model is derived.

**Chapter 4: Independent P-Q model and control**

This chapter is concerned with the design and implementation of the independent P-Q controller for STATCOM.

## Chapter 5: Simulation results

Simulation results of the system in the presence of short and sudden wind gust is presented. Various graphical plots are presented to show the transient performance and the stability of the system to show the effectiveness of the controller.

## Chapter 5: Conclusion and future work

Finally, the project work is summarized and concluded in this section along with the future work.

# Chapter 2

# LITERATURE REVIEW

In this chapter, the literature survey done for the successful accomplishment of the project is summarized. The chapter is categorized into four major sections. The first section of literature review introduces the types of wind turbine with latest research on the implementation of permanent magnet synchronous generator in conjunction with power electronic devices for variable speed operation. The second section will discuss the various ways as to how the FACTS devices can be integrated into the grid powered by variable speed wind generator. Various control techniques to enhance the performance of variable speed operation of PMSG WECS have been discussed in the last section.

## 2.1 Wind Turbine Generators

The modern wind turbine systems are AC generator system. They are Squirrel-Cage rotor Induction Generator (SCIG), Wound-Rotor Induction Generator (WRIG), Doubly-Fed Induction Generator (DFIG), Synchronous Generator (With external field excitation) and Permanent Magnet Synchronous Generator (PMSG) [24].

The different wind turbine technologies depending upon the rated operating speed, cut out speed, types of generators and mode of power control are available in the market. A conventional wind turbine operating at fixed speed tied to the simple utility grid is modeled in [25]. The detailed short circuit analysis is performed with the emulation of three phase fault in the vicinity of turbine generator side for the short period of the time. Besides the impact on the electro mechanical system and operating conditions for various fault clearing time is also discussed. The proposed methodology is seamlessly structured to analyze the transient stability performance in fixed speed wind system. The various physical and electrical parameters examined are the wind speed, the power output, the short – circuit power at the point of common coupling, the distance to the fault, the reactive power compensation etc.

The same wind system model is subjected to fixed speed in [26] aggregating the wind turbines into a singular wind turbine system. Two wind turbine cases have been proposed. Two of them differ in the variability of wind speed in a sense that one case is operated properly at identical wind speeds while other with different available wind speed.

In [27], a reduced third order equivalent model of wind systems including stator flux has been developed. The paper presents the power system stability incorporating this comprehensive model. The fault ride through capability of the generator has been studied for a symmetrical three phase fault on the grid bus.

The research has been accelerating forward in making the wind turbine system as efficient as possible. This can be substantiated by the improvement in the blade pitch angle control system so that the blade can orient itself into the tolerable wind speed direction. The inclusion of capacitor bank in the SCIG wind turbine for reactive power compensation. Minimization of power fluctuation by utilizing the soft starter before connecting to the grid [28].

Varieties of configuration for variable speed wind turbines are feasible. Most commonly there are three different types of wind turbine. They are Type A. Type – B, Type – C, Type – D wind turbine. Type – A refers to the constant speed wind turbine which is further categorized into two different categories: Type – A0, Type – A1 and Type – A2. The SCIG Type -a wind turbine is SCIG which is shown in Fig 2.1 (a). Type – B refers to the limited variable speed WT that uses wound rotor induction generator. It is shown in Fig 2.1 (b). This wind turbine has been used by manufacturer Vesta since mid – 1990s. The generator is directly connected to the grid here. The need of reactive power for the induction generator to operate efficiently makes it very difficult to operate in the standalone mode unless provided the strong and reliable power electronic devices for reactive power compensation. So, the operation of the induction generator halts in the lack of reactive power compensation either from utility gird or power electronic devices.

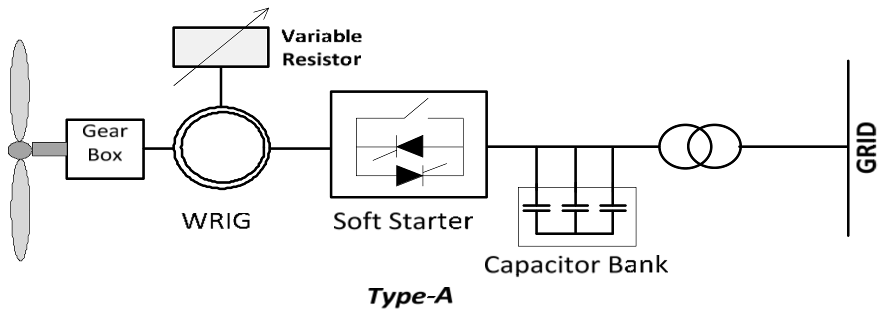


Figure 2.1 (a) Type – A variable speed wind turbine

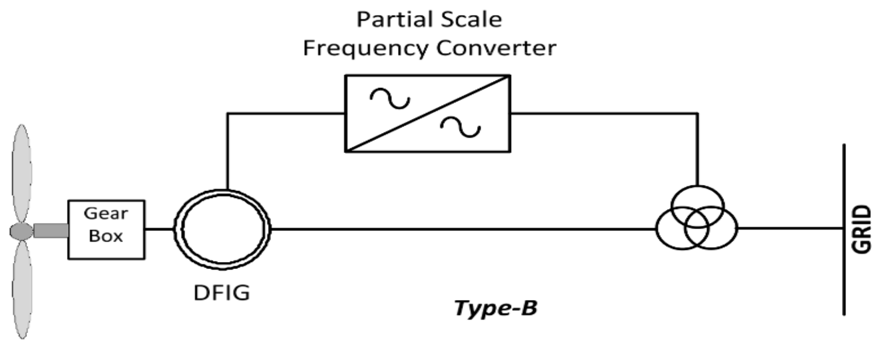


Figure 2.1 (b) Type – B variable speed wind turbine

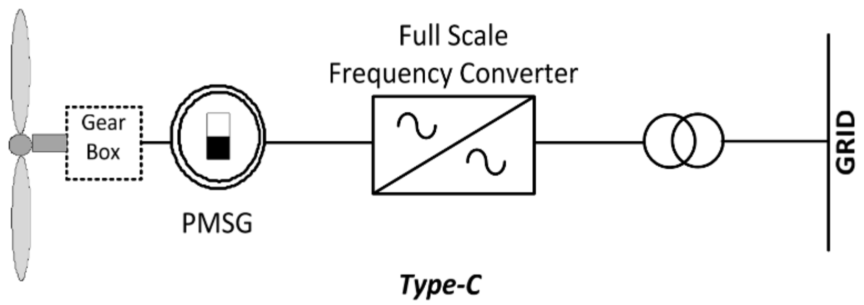


Figure 2.1 (c) Type – C variable speed wind turbine

Type – C is a permanent magnet synchronous generator (PMSG) which consists of gear box to get connected with the wind turbine and has full scale frequency converter to get connected with the main grid. PMSG wind turbine enjoys numerous benefits like the gear box can be omitted reducing the size and the space required for installation. This reduces its cost too. No excitation systems are required as the permanent magnet itself generates the electricity with the rotatory movement provided by shaft connected to the wind turbine. It possesses large range for variable speed wind operation for wide wind speed. As the PMSG can be set without the gearbox the chances of mechanical failure are high and it has very good up time at the cost of low power production. The PMSG has caught the attention of all the researchers and the wind turbine manufacturer because of its variable speed operation enhanced by the improvements in power electronic converters [29].

Two popular wind energy system in the market are PMSG and DFIG equipped with the static converters [30]. The inevitable and prime concern while modelling the variable wind speed system is the nature of the converters. The model so formed should be inclusive to cater all the physical phenomenon and mathematical equations to emulate the real machine system. DFIG carries a lot of weightages in the crowd of variable speed system than the conventional induction generator [31] like independent control of active and reactive power, maximizing the efficiency using the frequency converter properly.

DFIG employing variable speed wind turbine has established the proper recognition in the field of the wind market in comparison to other wind turbine owing to its remarkable advantages [31]. DFIG system has the configuration of doubly fed as name implies, stator terminals of generator are connected to the grid while the rotor terminal is connected to the same grid via the combination of generator side converter (AC-DC) and back-to-back converter (DC to DC) and the grid side converter (DC-AC). This combination of converter supplies only 25 – 30% of the total power for the full operation and control of the generator. The ability to provide independent control of active and reactive power of the generator, substantial energy production, enhanced power quality and satisfactory system performance during various disturbances such as voltage sags and short circuits [32]. The doubly fed Induction generator has a small configuration of the converter circuitry than full loaded converter based synchronous generator. This results in reduction of the size and make the system economical. The effect of VSWT on system oscillations, small signal stability for both open – loop and control loop has been revealed with a constant power model [33-35]. In [36], PWM converters with back-to-back converter has been applied in the variable speed wind generation systems. All these various research paper substantiates that the DFIG is getting lots and lots popular than the induction generator in terms of performance, quality and robustness to the disturbances.

Besides induction generator, synchronous generator has been extensively used in numerous research using variable speed generation applicable. The peculiarity with this synchronous generator is that the it can operate without gearbox and directly drive the electrical part of the wind generator system through its mechanical rotational movement [7-13]. The synchronous generator has the ability to generate electricity by the external excitation field or by the permanent magnet acting as rotor [37]. The PM generator distinguish itself from induction generator on the basis of this mode of excitation of the rotor. The positive side on PM generator is that it doesn't need external source for excitation and can produce higher power output with maximum efficiency. Besides, simple construction, lack of gear box, high power output, thermal management and satisfactory efficiency are the positive aspects of synchronous generator [38].

In [16], both the DFIG and PMSG for 5 MW and 5 MVA base has been modeled with the implementation of the LCL filter applied on 3 bus system. The model uses optimum tip speed ratio for MPPT. The Simulink model in made in MATLAB considering all the mathematical model representing the PMSG system. The machine side converter and grid side converter are developed based on PI controller for the optimum speed and power production.

The back-to-back converter that is inherently the dc link capacitor acts as a power balance circuit maintaining strict regulation of dc link voltage. DFIG system uses the double mass gear train model while the PMSG uses single mass model. Finally, the dynamic simulation for the change in wind speed and the change in grid voltage was given as disturbances and the controller system brings the system to the normal with few seconds. Also, the model here uses LCL filter instead of LC filter to smoothen the output power at grid and remove the harmonics that are inevitable due to the presence of electronic components which involves lots of switching operations.

This project derives a lot of necessary pieces of information from this book [16] in modelling the system model. In our project, we extend the system here with the addition of FACTS device STATCOM and model the system and control it for the short and sudden change in wind speed.

## 2.2 Application of STATCOM in WECS

Various flexible ac transmission system (FACTS) such as static var compensator (SVC), static synchronous compensator (STATCOM) and unified power flow controllers (UPFC) has been designed as damping controllers to improve transient stability of the wind energy systems [9] [10] [11]. In [12], the LVRT capability improvement has been presented with the controlled reactive power supply.

Some of the grid codes are: LVRT capability, reactive power control, active power control and frequency control. These grid codes necessitate that the wind turbine generators to be involved in safe, secure and effective functioning with grid voltage and frequency control [39]. The frequency control is very crucial and it can be implemented either on the generation side or the grid side. Under generation side control, it has to associate with turbine that has the ability to sway away reactive power control. On the other hand, in grid side switched capacitors or FACTS devices are employed at point common coupling to support the reactive power [40].

The important concern in the wind energy system is the stable power requirement which is not possible and they are prone to fluctuate because of the random wind speed, short circuit in the system. The situation is very worst for the weak grid system and the analysis of reactive power is inevitable. Therefore, there should be more concern for power control in the weak grid during and after the fault [17,18,41,42].

Low voltage ride through (LVRT) capability is the ability of the system to fight back the transient voltage dip without disconnecting from the system. The voltage dip that results from fault can lead to the loss of generation units. The loss of system could lead to the black out and irreparable damage to both the utility and the consumers. Therefore, it is very important to find the solution so that the system during voltage dip can be rescued by supplying extra reactive power to it. Here comes the FACTS device such as STATCOM which can act as a supplier of the required reactive power and absorber of the excess power [17,18,42]. FACTS devices can be classified according to the way they are connected or their operation nature. Based on the way they are connected, there are shunt or the series device. While based their operation they can be static and dynamic.

STATCOM has been the popular device in the grid support because of its effective performance during the faults. As it has the ability to supply and absorb the reactive power as required depending upon the situation. In this project, the generator side and grid side PWM technique-based converter is proposed to stabilize the STATCOM based PMSG variable speed wind turbine connected to the grid.

## 2.3 Control techniques of variable speed WT – PMSG system

As the penetration wind energy system is increasing rapidly, so is the case with the power electronic converters for the smooth power and transport of that power from the source to the grid. The complexities increase as the component number increases and chances of faults also causing the instability problem in the power system. The power quality issues can be handled with the judicious integration of the STATCOM in variable speed wind turbine – PMSG system.

The design of the control technique should be based on the meticulous study of the system parameters, like which variables are highly influenced by the changes in the system. Identifying the proper variables for damping require identification of influencing mode or damping mode. One of the methods is the singular value decomposition method (SVD) to measure the influence of the inputs as a control [43].

The variable speed wind turbine PMSG includes various mechanical and electrical parameters resulting from the blade, turbine, generator and power electronic devices. A simple disturbance or failure in the system will change all these parameter values and controlling all these parameters to some steady state require great knowledge and understanding of the operation and interconnection of the system. Without precisely tuning the controller the system operation may not reach to the stability. There are various methods like PI controller based on ai, fuzzy, hybrid and genetic algorithm-based model [44].

In this project, STATCOM based PMSG system is modeled and implemented. An independent P-Q controller based on decoupling of direct and quadrature component of current is used to supply necessary reactive power to the system.

# Chapter 3

# Modelling of STATCOM based PMSG system

## 3.1 PMSG System

A schematic diagram of the PMSG system connected to the wind turbine on one end and power system grid on the other end is shown in Fig 3.1. The PMSG generator is directly driven by the horizontal axis wind turbine. The converters are connected on both the generator side and the grid side with the back-to-back converter in between them. The schematic diagram shows the wind turbine, PMSG, rectifier block, back-to-back converter and the local load before the transformer connecting transmission line to the infinite bus.

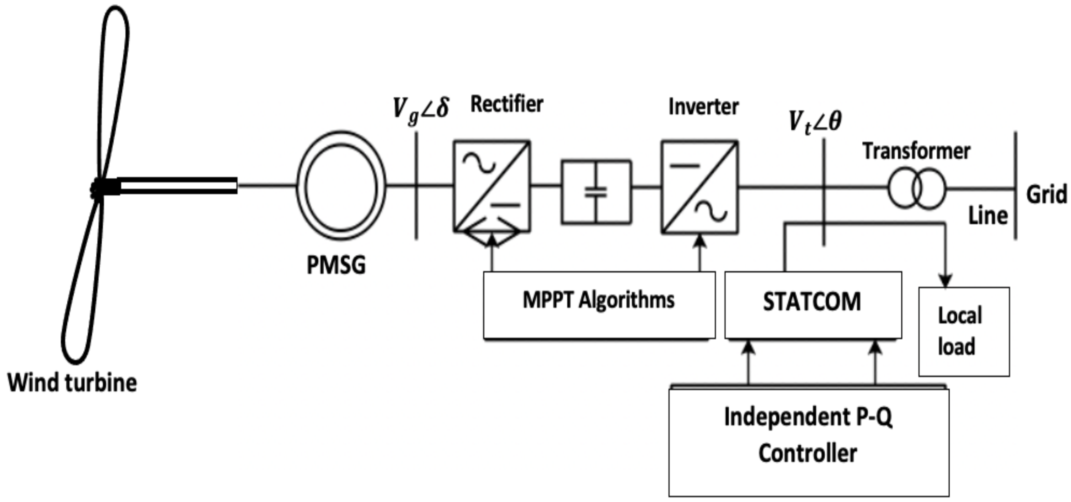


Figure 3.1: Schematic diagram of PMSG wind turbine system

As seen in the schematic, the PMSG is connected to the grid through converter. There are namely three converters present in the system: rectifier, dc link capacitor, inverter and independent P-Q controller. Both rectifier and inverter emulate the PWM signal generation using tip speed ratio maximum power point algorithm (MPPT). The Dc link capacitor in back-to-back converter is responsible for power transfer between generation and grid side. The machine side converter works for the maximum power delivery using Tip Speed Ratio (TSR) MPPT techniques. The grid side converter, in conjunction with the dc link capacitor and the generator side converter regulate the dc link voltage to the constant value. Both these converters are power electronics converter which is subjected to work with variable frequency system and output the required frequency with minimum delay and latency with fast switching. The frequency converter required to provide electrical coupling to the stator circuit, which operates at varying frequency up to 10 Hz, to the power grid characterized by 50/60 Hz.

## 3.2 Wind Turbine and Aerodynamic System

The wind turbine and its aerodynamic is very essential in relating the wind velocity with the generator rotor speed. Mostly the wind turbine configuration has three blades that capture wind energy and rotate the generator rotor. The mechanical power output of a wind turbine is related to the wind speed $V_\omega$ by [45],

$$P_t = 0.5\rho A C_p(\lambda,\beta) V_\omega{}^3 \tag{3.1}$$

where, $\rho$ is air density, $A$ is the area swept by the blades, $C_p(\lambda,\beta)$ is the power coefficient of the blade. Equation (3.1) shows that for a given wind speed $V_\omega$, the turbine output power depends upon $C_p(\lambda,\beta)$ which is given by [10]

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda + 0.08\beta} - \frac{4.0}{1+\beta^{\,3}} - 0.4\beta\ - 5\right)e^{\left(\frac{-21}{\lambda+0.08\beta} - \frac{0.735}{1+\beta^{\,3}}\right)} + 0.0068\lambda$$

The blades of the turbine can be oriented in and out of the wind speed to control the wind speed. This angle of orientation of the blades on its longitudinal axis is known as pitch angle. The tip speed ratio is the ratio of the tip of the turbine blade to the wind speed. Mathematically,

$$\lambda = \frac{\omega_t R}{V_\omega} \tag{3.2}$$

where, $\omega_t$ is the turbine rotational speed in rad/sec

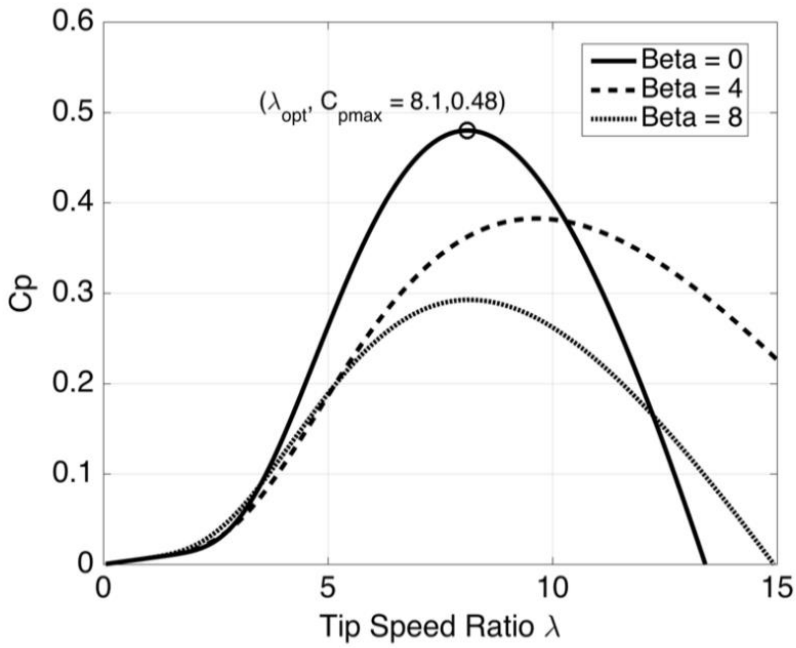


Figure 3.2 shows the plot of $C_p(\lambda, \beta)$ for the various values of $\lambda$ and $\beta$ [16]

It is clear from the above Figure 3.2 that, the optimal tip speed ratio is obtained for the pitch angle $\beta = 0$. As the beta value increased as depicted by the other lines, the turbine power coefficient decreases and at the optimum tip speed ratio 8.1 with $\beta = 8$ has the lowest Cp. Wind turbine data is given in the Appendix A.

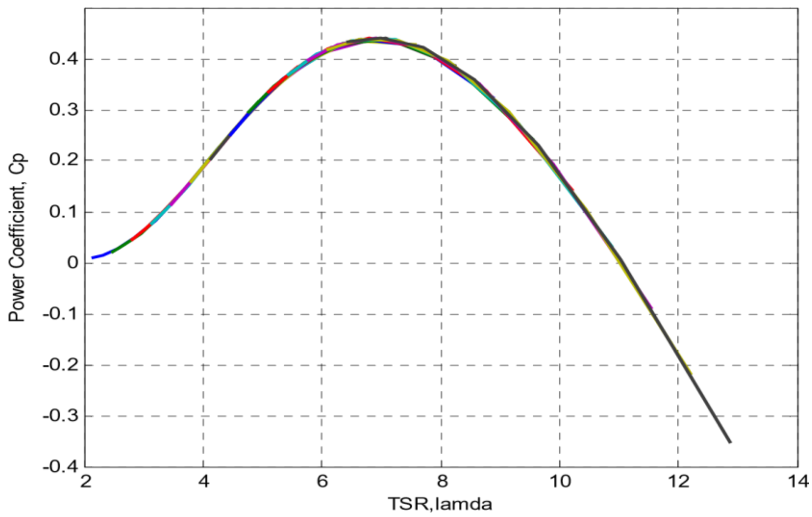


Figure 3.3: Plot of turbine performance coefficient vs tip speed ratio for different values of pitch angles

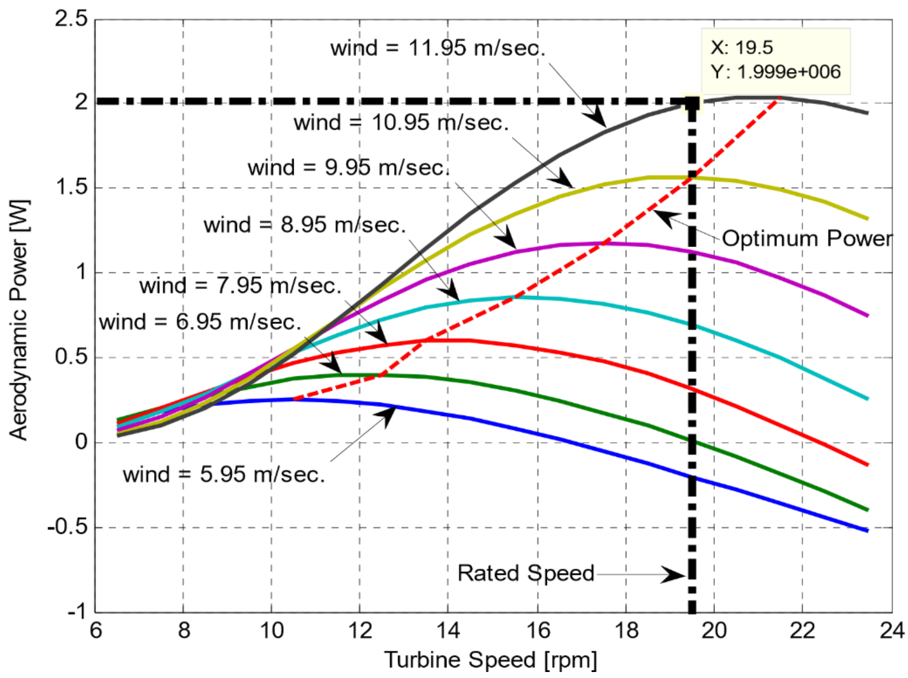


Figure 3.4: Power output vs turbine speed characteristics of a wind turbine

Figure 3.3 shows the power output varies greatly for the different wind speed. The red dotted line cuts the graph related to different wind speed ranging from 5.95 m/s to 11.95 m/s. The point of intersection of red dotted line and wind speed curve gives the maximum power point corresponding to that wind speed. For the variable wind speed, the maximum value of mechanical power is 2MW which is rated power. The corresponding turbine speed is 19.5 rpm. For TSR MPPT, an optimum value of turbine speed is considered in the region below rated turbine speed. 3.3 Variable Speed PMSG Model

In this section, a non – linear model of the variable speed wind turbine – PMSG system with its drive train system is developed. The stator- flux relationships of PMSG are:

$$\psi_d = -X_d i_{sd} + X_{afd} i_{fd}$$

$$\psi_q = -X_q i_{sq}$$

$$\psi_{fd} = -X_{afd} i_{sq} + X_{ffd} i_{fd} \qquad (3.3)$$

The stator voltage – current relationship is given by:

$$V_{sd} = -R_a i_{sd} - \omega_g \psi_q + \frac{1}{\omega_0} p(\psi_d)$$

$$V_{sq} = -R_a i_{sq} + \omega_g \psi_d + \frac{1}{\omega_0} p(\psi_q) \qquad (3.4)$$

In the above equation, the term $X_{afd} i_{fd} = \psi_0$ is a constant, where $\psi_0$ is the residual flux linkage of permanent magnet rotor. With this substitution, equations (3.2) and (3.3) becomes as follows:

$$\psi_d = -X_d i_{sd} + \psi_0$$

$$\psi_q = -X_q i_{sq} \qquad (3.5)$$

$$V_{sd} = -R_a i_{sd} - \omega_g \psi_q + \frac{1}{\omega_0} p(\psi_d)$$

$$V_{sq} = -R_a i_{sq} + \omega_g \psi_d + \frac{1}{\omega_0} p(\psi_q) \qquad (3.6)$$

The equivalent circuit of a 3 – Φ permanent magnet synchronous generator in ac domain is shown in the Fig 3.5

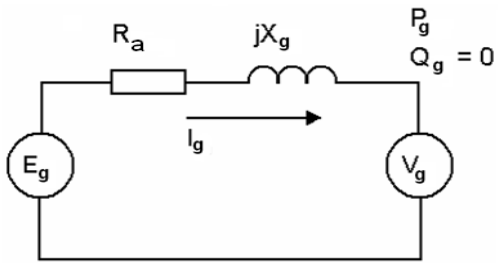


Figure 3.5 Equivalent circuit of PMSG

Substituting equation (3.5) in (3.6), we obtain;

$$V_{sd} = -R_a i_{sd} + \omega_g X_q i_{sq} - \frac{X_d}{\omega_0} p(i_{sd})$$

$$V_{sq} = -\omega_g X_d i_{sd} - R_a i_{sq} + \omega_g \psi_0 - \frac{X_q}{\omega_0} p(i_{sq}) \qquad (3.7)$$

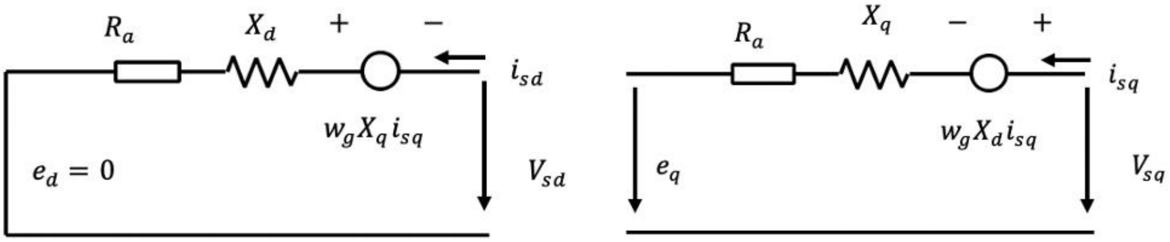


Figure 3.6 Equivalent circuit of PMSG in d-q axes

The partial differential equations pertaining to voltage and current are:

$$p(i_{sd}) = \frac{w_0}{X_d}\left[-R_a i_{sd} + \omega_g X_q i_{sq} - V_{sd}\right]$$

$$p(i_{sq}) = \frac{w_0}{X_q}\left[-\omega_g X_d i_{sd} - R_a i_{sq} + \omega_g \psi_0 - V_{sq}\right] \qquad (3.8)$$

## 3.2.1 Drive Train Model of a Two Mass System

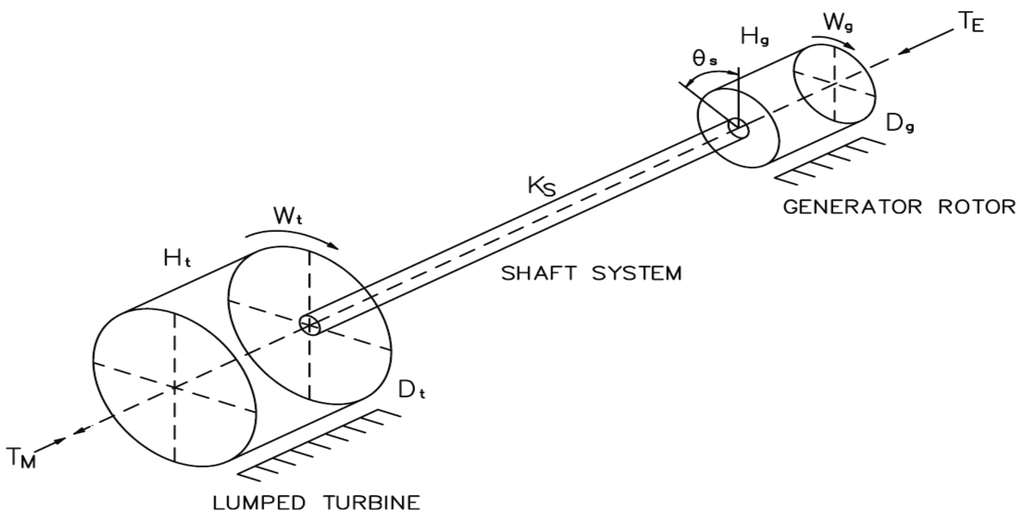


Figure 3.7 Drive train model of a two-mass system

Drive train model is the interconnecting medium of the wind turbine with the rotor of the PMSG system. It collectively represents the turbine and in between the gear box and generator masses at the other end. The drive train model with shaft system between turbine masses and generator masses is show in the Figure 3.7. The inertia of the wind turbine system and the PMSG are $H_t$ and $H_g$ respectively. The shaft in between provides the stiffness and represented by stiffness – coefficient $K_s$. The damping coefficients for turbine and generator with respect to shaft system are $D_t$ and $D_g$ respectively.

The electromechanical equations relating the drive train model can be represented by four – first order differential equations [13]:

$$p(\delta) = w_0(w_g - 1)$$

$$p(w_g) = \frac{1}{2H_g}(K_s\theta_s - P_{ag} - D_g(w_g - 1)) \quad (3.9)$$

$$p(\theta_s) = w_0(w_t - w_g)$$

$$p(w_t) = \frac{1}{2H_t}(P_m - K_s\theta_s - D_t(w_t - 1)) \quad (3.10)$$

Here, $\delta$ is the load angle of the PMSG . And $w, K, \theta$ and D represent rotational speed, stiffness constant, twist angle and damping coefficients. The subscript g, s, m and t related to the generator, shaft, mechanical and turbine respectively. $P_{ag}$ is the electrical air – gap power. Mathematically,

$$P_{ag} = (\psi_0 i_{sq} + (X_d - X_q)\, i_{sq} i_{sd})\, w_g \quad (3.11)$$

Alternatively,

$$P_{ag} = V_{sd} i_{sd} + V_{sq} i_{sq} + R_a({i_{sd}}^2 + {i_{sq}}^2) \quad (3.12)$$

## 3.3 Converter Models

The schematic of the converters in the PMSG system is shown in the Figure 3.8

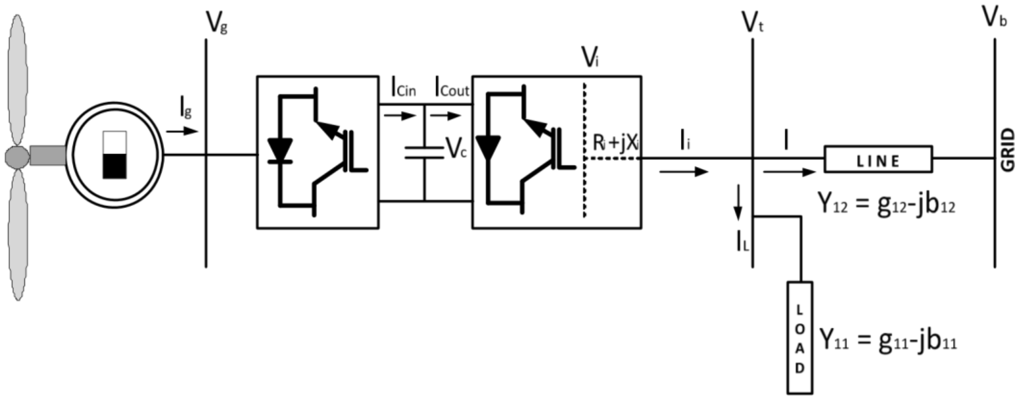


Figure 3.8 Variable Speed WT-PMSG connected to grid

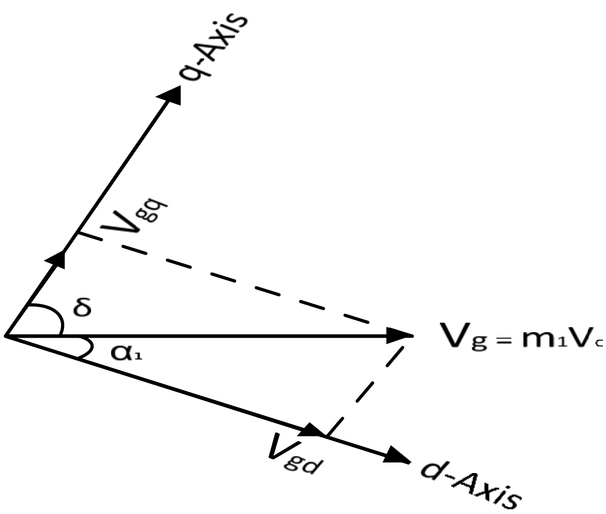


Figure 3.9 Phasor diagram of PMSG

From the above figure, the voltage equation can be written as;

$$V_s = m_1 V_c \alpha_1 \tag{3.13}$$

In direct and quadrature axis form,

$$V_{sd} = m_1 V_c \cos\alpha_1$$

$$V_{sq} = m_1 V_c \sin\alpha_1 \tag{3.14}$$

where, $m_1$ is the modulation index of the machine side converter or generator side converter, $\alpha_1$ is the firing angle and $V_c$ is the DC link capacitor voltage. The equation (3.14) can be rewritten in terms of the load angle of the rotor as shown in Figure 3.9.

$$V_{sd} = m_1 V_c \cos\delta$$

$$V_{sq} = m_1 V_c \sin\delta \qquad (3.15)$$

The firing angle is changed into the load angle because we can either modulate the generator stator voltage with modulation index or the firing angle. As we have picked the modulation index as the modulator, changing firing angle to load angle makes the computation little easier and faster.

Substituting equation (3.15) into equation (3.8), we get;

$$p(i_{sd}) = \frac{w_0}{X_d}\left[-R_a i_{sd} + \omega_g X_q i_{sq} - m_1 V_c \cos\delta\right]$$

$$p(i_{sq}) = \frac{w_0}{X_q}\left[-\omega_g X_d i_{sd} - R_a i_{sq} + \omega_g \psi_0 - m_1 V_c \sin\delta\right] \qquad (3.16)$$

Applying KVL at grid side converter system at the point $V_i$ in the figure 3.8 gives

$$V_i = V_t + R_i I_i + \frac{X_i}{\omega_0} p(I_i) \qquad (3.17)$$

Transforming this equation with respect to d – q axes for $V_i$, $I_i$, $V_t$ with rotating at grid frequency $\omega_e$, the differential equations for the grid side converter(inverter) can be written as;

$$p(i_{id}) = \frac{w_0}{X_i}\left[-R_a i_{id} + \omega_e X_i i_{iq} - V_{id} - V_{td}\right]$$

$$p(i_{iq}) = \frac{w_0}{X_i}\left[-\omega_e X_i i_{id} - R_a i_{iq} + \omega_g \psi_0 - V_{iq} - V_{td}\right] \qquad (3.18)$$

In the d – q axes,

$$V_i = -V_{id} + jV_{iq}$$

$$I_i = i_{id} + ji_{iq}$$ and

$$V_t = V_{td} + jV_{tq} \quad (3.19)$$

Similarly, for the grid side converter system, the inverter output voltage is given by

$$V_i = m_2 V_c \alpha_2 \quad (3.20)$$

In d – q axes,

$$V_{id} = m_2 V_c \cos\alpha_2$$

$$V_{iq} = m_2 V_c \sin\alpha_2 \quad (3.21)$$

Like in the generator side converter, here also $m_2$ means the modulation index of the grid side converter, $\alpha_2$ the extinction angle of the inverter.

On applying KCL at the point of common coupling $V_t$ of Figure 3.6

$$I_i = I_L + I = V_t Y_{11} + (V_t - V_b)\, Y_{12}$$

In above equation, $Y_{11} = g_{11} - jb_{11}$ and $Y_{12} = g_{12} - jb_{12}$ are the admittance for the load and the transmission line.

The terminal voltage at the point of common coupling where local load is connected can be presented as:

$$v_{td} = c_1 i_{id} + c_2 i_{iq} + V_b(c_1 g_{12} - c_2 g_{21})$$

$$v_{tq} = c_3 i_{id} + c_4 i_{iq} + V_b(c_3 g_{12} - c_4 g_{21}) \quad (3.22)$$

Substituting equation (3.21) and (3.24) in equation (3.18), we get;

$$p(i_{id}) = \frac{w_0}{X_i}\left[-(R_i + c_1)i_{id} + (\omega_e X_i - c_2)i_{iq} - m_2 V_c \cos\alpha_2 - V_b(c_1 g_{12} - c_2 g_{21})\right]$$

$$p(i_{iq}) = \frac{w_0}{X_i}\left[-(\omega_e X_i + c_1)i_{id} - (R_i + c_4)i_{iq} + m_2 V_c \sin\alpha_2 - V_{id} - V_b(c_3 g_{12} - c_4 g_{21})\right] \qquad (3.23)$$

The expression for the constant $c_1, c_2, c_3$ and $c_4$ is presented in Appendix B.

## 3.4. DC link Capacitor

The dc link capacitor is located between the generator side converter and the grid side converter that is responsible for the power balance between generation and transmission. The output of the generator side converter which is input to the dc link capacitor is not smooth because of the frequent switches of the current in the converter. This results ripples in the output voltage. The solution can be introducing the dc link capacitor that smoothens the ripples and transfer the almost continuous. The size of the capacitor plays significant role as the smaller the capacitor size faster will be the regulation of the dc link voltage while there is fast response but the voltage will not be constant. There is a tradeoff for the selection of the size of capacitor for the response time and the regulation of the voltage. From the Figure 3.8, the dc link capacitor in terms of power flow can be written as;

$$P_{DC} = V_c[C\frac{d}{dt}(V_c)] \qquad (3.24)$$

For the lossless converter,

$$P_{DC} = P_{Cin} + P_{Cout} \qquad (3.25)$$

Here,

$$P_{cin} = V_{sd}i_{sd} + V_{sq}i_{sq}$$

$$P_{cout} = -V_{id}i_{id} + V_{iq}i_{iq} \qquad (3.26)$$

Substituting equation (3.24) and (3.26) in equation (3.25), we get;

$$V_c C\, p(V_c) = V_{sd} i_{sd} + V_{sq} i_{sq} + -V_{id} i_{id} + V_{iq} i_{iq}$$

In terms of modulation index, substituting related equations in here, we get;

$$p(V_c) = \frac{1}{C}[m_1 i_{sd} \sin\delta + m_1 i_{sq} \cos\delta - m_2 i_{id} \cos\alpha_2 + m_2 i_{iq} \sin\alpha_2 ] \qquad (3.27)$$

## 3.5 STATCOM Model

STATCOM is one of the most widely used FACTS device in the renewable energy conversion system. It is a shunt device, which is connected to support the grid to maintain their respective "grid codes". Most extensive use has been LVRT case in the intermittent wind power generation grid system and even during the contingencies like fault in the lines. During such situation, the system goes in the voltage dip resulting the transients which should be cleared before the protective measures like circuit breaker comes into operation. The STATCOM mostly supply and absorb the reactive power. The use of the STATCOM is varied according to the need and vulnerability of sub system like in the generation subsystem or the transmission grid system commonly known and point of common coupling where most of the loads and the distributions lines are connected and vulnerability is high. The situation is worst for the weak grid [18,19,45].

This project integrates the STATCOM in the grid side and obtain the realistic model considering the whole wind energy based PMSG system. The STATCOM is modelled as the voltage source device whose voltage can be controlled to supply the necessary reactive power in the system. The reactive power will be supplied varying the magnitude of the voltage while the active power by varying the phase angle. For the energy supplying device in STATCOM, either supercapacitor or the battery can be employed in our case we have assume simple storage capacitor as shown in the Figure 3.10

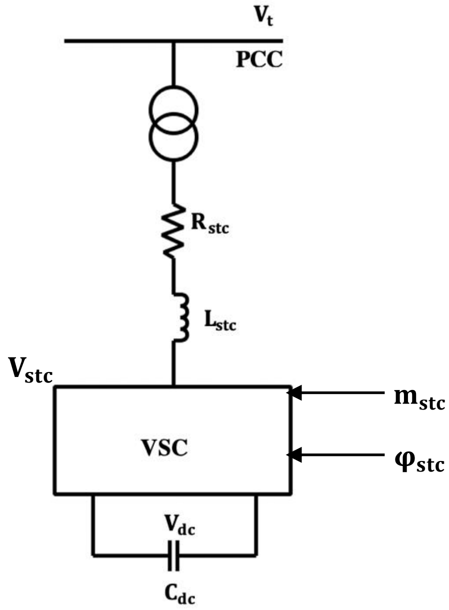


Figure 3.10 Model of STATCOM

From the Figure 3.8, the terminal voltage can be written in phasor form as:

$$V_t = |V_t|\angle\theta_t \qquad (3.28)$$

The output voltage of the STATCOM can be written as:

$$V_{stc} = m_{stc}\,(V_t \angle \psi_{stc}) \qquad (3.29)$$

In d – q components,

$$V_{stcd} = m_{stc} V_t \cos\psi_{stc}$$

$$V_{stcq} = m_{stc} V_t \sin\psi_{stc} \qquad (3.30)$$

Applying KVL at the terminal $V_{stc}$ of the Figure 3.10, we get;

$$V_{stc} = V_t + R_{stc} I_{stc} + \frac{L_{stc}}{\omega_0} p(I_{stc}) \qquad (3.31)$$

In above equation (3.31), we get;

$$V_{stc} = V_{stcd} + jV_{stcq}$$

$I_{stc} = i_{stcd} + ji_{stcq}$ and

$$V_t = V_{td} + jV_{tq} \quad (3.32)$$

Where, $R_{stc}$ and $L_{stc}$ are the resistance and inductance of the STATCOM and $V_{stc}$ and $I_{stc}$ are the STATCOM output voltage and output current respectively.

In the d – q axes, the expression for the voltage and current break down as:

$$V_{stcd} = V_{td} + R_{stc}i_{stcd} - \omega_x L_{stc}i_{stcq} + \frac{L_{stc}}{\omega_0} p(i_{stcd})$$

$$V_{stcq} = V_{tq} + R_{stc}i_{stcq} - \omega_x L_{stc}i_{stcd} + \frac{L_{stc}}{\omega_0} p(i_{stcq}) \quad (3.33)$$

Substituting the expression for $V_{stcd}$ and $V_{stcq}$ from equation (3.30) in equation (3.33);

$$p(i_{stcd}) = \frac{w_0}{X_i}[-V_{td} - R_{stc}i_{stcd} + \omega_x L_{stc}i_{stcq} + m_{stc}V_{dc}\cos\psi_{stc}]$$

$$p(i_{stcq}) = \frac{w_0}{X_i}[-V_{tq} - R_{stc}i_{stcd} - \omega_x L_{stc}i_{stcd} + m_{stc}V_{dc}\cos\psi_{stc}] \quad (3.34)$$

Considering the local load admittance and the transmission line admittance,

$$p(i_{stcd}) = \frac{w_0}{L_{stc}}[-c_1 i_{id} - c_2 i_{iq} - R_{stc}i_{stcd} + \omega_e L_{stc}i_{stcq} + m_{stc}V_{dc}\cos\psi_{stc} - V_b(c_1 g_{12} - c_2 b_{12})]$$

$$p(i_{stcq}) = \frac{w_0}{L_{stc}}[-c_3 i_{id} - c_4 i_{iq} - R_{stc}i_{stcd} - \omega_e L_{stc}i_{stcd} + m_{stc}V_{dc}\sin\psi_{stc} - V_b(c_3 g_{12} - c_4 b_{12})] \quad (3.35)$$

The expression for the dc link capacitor voltage for STATCOM follows the same intuition as the PMSG DC link capacitor and given by,

$$V_{dc}\left[C_{dc}\frac{d}{dt}(V_{dc})\right] = -V_{stcd}i_{stcd} - V_{stcq}i_{stcq}$$

On further simplification,

$$p(V_{dc}) = \frac{m_{stc}V_t}{C_{dc}V_d}[-\cos\psi_{stc}i_{stcd} - \sin\psi_{stc}i_{stcq}] \quad (3.36)$$

## 3.6 STATCOM independent P-Q controller

At steady state, the STATCOM is considered not to be involving in system operation. Any change from the steady condition results the VSC into operation. By transforming the STATCOM current through the relationship, $I_{stc}^{new} = I_{stc}^{old} e^{-j\theta_s}$, a set of independent relationships of real and reactive power of STATCOM is obtained as follows [47]:

$$P_{stc} = V_t i_{stcd}^{new} \text{ and } Q_{stc} = V_t i_{stcq}^{new} \tag{3.37}$$

In the above, $\theta_s$ is the angle of voltage $V_t$. With the transformed quantities, the d-q components of the original STATCOM current – voltage relationship,

$$L_{stc}\frac{dI_{stc}}{dt} + R_{stc}I_{stc} = V_{stc} - V_s \tag{3.38}$$

In d-q frame, using equation 3.34

$$p(i_{stcd}) = \frac{w_0}{L_{stc}}[-c_1 i_{id} - c_2 i_{iq} - R_{stc}i_{stcd} + \omega_e L_{stc} i_{stcq} + m_{stc}V_{dc}\cos\psi_{stc} - V_b(c_1 g_{12} - c_2 b_{12})]$$

$$p(i_{stcq}) = \frac{w_0}{L_{stc}}[-c_3 i_{id} - c_4 i_{iq} - R_{stc}i_{stcd} - \omega_e L_{stc} i_{stcd} + m_{stc}V_{dc}\sin\psi_{stc} - V_b(c_3 g_{12} - c_4 b_{12})] \tag{3.39}$$

It can be expressed as follows,

$$p(i_{stcd}^{new}) = -\frac{R_{stc}w_b}{L_{stc}} i_{stcd}^{new} + X_1 \tag{3.40}$$

$$p(i_{stcq}^{new}) = -\frac{R_{stc}w_b}{L_{stc}} i_{stcq}^{new} + X_2$$

where $X_1$ and $X_2$ are control inputs with no cross – coupling. Control inputs $X_1$ and $X_2$ are obtained using PI controller as follows:

$$X_1 = \left(k_{p1} + \frac{k_{i1}}{s}\right)(i_{stcd}^{*} - i_{stcd})$$

$$X_2 = \left(k_{p2} + \frac{k_{i2}}{s}\right)(i^*_{stcd} - i_{stcd}) \tag{3.41}$$

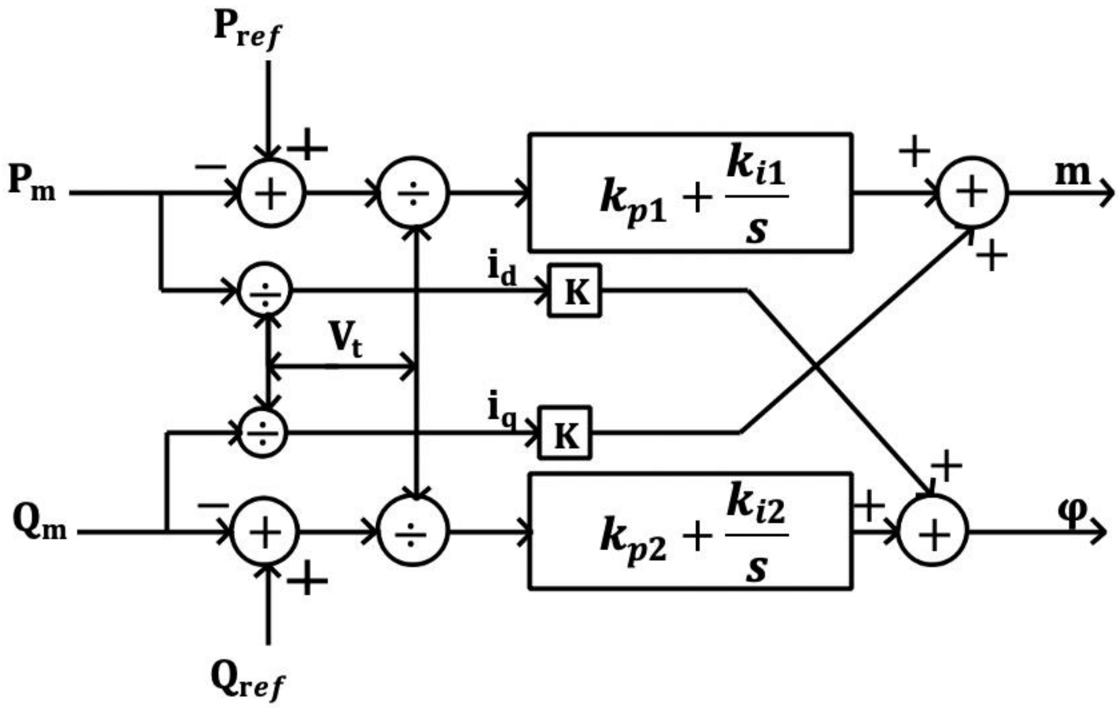


Figure 3.11 STATCOM independent control strategy

A block diagram showing the control strategy is presented in Fig. 4. The reference signals are generated using a set of PI controllers. The active power reference, $P_{ref}$ is obtained based on change in the phase angle of the terminal voltage while the reactive power reference, $Q_{ref}$ is found based on the change in the magnitude of terminal voltage using a PI controller. $m_{stc}$ and $\varphi_{stc}$ are the control signals modulated by the designed independent P-Q controller to control the STATCOM to supply necessary active and reactive power during a disturbance or change in the system.

## 3.7 Nonlinear Model of the Overall system

The modelling performed so for the various components now can be written in state space form representation. The overall mathematical expression derived so far can be represented by,

$$\dot{x} = f(x, u) \tag{3.42}$$

where x and u denote the state vector and input vector for the converter controls given by,

$x = [i_{sd}\ \ i_{sq}\ \ \delta\ \ w_g\ \ \theta_s\ \ w_t\ \ V_c\ \ i_{id}\ \ i_{iq}\ \ i_{stcd}\ \ i_{stcq}\ \ V_{dc}]$ & $u = [m_1\ \ m_2\ \ \alpha_2\ \ m_{stc}\ \ \psi_{stc}]$

The differential equations pertaining to the complete model is reordered here as:

$$p(i_{sd}) = \frac{w_0}{X_d}[-R_a i_{sd} + \omega_g X_q i_{sq} - m_1 V_c \cos\delta]$$

$$p(i_{sq}) = \frac{w_0}{X_q}[-\omega_g X_d i_{sd} - R_a i_{sq} + \omega_g \psi_0 - m_1 V_c \sin\delta]$$

$$p(\delta) = w_0(w_g - 1)$$

$$p(w_g) = \frac{1}{2H_g}(K_s\theta_s - P_{ag} - D_g(w_g - 1))$$

$$p(\theta_s) = w_0(w_t - w_g)$$

$$p(w_t) = \frac{1}{2H_t}(P_m - K_s\theta_s - D_t(w_t - 1))$$

$$p(V_c) = \frac{1}{C}[m_1 i_{sd}\sin\delta + m_1 i_{sq}\cos\delta - m_2 i_{id}\cos\alpha_2 + m_2 i_{iq}\sin\alpha_2]$$

$$p(i_{id}) = \frac{w_0}{X_i}[-(R_i + c_1)i_{id} + (\omega_e X_i - c_2)i_{iq} - m_2 V_c\cos\alpha_2 - V_b(c_1 g_{12} - c_2 g_{21})]$$

$$p(i_{iq}) = \frac{w_0}{X_i}[-(\omega_e X_i + c_1)i_{id} - (R_i + c_4)i_{iq} + m_2 V_c \sin\alpha_2 - V_{id} - V_b(c_3 g_{12} - c_4 g_{21})]$$

$$p(i_{stcd}) = \frac{w_0}{L_{stc}}[-c_1 i_{id} - c_2 i_{iq} - R_{stc} i_{stcd} + \omega_e L_{stc} i_{stcq} + m_{stc} V_{dc}\cos\psi_{stc} - V_b(c_1 g_{12} - c_2 b_{12})]$$

$$p(i_{stcq}) = \frac{w_0}{L_{stc}}[-c_3 i_{id} - c_4 i_{iq} - R_{stc} i_{stcd} - \omega_e L_{stc} i_{stcd} + m_{stc} V_{dc}\sin\psi_{stc} - V_b(c_3 g_{12} - c_4 b_{12})]$$

$$p(V_{dc}) = \frac{m_{stc} V_t}{C_{dc} V_d}[-\cos\psi_{stc} i_{stcd} - \sin\psi_{stc} i_{stcq}] \tag{3.43}$$

# Chapter 4

# SIMULATION AND ANALYSIS

## 4.1 Transient Stability Analysis

The dynamic performance of the PMSG system is simulated using MATLAB ‘ode’ program. The disturbance simulates a short wind gust resulting from mean speed change from 10 m/s to 11 m/s as input torque pulse. The other disturbance simulates input torque pulse of 0.4 pu for 0.5s.

For short wind gust as disturbance, during normal operation at steady state, the PMSG is running at a speed of 1.1497 pu with generated active and reactive power 0.7 pu and 0.099 pu respectively. The terminal voltage is set to 1pu and initial mean speed is 10m/s. The disturbance simulates a short wind gust resulting from mean speed change from 10 m/s to 11 m/s. Fig. 5.1 to Fig. 5.5 shows the transient variations of the turbine speed, stator voltage, generator speed and DC link capacitor with and without independent controller.

From Fig. 5.1, It is observed that at the initial turbine speed 1.1497 pu Following a 1m/s change in mean speed of wind at time 1.5 sec for a duration of 0.5 sec, there are significant oscillations. With no additional converter control, the maximum turbine speed is 1.155 pu and settles very slowly with oscillation. The STATCOM control provides good damping with peak value of 1.153 pu and settles very quickly with less steady state error within 14 sec. Fig. 5.2 shows that at steady state, stator current is 0.77 pu. Without controller, the stator current jumps to 1.04 pu and doesn’t get back to previous steady state value. With STATCOM control, the maximum overshoot is 0.98 pu and the oscillations are less and attains fairly steady state within 14 sec. Fig. 5.4 shows the variation of dc link voltage which is very high in case of absence of controller and attains the steady state value of 1.111 pu in the presence of STATCOM control.

From these results, it is seen that the proposed STATCOM controller improves the transient stability of a variable speed PMSG during a sudden wind gust.

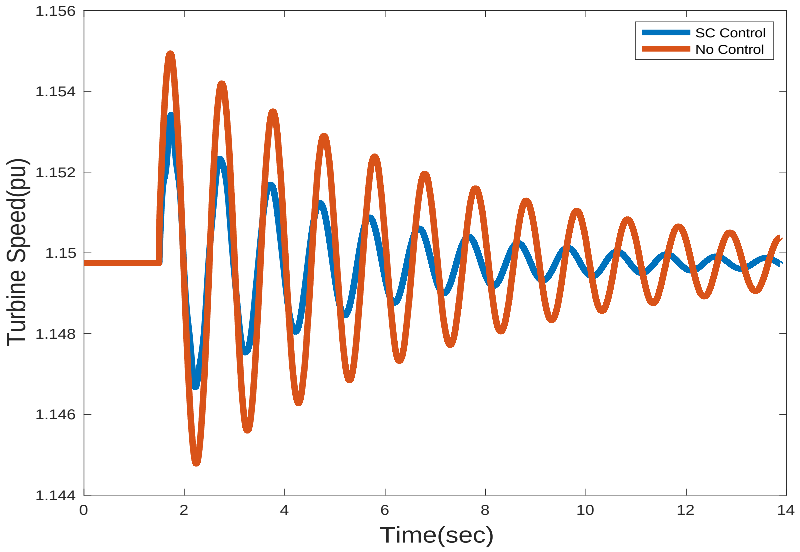


Figure 5.1 Turbine speed variations of the PM synchronous generator following a 1m/s change in Mean speed of wind with no additional converter control and STATCOM independent PQ control.

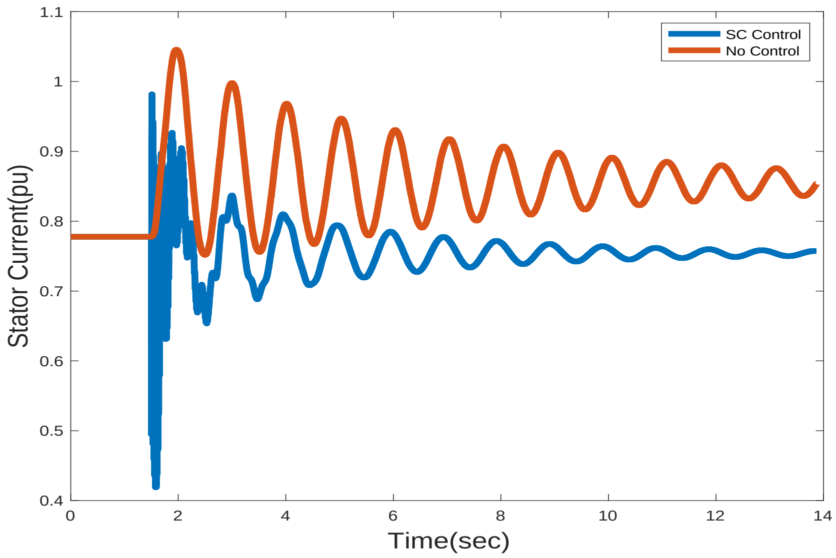


Figure 5.2 Stator current variations of the PM synchronous generator following a 1m/s change in Mean speed of wind with no additional converter control and STATCOM independent PQ control.

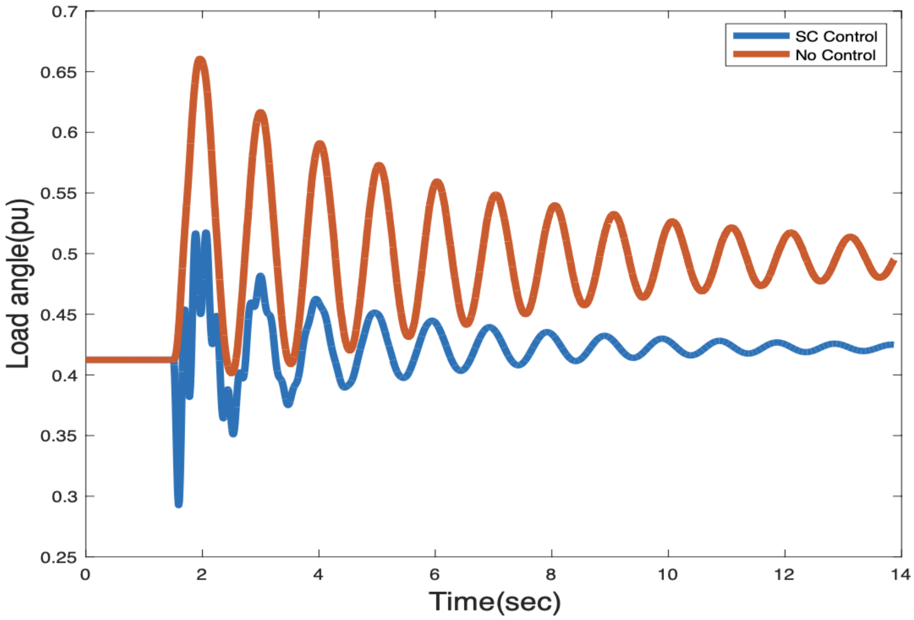


Figure 5.3 Rotor angle variations of the PM synchronous generator following a 1m/s change in Mean speed of wind with no additional converter control and STATCOM independent PQ control

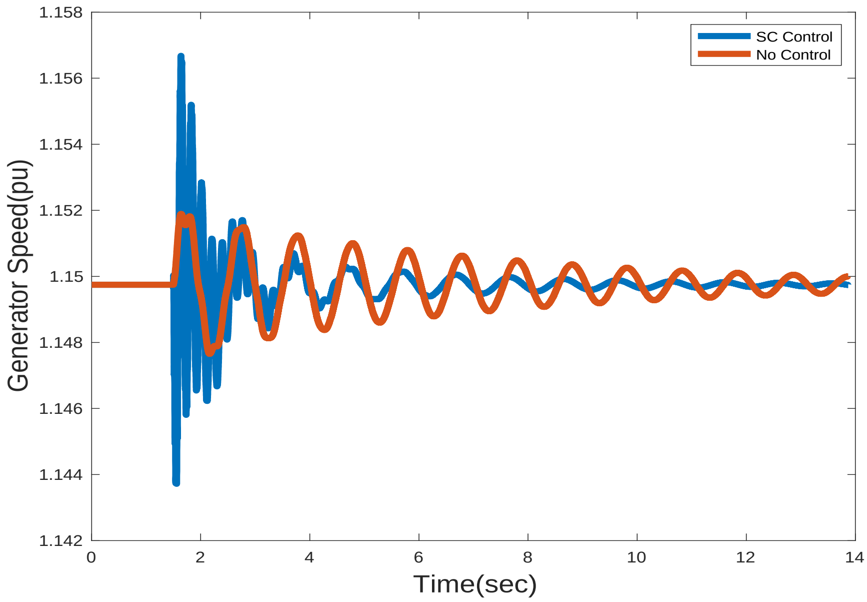


Figure 5.4 Generator speed variations of the PM synchronous generator following a 1m/s change in Mean speed of wind with no additional converter control and STATCOM independent PQ control.

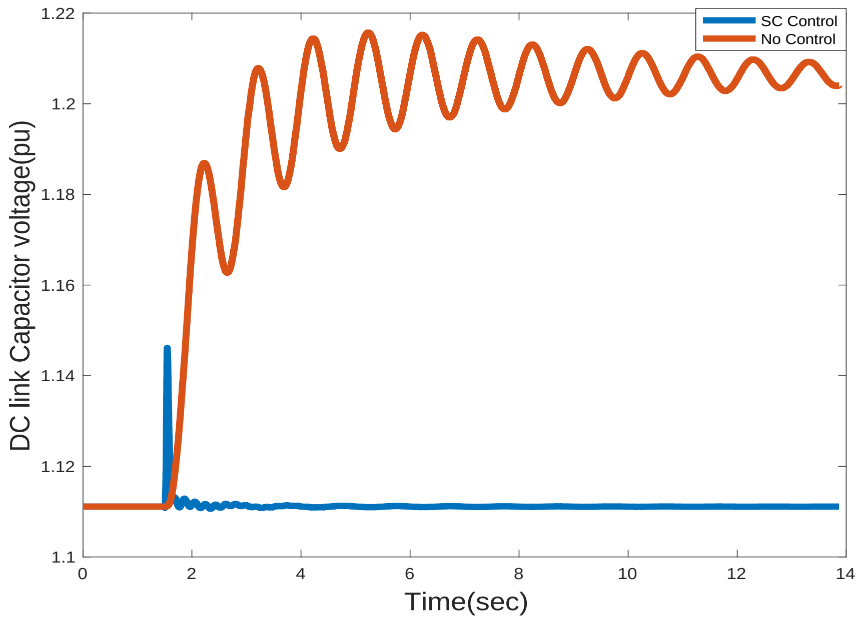


Figure 5.5 DC link capacitor voltage of the PM synchronous generator following a 1m/s change in Mean speed of wind with no additional converter control and STATCOM independent PQ control.

For input torque pulse as disturbance, Fig. 5.5 to Fig 5.9 shows transient variation for input torque pulse of 0.4 pu for 0.5s. Fig. 5.5 shows the turbine speed variation provides good damping with peak value of 1.153 pu and settles very quickly with less steady state error within 14sec with STATCOM control. Fig. 5.5 shows the turbine speed variation with large oscillations and maximum peak value of 1.16275 pu without using controller. Fig. 5.6 depicts the rotor angle variation with rapid oscillation in case of uncontrolled with maximum peak value of 1.3317. The maximum overshoot is 0.65 pu in case of STATCOM controller which comes to almost zero steady state. From these results, the proposed independent P-Q controller for STATCOM enhances the transient stability of the variable speed PMSG system during torque pulse situation also. Fig. 5.7 shows the generator speed variation with less oscillation using controller than without using the controller. Fig. 5.8 shows that the dc link capacitor voltage is properly damped by the controller with less oscillations and little steady state error. Fig, 5.9 shows the stator current variation, there is maximum peak without using controller and the steady state error is also high.

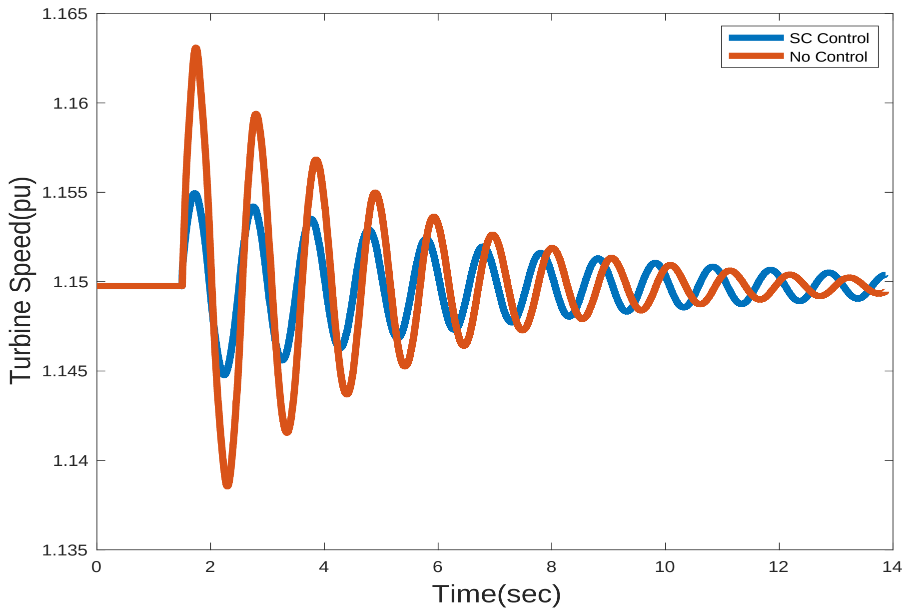


Figure 5.5 Turbine speed variation following 0.4 pu torque pulse disturbances for 0.5 sec with no additional converter control and STATCOM independent PQ control.

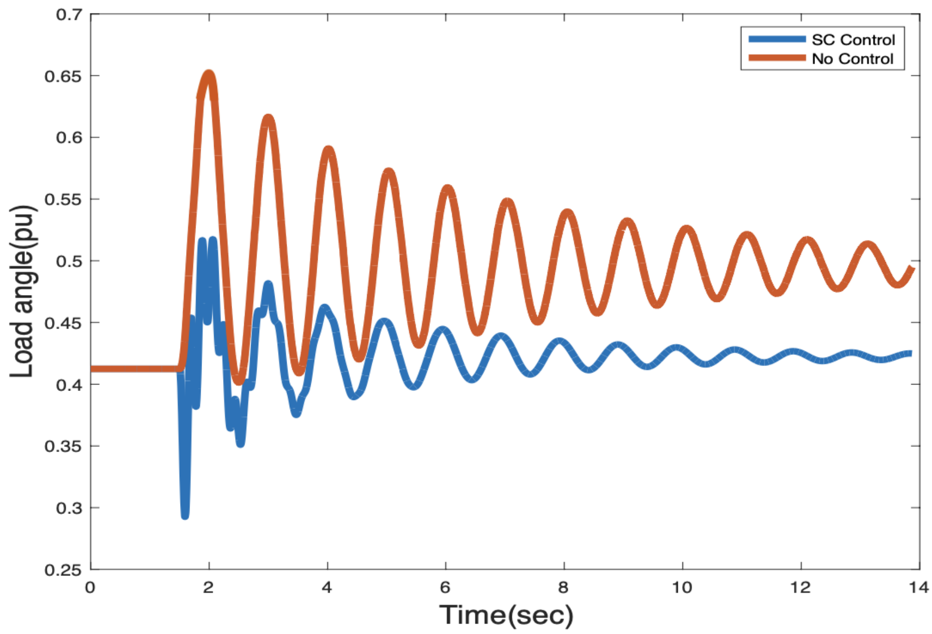


Figure 5.6 Rotor angle variation following 0.4 pu torque pulse disturbances for 0.5 sec with no additional converter control and STATCOM independent PQ control.

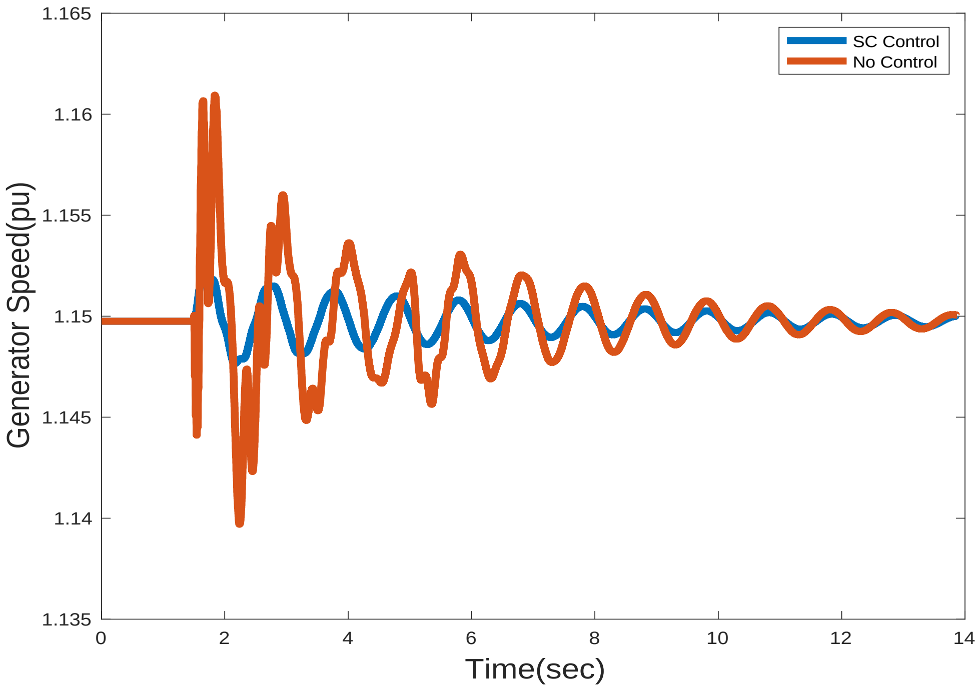


Figure 5.7 Generator speed variation following 0.4 pu torque pulse disturbances for 0.5 sec with no additional converter control and STATCOM independent PQ control.

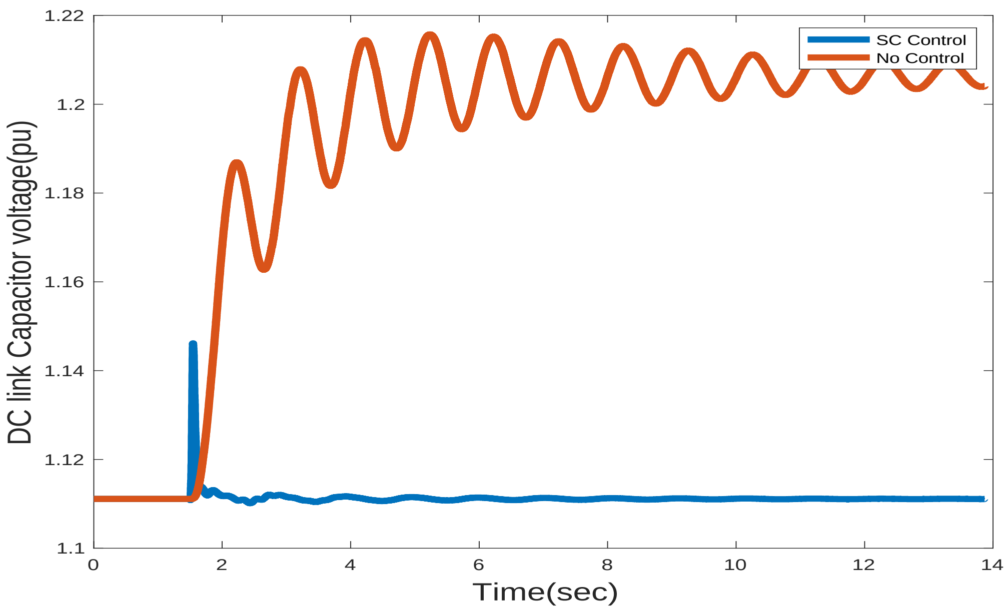


Figure 5.8 DC link voltage variation following 0.4 pu torque pulse disturbances for 0.5 sec with no additional converter control and STATCOM independent PQ control.

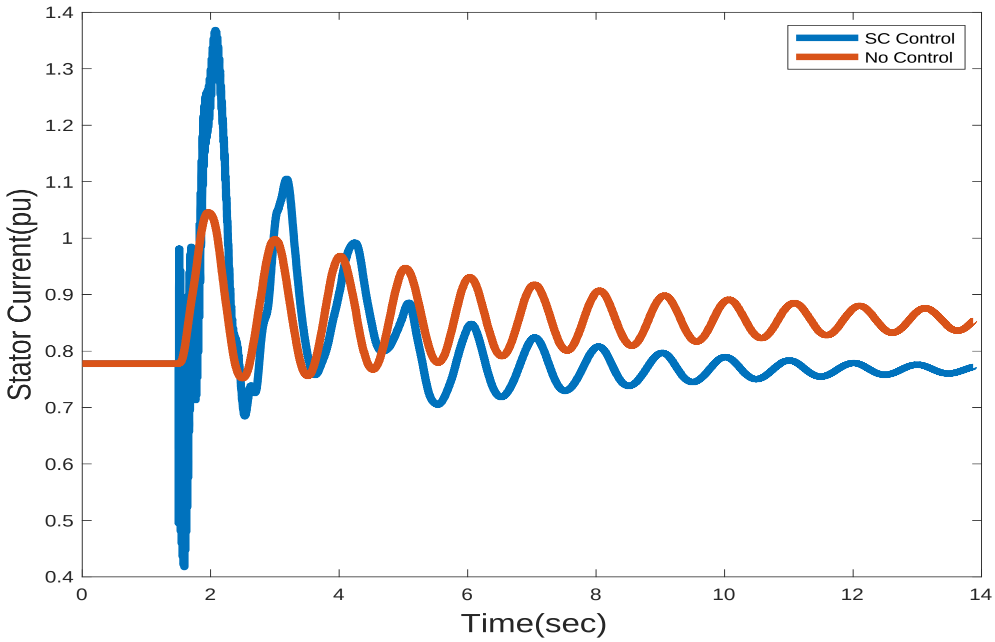


Figure 5.9 Stator current variation following 0.4 pu torque pulse disturbances for 0.5 sec with no additional converter control and STATCOM independent PQ control.

The effectiveness of the independent STATCOM PQ controller is evaluated for both the cases and tabulated. Table 1 shows the damping performance of the controller based on the maximum overshoot value. Table 2 shows the steady state performance of the controller.

*Table 5.1: Maximum overshoot (in pu) for sudden wind gust*

| Variables | Without Controller | With Controller |
|---|---|---|
| Turbine Speed | 1.15494 | 1.15342 |
| Stator Current | 1.04522 | 0.981528 |
| Generator Speed | 1.15668 | 1.15184 |
| Rotor angle | 0.6519 | 0.5219 |
| DC link capacitor Voltage | 1.18654 | 1.14586 |

*Table 5.2: Steady state value (in pu) for sudden wind gust*

| Variables | Without Controller | With Controller | Initial Steady State Value |
|---|---|---|---|
| Turbine Speed | 1.3198 | 1.1497 | 1.1497 |
| Stator Current | 0.8534 | 0.7542 | 0.7778 |
| Generator Speed | 1.3224 | 1.14975 | 1.1497 |
| Rotor angle | 0.6519 | 0.4708 | 0.4719 |
| DC link capacitor Voltage | 1.2063 | 1.11 | 1.1111 |

From Table 1 and Table 2, it is clear that the designed independent P-Q controller has good damping properties with less maximum overshoot and little steady state error for the sudden wind gust as disturbance.

Similarly, for the torque pulse as disturbance the transient characteristics and the damping performance of the controller is studied based on the maximum overshoot and steady state error.

*Table 5.3: Maximum overshoot (in pu) for torque pulse*

| Variables | Without Controller | With Controller |
|---|---|---|
| Turbine Speed | 1.16552 | 1.15484 |
| Stator Current | 0.65 | 0.5232 |
| Generator Speed | 1.16092 | 1.15181 |
| Rotor angle | 1.36825 | 0.980998 |
| DC link capacitor Voltage | 1.18629 | 1.14588 |

*Table 5.4: Steady state value (in pu) for torque pulse*

| Variables | Without Controller | With Controller | Initial Steady State Value |
|---|---|---|---|
| Turbine Speed | 1.15 | 1.1497 | 1.14975 |
| Stator Current | 0.4794 | 0.4798 | 0.412443 |
| Generator Speed | 1.1497 | 1.1497 | 1.14976 |
| Rotor angle | 0.85401 | 0.76775 | 0.76775 |
| DC link capacitor Voltage | 1.2221 | 1.111 | 1.111 |

The maximum overshoot values from Table 5.3 and the steady state value from the Table 5.4 also shows that the transients are well damped. This shows that the transients are quite effectively handled by the designed independent STATCOM P-Q controller in case of torque pulse as well.

# Chapter 5

# CONCLUSION AND FUTURE WORK

## 5.1 Conclusion

A detailed model of the PMSG including converter control system and STATCOM was derived. The variable speed PMSG wind turbine suffers from various disturbances such as wind power fluctuation, faults in the line. During such scenarios, the power supply to the grid may be imbalance. The grid may not be able to supply the necessary reactive power supply for the smooth operation. A STATCOM is voltage source-controlled device able to supply the required reactive power during such contingencies. It is connected at the inverter side of the system at which local load is connected, commonly called as point of common coupling. For the operation of the STATCOM to supply necessary reactive power, an independent P-Q controller is designed to modulate control signals $m_{stc}$ and $\varphi_{stc}$.

This article shows that an adequately controlled STATCOM can provide significant control of transients in a PMSG wind system. This PMSG wind system was modeled in detail along with the converters, STATCOM and the STATCOM controller to produce a robust dynamic model. Small torque steps and wind gust disturbances were simulated to show a comparison of performance of the PMSG wind generator system with and without independent P-Q control of STATCOM. It has been observed that the STATCOM independent P-Q controller can adequately control the oscillations in the system following even wind gust.

## 5.2 Future work

The following research may be carried out as extension of this project:

- PMSG with pitch angle control will be interesting.
- It will be interesting to study the response in multimachine power system environment.

- Controllers other than PI should be implemented to explore more about the performance of the system.
- STATCOM with energy storage devices can be implemented.

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# Appendix A

System parameters and operating values

**Wind Plant:**

Nominal Power = 2MW

Rotor diameter = 75 m

Rotating Speed = 6.0 – 19.5 rpm

Nominal Wind Speed = 11.95 m/sec

**PMSG:**

Rated Power = 2MW; Stator rated line voltage = 690V;

Rated frequency = 50Hz. Number of Pole Pairs = 154

$qqR_a = 0.01$ p.u. $X_d = 0.8$ p.u. $X_q = 0.5$ p.u. $D_g = 0.6$ p.u.

$H_g = 0.5$ p.u. $H_t = 3$ p.u. $K_s = 0.3$ p.u. $D_t = 0.6$ p.u.

$R_i = 0.01$ p.u. $X_i = 0.1$ p.u. $C = 1$ p.u.

**STATCOM:**

$R_{stc} = 0.01$ p.u. $L_{stc} = 0.1$ p.u. $C_{dc} = 1$ p.u.

**Load & Transmission Line:**

Load Admittance ($Y_{11}$ ) =0.2- j0.4p.u.

Transmission Line Impedance ($Z_{line}$) = R+jX = 0.16+j0.2 p.u.

# Appendix B

### The LOAD and LINE Model

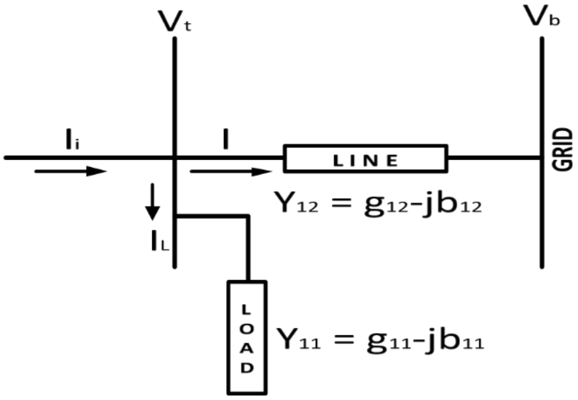


**Figure B .1The transmission line-load network**

Retaining the notation for generator operation, the current in the transmission line shown in Fig.B.1 is written as,

$$I_i = I_L + I = V_t Y_{11} + (V_t - V_b) Y_{12} \qquad (B.1)$$

Here,

$Y_{11} = g_{11} - jb_{11}$ is the local admittance and $Y_{12} = g_{12} - jb_{12}$ is the Tr. line admittance,

$V_t = (V_{td} + jV_{tq})$ is the load terminal voltage, and $V_b = V_{bd} + j0$ is the grid voltage referenced along the d – axis. Substituting the above expressions in equation (B.1), we get;

$$i_{id} + ji_{iq} = (V_{td} + jV_{tq}).(g_{11} - jb_{11}) + (V_{td} - V_{bd} + jV_{tq})(g_{12} - jb_{12}) \qquad (B.2)$$

Equating real and imaginary parts, we get;

$$i_{id} = \left(V_{td} g_{11} + V_{tq} b_{11}\right) + ((V_{td} - V_{bd}) g_{12} + V_{tq} b_{12})$$

$$i_{iq} = \left(V_{tq}g_{11} - V_{td}b_{11}\right) + (V_{tq}g_{12} - (V_{td} - V_{bd})b_{12}) \quad \text{(B.3)}$$

Simplifying the above equation and replacing $V_{bd}$ by $V_b$, we get;

$$i_{id} = V_{td}(g_{11} + g_{12}) + V_{tq}(b_{11} + b_{12}) - V_b g_{12}$$

$$i_{iq} = -V_{td}(b_{11} + b_{12}) + V_{tq}(g_{11} + g_{12}) + V_b g_{12} \quad \text{(B.4)}$$

In the matrix form, above equation changes to:

$$\begin{bmatrix} i_{id} \\ i_{iq} \end{bmatrix} = \begin{bmatrix} (g_{11} + g_{12}) & (b_{11} + b_{12}) \\ -(b_{11} + b_{12}) & (g_{11} + g_{12}) \end{bmatrix} \begin{bmatrix} V_{td} \\ V_{tq} \end{bmatrix} + \begin{bmatrix} -g_{12} \\ b_{12} \end{bmatrix} [V_b] \quad \text{(B.5)}$$

Modifying the above equation to get expression for $V_{td}$ $V_{tq}$, we get;

$$\begin{bmatrix} i_{id} + V_b g_{12} \\ i_{iq} - V_b b_{12} \end{bmatrix} = \begin{bmatrix} (g_{11} + g_{12}) & (b_{11} + b_{12}) \\ -(b_{11} + b_{12}) & (g_{11} + g_{12}) \end{bmatrix} \begin{bmatrix} V_{td} \\ V_{tq} \end{bmatrix} \quad \text{(B.6)}$$

On taking inverse, we get;

$$\begin{bmatrix} V_{td} \\ V_{tq} \end{bmatrix} = \begin{bmatrix} (g_{11} + g_{12}) & (b_{11} + b_{12}) \\ -(b_{11} + b_{12}) & (g_{11} + g_{12}) \end{bmatrix}^{-1} \begin{bmatrix} i_{id} + V_b g_{12} \\ i_{iq} - V_b b_{12} \end{bmatrix}$$

For convenience, let us take;

$$\begin{bmatrix} (g_{11} + g_{12}) & (b_{11} + b_{12}) \\ -(b_{11} + b_{12}) & (g_{11} + g_{12}) \end{bmatrix}^{-1} = \begin{bmatrix} c_1 & c_2 \\ c_3 & c_4 \end{bmatrix} \quad \text{(B.7)}$$

Therefore, the equations for $V_{td}$, $V_{tq}$ becomes;

$$\begin{bmatrix} V_{td} \\ V_{tq} \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \\ c_3 & c_4 \end{bmatrix} \begin{bmatrix} i_{id} + V_b g_{12} \\ i_{iq} - V_b b_{12} \end{bmatrix}$$

Simplifying above expression, we get;

$$v_{td} = c_1 i_{id} + c_2 i_{iq} + V_b(c_1 g_{12} - c_2 b_{12})$$

$$v_{td} = c_3 i_{id} + c_4 i_{iq} + V_b(c_3 g_{12} - c_4 b_{12}) \quad \text{(B.8)}$$