

REACTIVE POWER CONTROL OF WIND FARM USING FACTS DEVICES

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Wind energy is an attainable option to complement other types of pollution-free green generation. Grid connections of renewable energy resources are vital if they are to be effectively exploited, but grid connection brings problems of voltage fluctuation and harmonic distortion. FACTS devices are one of the power electronics revolutions to improve voltage profile, system stability, and reactive power control and to reduce transmission losses. The studied system here is a variable speed wind generation system based on Induction Generator (IG) with integration of different FACTS controllers in the wind farm. To harness the wind power efficiently the most reliable and expensive system in the present era is grid connected doubly fed induction generator. Induction generator with FACTS devices is a suitable economical replacement. The suggested scheme is implemented in MATLAB Simulink with real time parameters of GHARO wind power plant in Sind, and corresponding results and output waveforms prove the potential strength of proposed methodology.

Keywords: FACTS (Flexible AC transmission system), DFIG (Double Fed Induction Generator), PCC (Point of Common Coupling)

1. Introduction

The AC transmission system has various limits classified as static limits and dynamic limits. These inherent power system limits restrict the power transaction, which lead to the under utilization of the existing transmission resources. Traditionally, fixed or mechanically switched shunt and series capacitors, reactors and synchronous generators were being used to solve much of the problem.

However, there are restrictions as to the use of these conventional devices. Desired performance was not being able to achieve effectively. Wear and tear in the mechanical components and slow response were the heart of the problems. There was greater need for the alternative technology made of solid state devices with fast response characteristics. The need was further fuelled by worldwide restructuring of electric utilities, increasing environmental and efficiency regulations and difficulty in getting permit and right of way for the construction of overhead transmission lines. This, together with the invention of Thyristor switch (semiconductor device), opened the door for the development of power electronics devices known as Flexible AC Transmission Systems (FACTS) controllers [1]. The path from historical Thyristor based FACTS controllers to modern state-of-the-art voltage source converters based FACTS

Controllers, was made possible due to rapid advances in high power semiconductor devices. FACTS controllers have been in use in utilities around the world since 1970s, when the first utility

demonstration of first family of FACTS named as Static VAR Compensator (SVC) was accomplished. Since then the large effort was put in research and development of FACTS controllers. The history of development of these devices is presented along with the information regarding the first utility installation/demonstration of FACTS devices [2]. A comprehensive collection of major FACTS installations around the world is then presented. The first FACTS installation was at the C. J. Slatt Substation in Northern Oregon. This is a 500 kV, 3-phase 60 Hz substation, and was developed by EPRI, the Bonneville Power Administration and General Electric Company [3].

There are some basic terms to describe wind electricity production.

1.1 Wind Efficiency

It refers to how much useful energy (electricity, in this case) we can get from an energy source. A 100 percent energy efficient machine would change all the energy put into it into useful energy. Wind machines are just as efficient as most other plants, such as coal plants. Wind machines convert 30-40 percent of the wind's kinetic energy into electricity. The studied system has efficiency about 36.12%.

1.2 Wind Capacity Factor

It refers to the capability of a power plant to produce electricity. Wind plants depend on the availability of wind, as well as the speed of the wind. Therefore, wind machines cannot operate 24 hours a day, 365 days a year. A wind turbine at a typical wind farm operates 65-

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80 percent of the time, but usually at less than full capacity, because the wind speed is not at optimum levels. Therefore, studied system has capacity factor of 30-35 percent.

By capacity factor we mean its actual annual energy output divided by the theoretical maximum output, if the machine were running at its rated (maximum) power during all of the 8766 hours of the year.

Example: If a 600 kW turbine produces 1.5 million kWh in a year, its capacity factor is = $1500000 : (365.25 * 24 * 600) = 1500000 : 5259600 = 0.285 = 28.5$ per cent.

Capacity factors may theoretically vary from 0 to 100 per cent, but in practice they will usually range from 20 to 70 per cent, and mostly be around 25-30 per cent.

1.3 Wind Energy Production

Wind generated electric power output at Gharo has been estimated by using the 600kW wind turbine Bonus 600/40 MK IV type. The cut-in wind speed of turbine is 3m/s and cutout wind speed is 25m/s. Rotor diameter is 44 meters and hub height has been taken as 50 meter. The monthly and annual wind generated electric power output at Gharo-Sind along with capacity factor are given in Table and the month-wise hourly wind power output is given below.

Table 1. Hypothetical wind generated electric energy output & capacity factor for a 600/44MK turbine.

PMD Calculator (using 50M)		
Months	Capacity Factor	kWh per Month
January	13%	57745
February	16%	65384
March	16%	69869
April	30%	127689
May	60%	268240
June	45%	194703
July	68%	305321
August	35%	157142
September	43%	187858
October	12%	53867
November	10%	44324
December	13%	59327
Annual	28%	1495808

1.4 Effect of Altitude on Wind Speed

The winds aloft generally have a higher velocity than the winds at ground level. In other words, at any given time and place, wind speed usually increases with altitude. The effect of altitude on wind speed involves two factors:

- The degree of turbulent mixing prevailing in the atmosphere at the given time and place, as characterized by the Pasqual stability class
- The terrain's surface area roughness, which induces surface friction at the given place
- It has generally been agreed that the effect of altitude on wind speed is logarithmic and can be expressed as:

$$u_z / u_g = (h_z / h_g)^a$$

where:

u_z = wind velocity at height z

u_g = wind velocity at ground station height

h_z = height z

h_g = ground station height (usually 10 meters)

a = a function of the Pasquill stability class and the terrain type (see tables below)

Table 2. Value of a with respect to air humidity level.

Location	
Unstable air above open water surface	0.06
Neutral air above open water surface	0.10
Unstable air above flat open coast	0.11
Neutral air above flat open coast	0.16
Stable air above open water surface	0.27
Unstable air above human inhabited areas	0.27
Neutral air above human inhabited areas	0.34
Stable air above open coast	0.40
Stable air above human inhabited areas	0.60

2. System Model

The models used in Matlab simulink are used for making model diagram. Different blocks are connected to get the complete block diagram. Some of these blocks are common in block diagrams of all FACTS devices like grid model, transformer model PI section, wind turbine induction generator model and grounding transformer. Their detailed description is as follows.

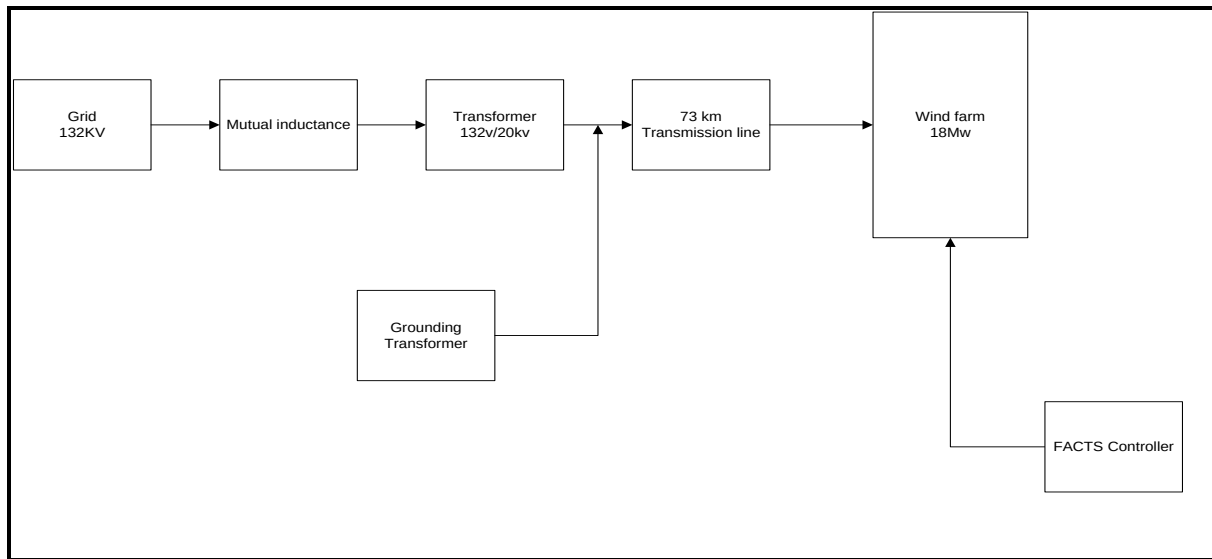


Figure 1. Model diagram for simulation.

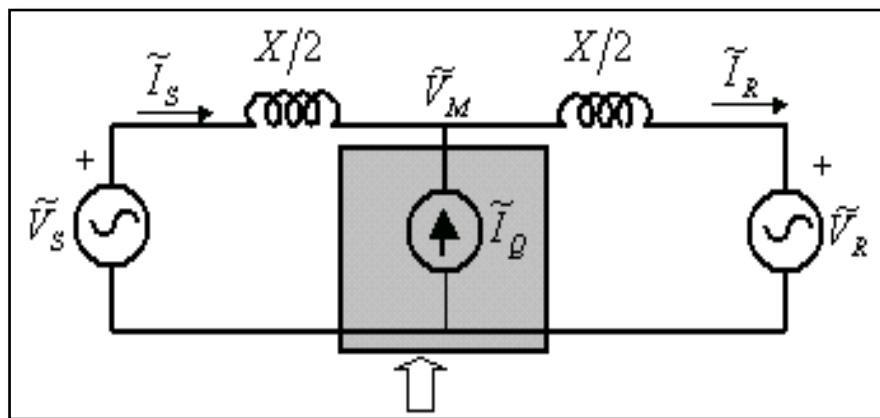


Figure 2. Ideal shunt compensator.

3. FACTS Controller

“A power electronic-based system and other static equipment that provide control of one or more ac transmission system parameters.”

Transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever [4-7]. The limitations of the transmission system can take many forms and may involve power transfer between areas or within a single area or region.

4. Classification of FACTS

FACTS controllers can be broadly classified into these types:

- 4.1 Shunt Compensator
- 4.2 Series Compensator

4.3 Compound Compensator

4.1 Shunt Compensator

A device that is connected in parallel with a transmission line is called a shunt compensator; these are referred to as compensators since they compensate for the reactive power in the ac system. We shall assume that the shunt compensator is always connected at the midpoint of transmission system, while the series compensator can be connected at any point in the line and it improves [8-9].

- Voltage profile
- Power-angle characteristics
- Stability margin
- Damping to power oscillations

The ideal shunt compensator is an ideal current source. We call this an ideal shunt compensator because we assume that it only supplies reactive power and no real power to the system.

4.2 Series Compensator

A device that is connected in series with the transmission line is called a series compensator.

Impact of Series Compensator on Voltage Profile

- Improving Power-Angle Characteristics
- An Alternate Method of Voltage Injection
- Improving Stability Margin
- Comparisons of the Two Modes of Operation
- Power Flow Control and Power Swing Damping

In series compensation, the FACTS are connected in series with the power system. It works as a controllable voltage source. Series inductance exists in all AC transmission lines. On long lines, when a large current flows, this causes a large voltage drop. To compensate, series capacitors are connected, decreasing the effect of the inductance. Series FACTS devices could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series FACTS devices inject voltage in series with the transmission line [10-14]. It generates controllable voltage over an identical capacitive and inductive range independent of line current. It also provides real and reactive power injection to the line. Hence damping Oscillations and Voltage Stability is improved.

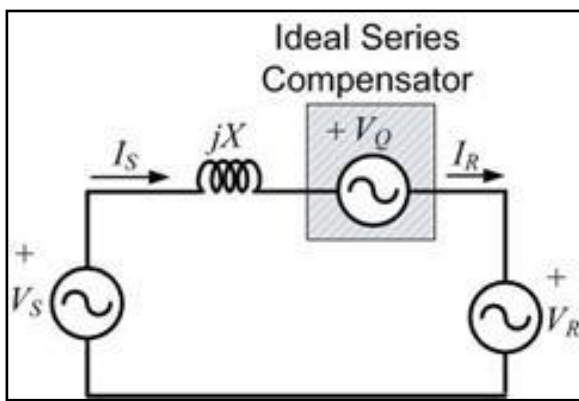


Figure 3. Schematic Diagram of an Ideal Series Compensated System.

4.3 Compound Compensator

In compound compensation, the FACTS are connected in a combination of series and parallel connections with the power system. It works as a

controllable voltage source. Two inverters, namely shunt inverter and series inverter which operate via a common dc link with a dc storage capacitor, allow controller to independently control active and reactive power flows on the line as well as the bus voltage.

Table 3. Classification of FACTS.

Shunt Compensators	SVC (Static VAR Compensators) STATCOM (Static Synchronous Compensator)
Series Compensators	SSSC (Static Synchronous Series Compensator) TCSC Thyristor Controlled Series Compensator TSSC
Combination of Parallel and Series Compensators	UPFC (Unified Power Flow Controller) IPFC (Inter-phase Power Flow Controller)
Other FACTS Controllers	TCPAR (Thyristor Control Phase Angle Regulators) TCVL (Thyristor Controlled Voltage Limiters) TSBR (Thyristor Switched Breaking Resistors) TCPST (Thyristor Controlled Phase Shifting Transformers)

In our system we have used following three controller

- SVC
- STATCOM
- UPFC

4.3.1 SVC (Static VAR Compensator)

“SVC is a shunt connected static VAR generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables.”

The Static VAR Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids [15]. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive) [16]. The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each

capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR).

4.3.2 STATCOM

“STATCOM is the voltage-source converter, which converts a DC input voltage into AC output voltage in order to compensate the active and reactive needed by the system.”

With the advancement in the power electronic technology, the application of a gate turn off thyristor (GTO) to high power application became commercially feasible. With this the second generation shunt compensator device was conceptualized and constructed. These devices use synchronous voltage sources for generating or absorbing reactive power. A synchronous voltage source (SVS) is constructed using a voltage source converter (VSC). Such a shunt compensating device is called Static Compensator (STATCOM) [17].

If $\theta = \Phi$, then the direction of the flow of purely reactive current I_q will depend on the voltage magnitudes V_1 and V_2 .

If $V_1 > V_2$ then the current flows from the ac system to the SVS and the converter absorbs reactive (inductive) power. If $V_2 > V_1$ then the current flows from the SVS to the ac system and the converter generates reactive (capacitive) power for the ac system. However, pure reactive injection or absorption is neither possible nor desirable. Since the converter is supplied by a dc capacitor, the voltage across the capacitor will fall if the STATCOM is not lossless. The dc capacitor voltage can be regulated by replenishing the losses due to switching and in the coupling transformer circuit by drawing power from the ac system.

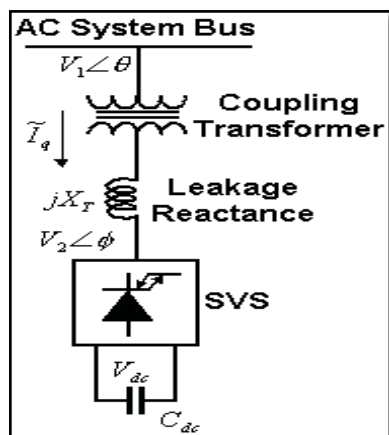


Figure 4. Working of STATCOM.

Therefore Φ must lag θ by a small amount such that the dc capacitor voltage is held constant.

4.3.3 UPFC (Unified Power Flow Controller)

Two inverters, namely shunt inverter and series inverter which operate via a common dc link with a dc storage capacitor, allow UPFC to independently control active and reactive power flows on the line as well as the bus voltage. The UPFC has two voltage source inverters (VSI) sharing a common dc storage capacitor. It is connected to the system through two coupling transformers.

The UPFC combines together the features of two FACTS devices: the *Static Synchronous Compensator* (STATCOM) and the *Static Synchronous Series Compensator* (SSSC) [18]. The DC terminals of the two underlying VSCs are now coupled, and this creates a path for active power exchange between the converters. Hence, the active power supplied to the line by the series converter, can now be supplied by the shunt converter.

The UPFC can be used to control the flow of active and reactive power through the line and to control the amount of reactive power supplied to the line at the point of installation.

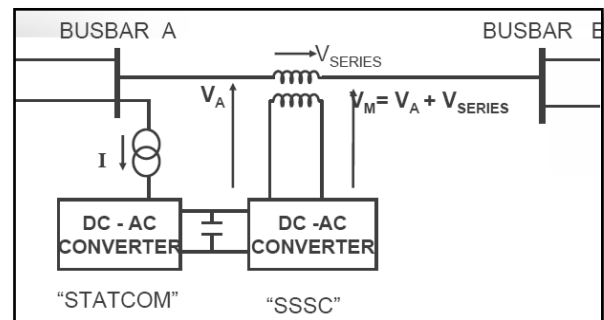


Figure 5. Unified power flow controller.

While operating both inverters as a UPFC, the exchanged power at the terminals of each inverter can be imaginary as well as real.

The UPFC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle).[19-20] The UPFC combines together the features of the *Static Synchronous Compensator* (STATCOM) and the *Static Synchronous Series Compensator* (SSSC). In practice, these two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer, connected to each other by a common dc link including a storage capacitor.

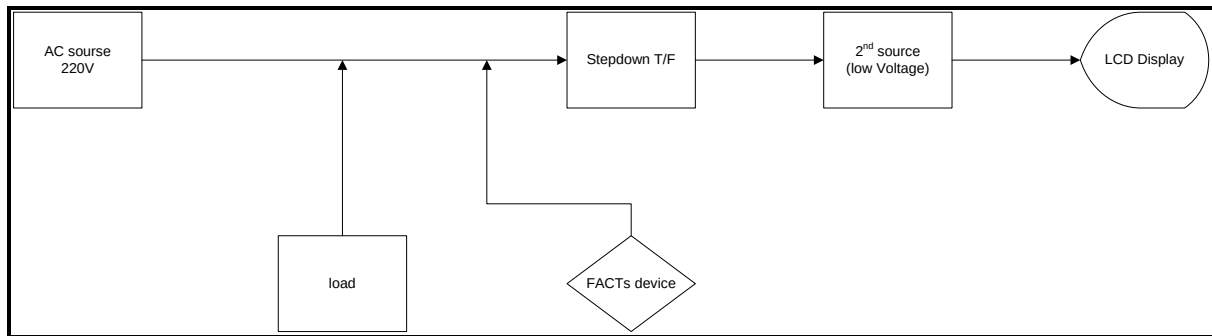


Figure 6. Hardware block diagram.

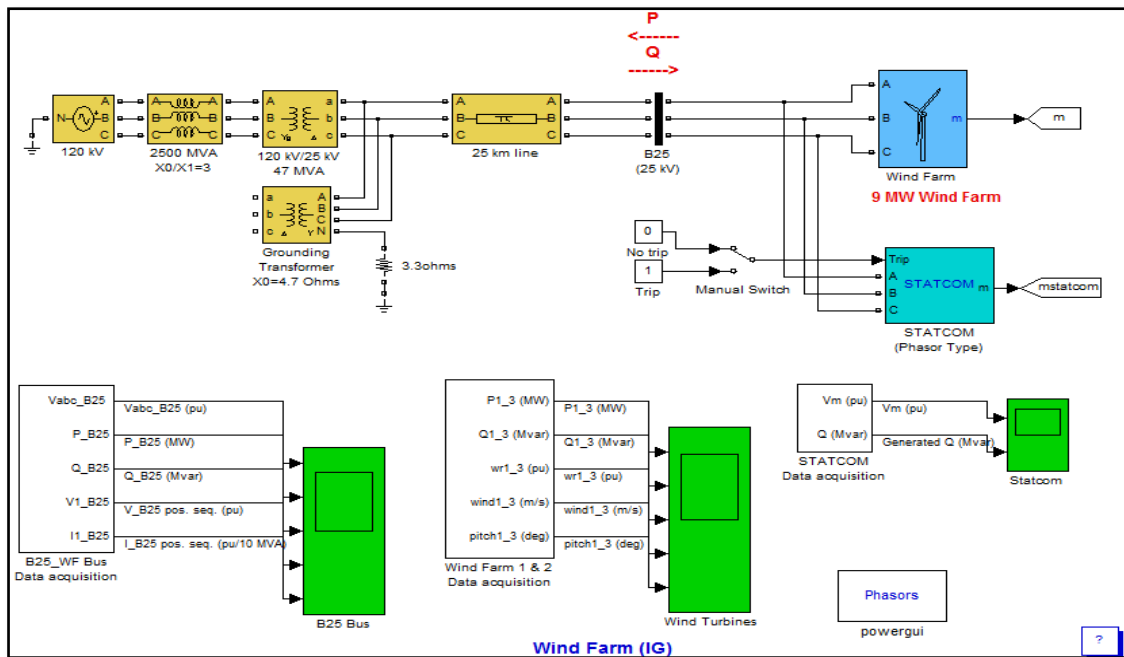


Figure 7. SIMULINK environment.

5. Hardware Implementation

A small scale model is developed to show the advantage of using FACTS device with the Wind farm induction generator. FACT device STATCOM is used in this scheme to implement the proposed strategy. In this model STATCOM is used for reactive power compensation at PCC. This model consists of following Components.

5.1 Generator

Since it can't be possible to implement Generator that's why for small scale implementation Generator is modeled as AC source of 220V.

5.2 Wind Farm

Wind farm is modeled as another voltage source with Step down Transformer to reduce the voltage level.

So that it can be used like another generator giving less supply as that of an original Ac source.

5.3. STATCOM

It is modeled as TRIAC with capacitor. TRIAC is bidirectional so current can flow through them in either direction. The impact of this device on steady state voltage and transient voltage stability is remarkable.

5.4 Inductive and Capacitive loads

Inductive and capacitive loads are used to check the performance of STATCOM in and out. In case of lagging voltage it provides reactive power and in case of leading voltage it absorbs it.

5.5 Step Down Transformer

Step down transformer is used to step down the voltage level from AC source which represents the wind Farm.

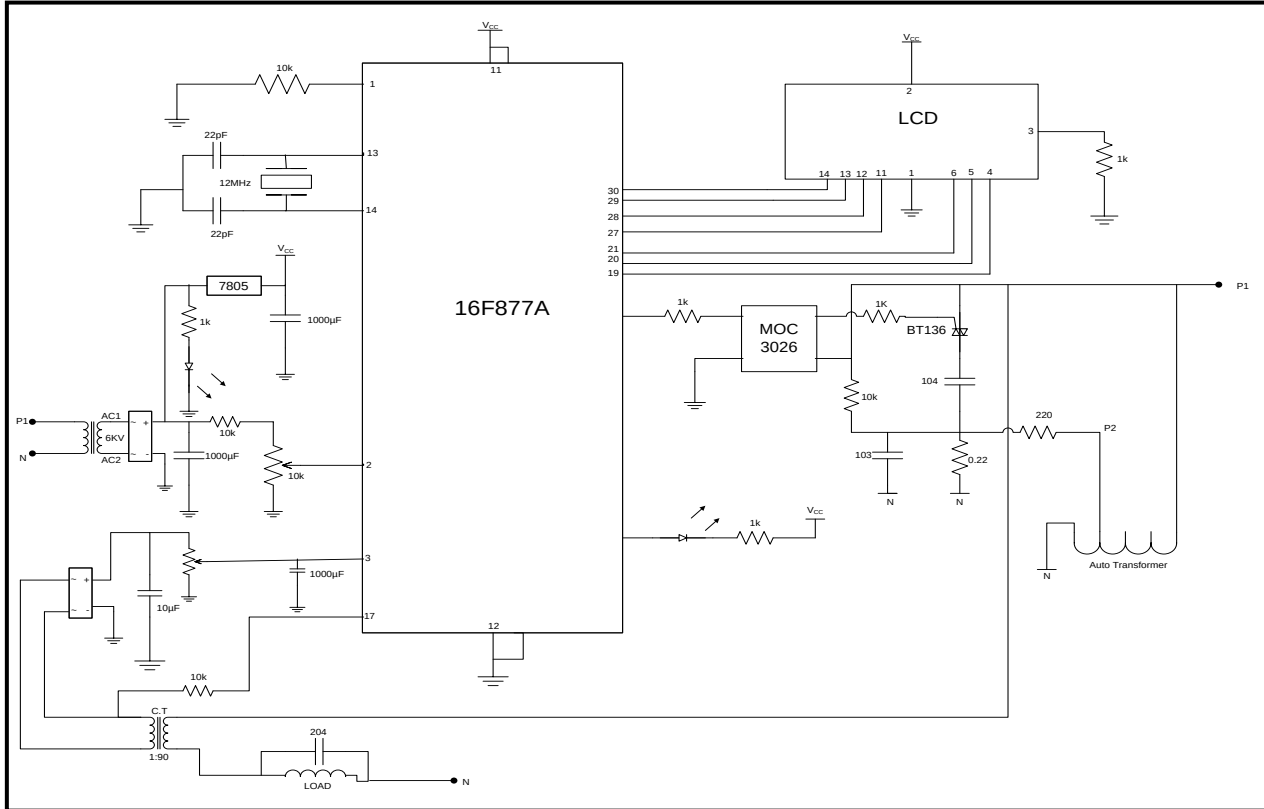


Figure 8. Circuit diagram of hardware.

5.6 Microcontroller

It is used for the automatic injection or removal of STATCOM. It works on the principle that when voltage is deviated from the certain limit it gives a signal to STATCOM into the circuit and to improve the voltage profile and voltage stability.

5.7 Interfacing of Microcontrollers

Microcontroller is interfaced with the following components :

- LCD
- Voltage Regulator (7805)
- Opto Coupler (250/400 v)
- Bridge
- Current Transformer (1:90)
- TRIAC BT136 (4A)
- Auto Transformer
- LEDs

- Capacitors
- Resistors

5.8 Explanation

At first Ac source give a supply of 220V. The voltage and power factor will be displayed on LCD. The 220 v is step down to 6v Ac, which is converted to DC by the Bridge.

The input from CT is also supplied to microcontroller through Bridge. The three inputs are given to microcontroller in the form of voltage at pin no 2, 3 and 17. Voltage, current and Phase angle is calculated. Then Step down transformer is used to reduce the voltage level from AC source which represents the IG wind Farm. Inductive load is used to consume some of its voltage, so there is voltage drop requiring the STATCOM to be in. So LCD displays “Applying STATCOM “. STATCOM is used for Reactive power compensation, when V is high it absorbs the Reactive power from the system and when V is low it supplies the reactive power to the system.

Thus Stability is maintained in the System. LCD is used for voltage and power factor display. So Voltage

and power factor is improved Power factor approaches to almost 0.999.



Figure 9. Hardware Model.

6. Wind Potential Area

Pakistan Meteorological Department has conducted a detailed Wind Power Potential Survey of Coastal Areas of Pakistan This study has enabled us to identify the potential areas where economically feasible wind farm can be established. Potential areas cover 9700 sq.km in Sind. The gross wind power potential of this area is 43000 MW and keeping in view the area utilization constrains etc. the exploitable electric power generation potential of this area is estimated to be about 11000MW. Feasibility study for the installation of 18 MW Model wind power project is prepared. Total cost of the project is estimated to be about Rs. 850 million and the payback period would be 7-8 years. The levelised cost of power generation is estimated as Rs. 2.9/kwh.

7. Case Studies

Following case Studies have been performed on test case.

- 7.1. Reactive power Investigations without Controller
- 7.2. Reactive power Investigations with STATCOM at 80 m altitude
- 7.3. Reactive power Investigations with STATCOM at 60 m altitude
- 7.4. Reactive power Investigations with SVC at 80m altitude
- 7.5. Reactive power Investigations with SVC at 60 m altitude
- 7.6. Reactive power Investigations with UPFC at 80 m altitude
- 7.7. Reactive power Investigations with UPFC at 60 m altitude

7.1 Without ontroller

The simulation results without any reactive power compensation device are given below:

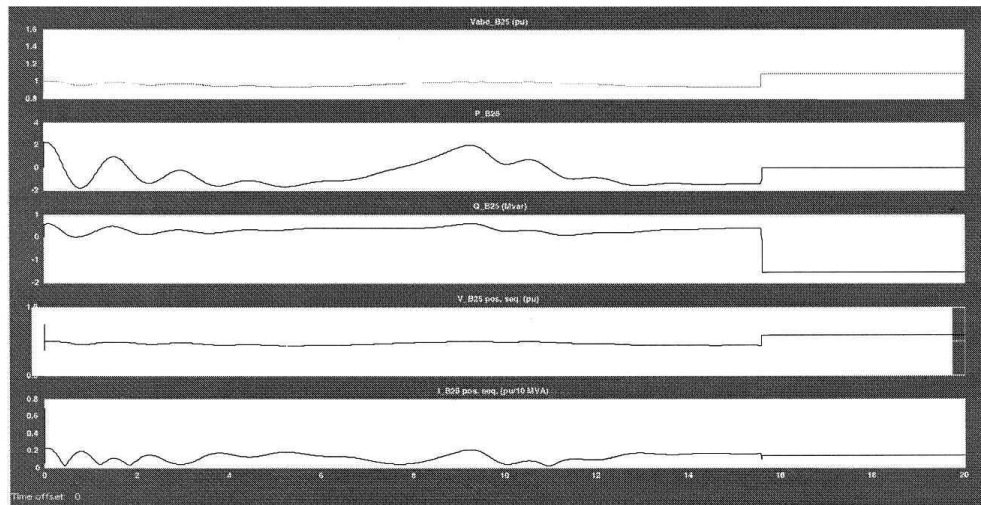


Figure 10. Simulation of Grid without Controller.

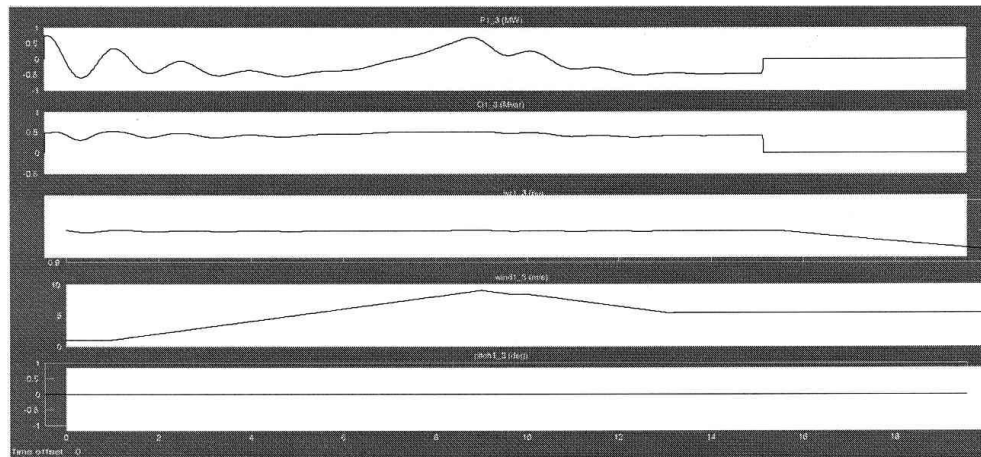


Figure 11. Simulation Result of Wind Turbine without Controller.

7.2 STATCOM Controller

With STATCOM at 80 m

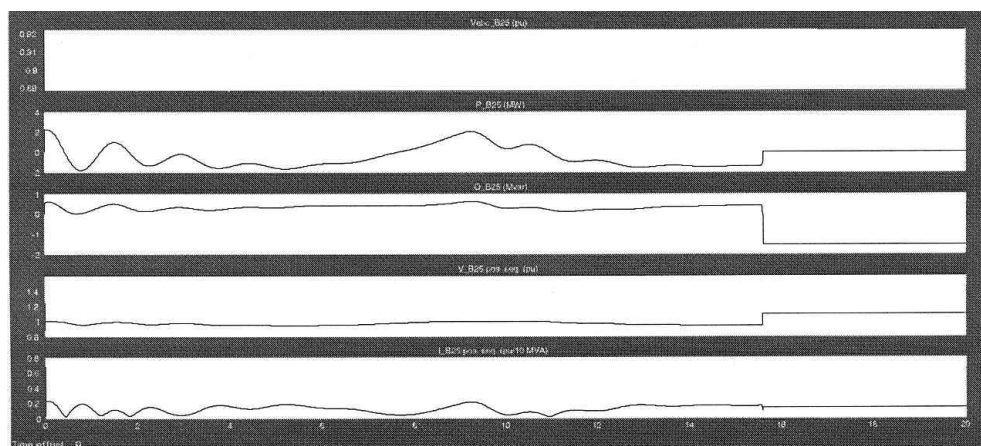


Figure 12. Simulation Result of Grid with STATCOM at 80m Height.

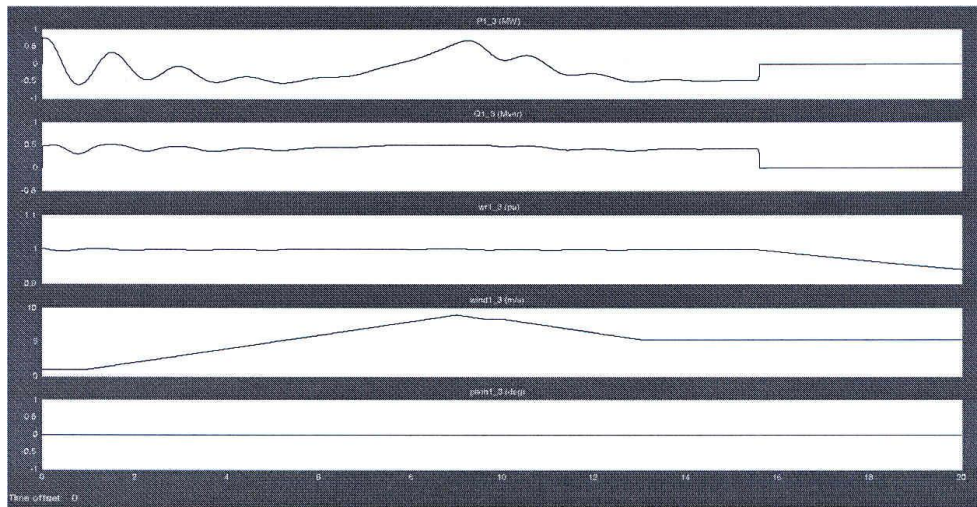


Figure 13. Simulation Result of Wind Turbine with STATCOM at 80m Height.

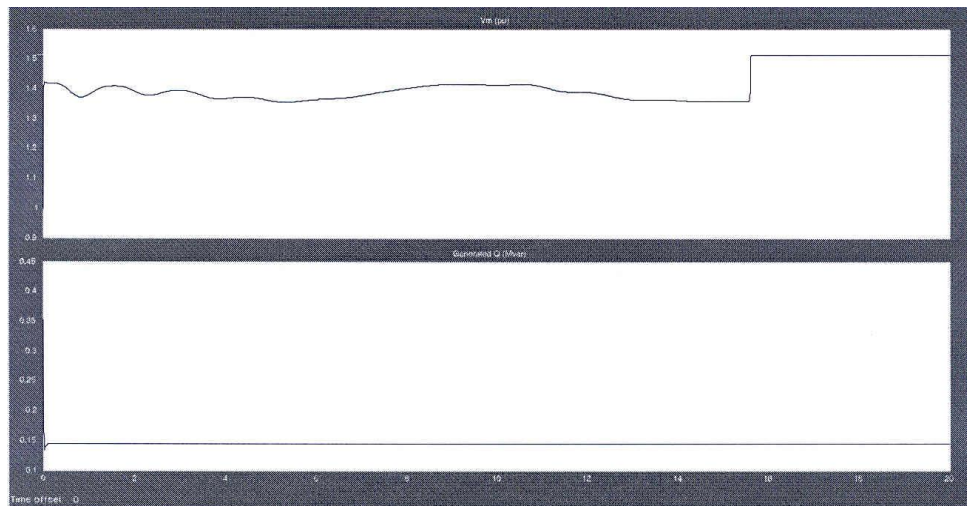


Figure 14. Simulation Result of STATCOM.

7.3 With STATCOM at 60 m

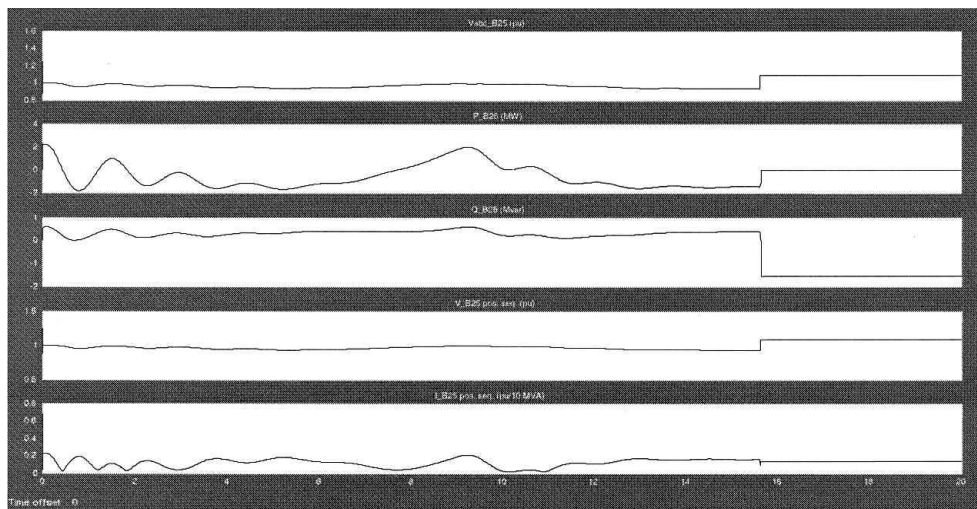


Figure 15. Simulation Result of Grid with STATCOM at 60m Height.

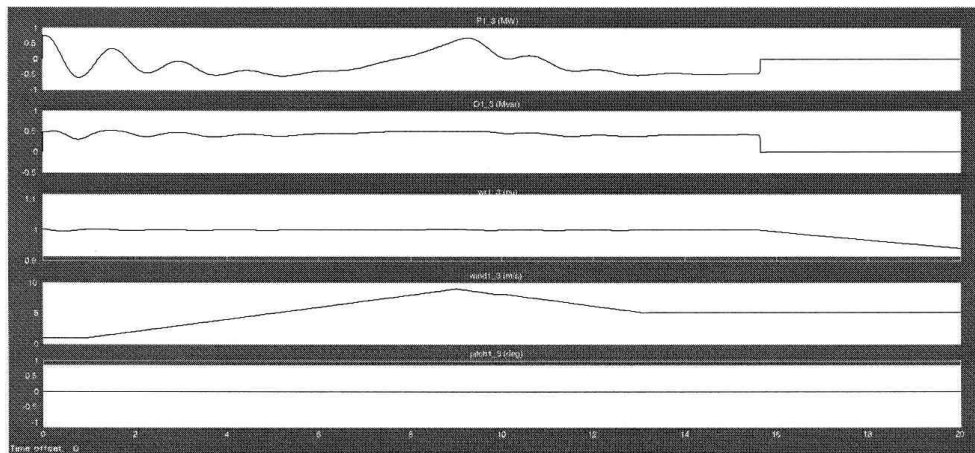


Figure 16. Simulation Result of Wind Turbine at 60m Height.

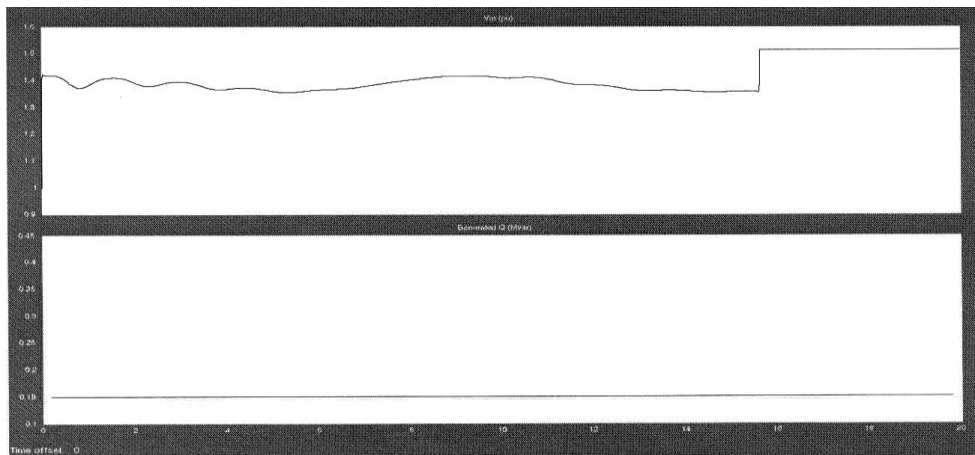


Figure 17. Simulation Result of STATCOM.

7.4 SVC Controller

With SVC at 80m

Using svc in wind power plant doesn't affect too much. The voltage and the reactive profile almost

remains the same. There is a very small regulation through svc. So it is not recommended to use svc for voltage and reactive power regulation in wind power plant.

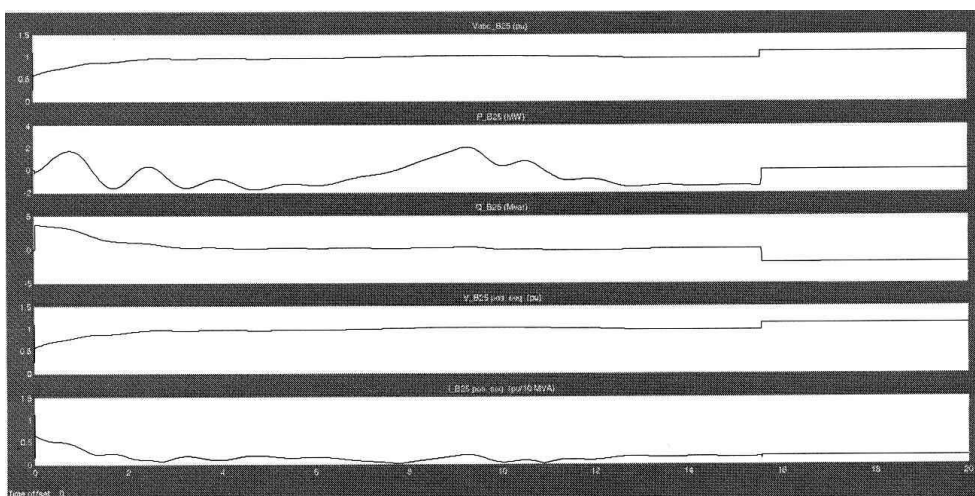


Figure 18. Simulation Result of Grid with SVC at 80m Height.

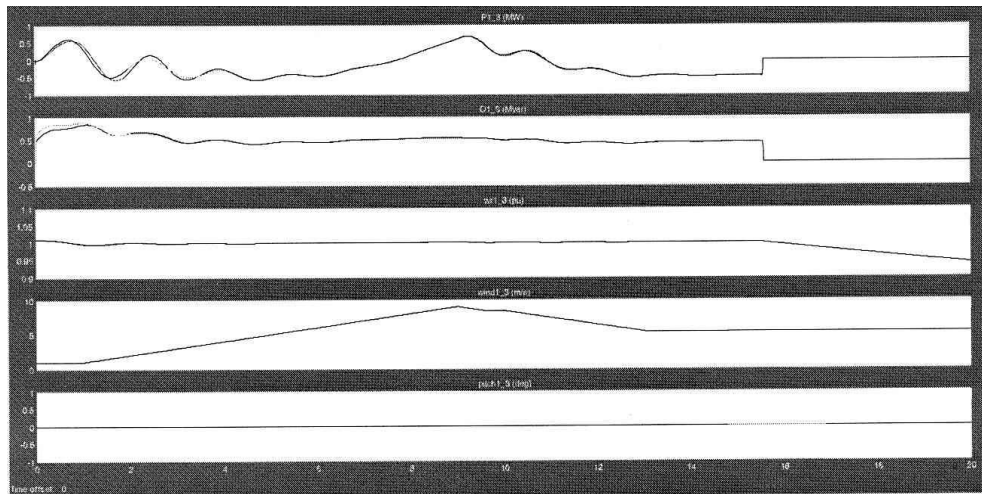


Figure 19. Simulation Result of Wind Turbine with SVC at 80m Height.

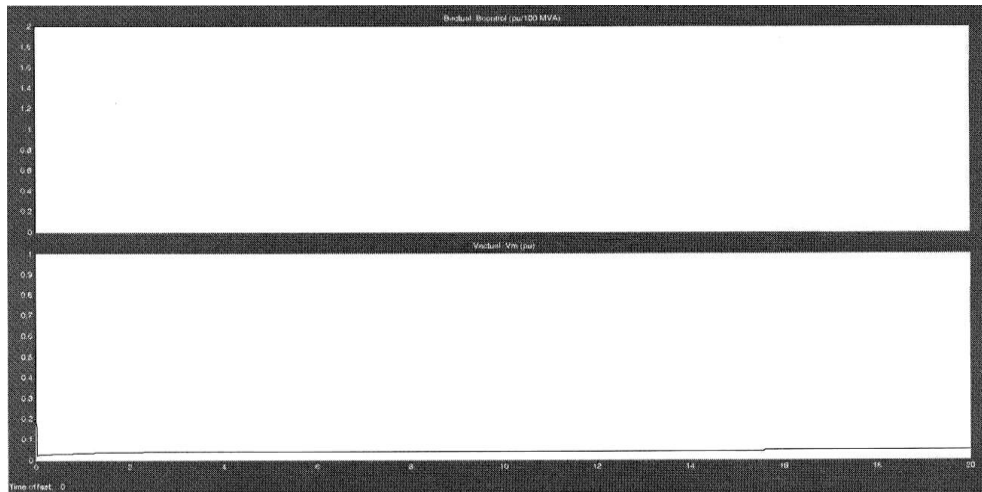


Figure 20. Simulation Result of SVC

7.5 With SVC at 60m

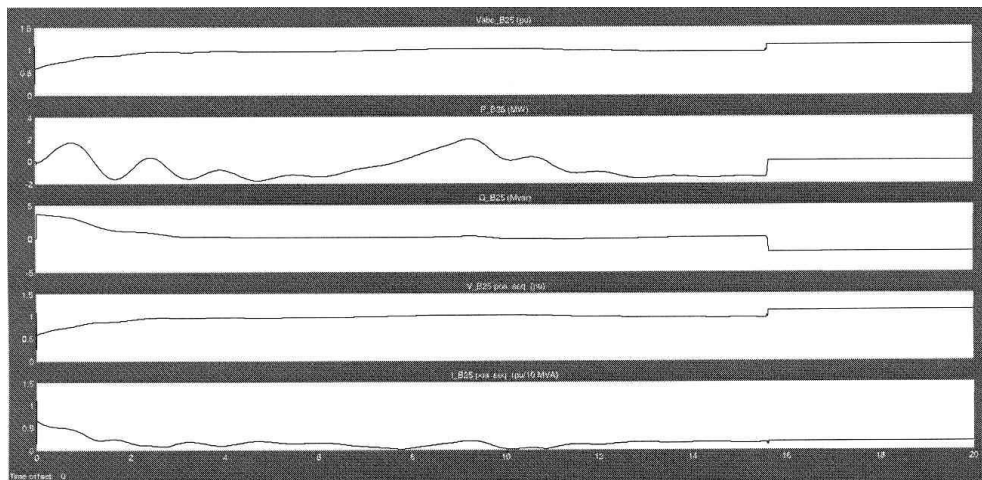


Figure 21. Simulation Result of Grid with SVC at 60m Height.

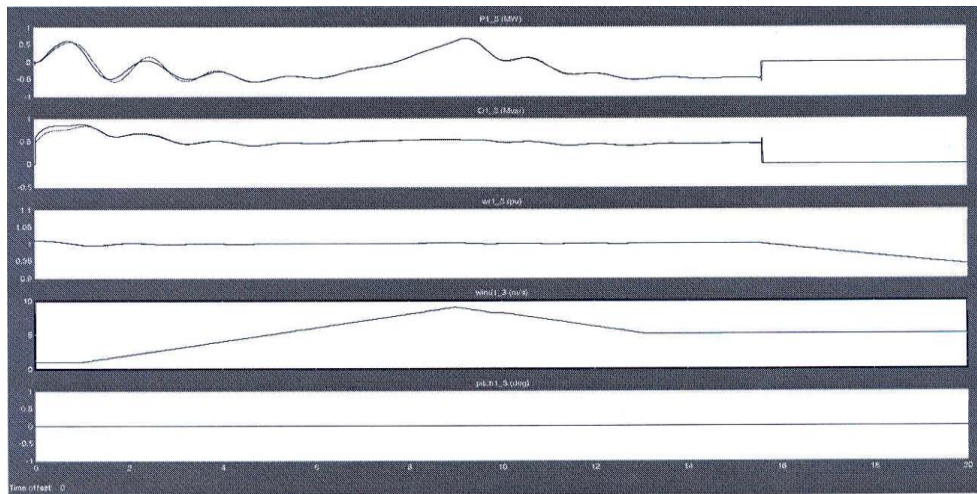


Figure 22. Simulation Result of Wind Turbine with SVC at 60m Height.

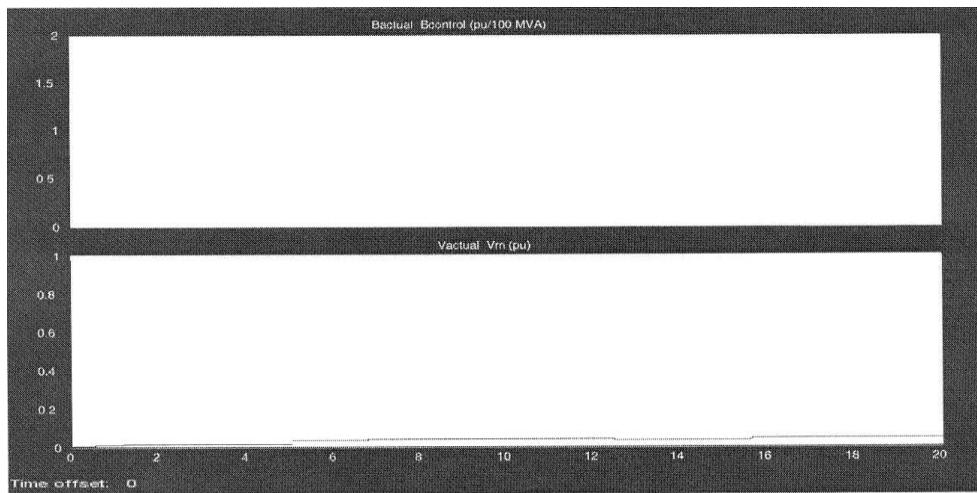


Figure 23. Simulation Result of SVC.

7.6 UPFC Controller

With UPFC at 80m

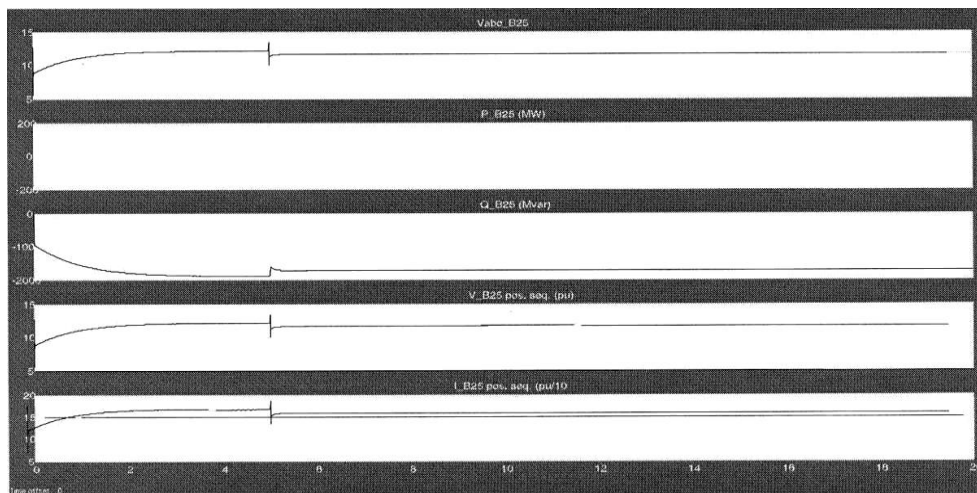


Figure 24. Simulation Result of Grid with UPFC at 80m Height.

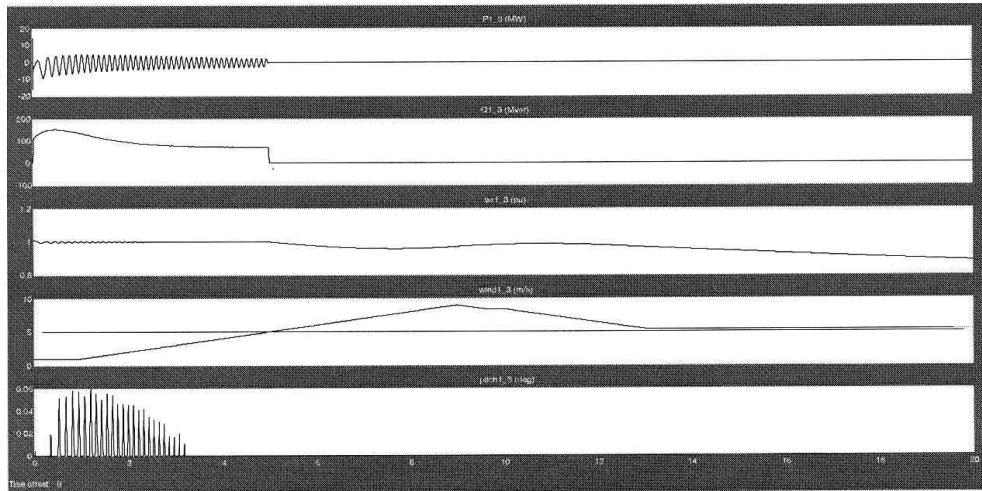


Figure 25. Simulation Result of Wind Turbine with UPFC at 80m Height.

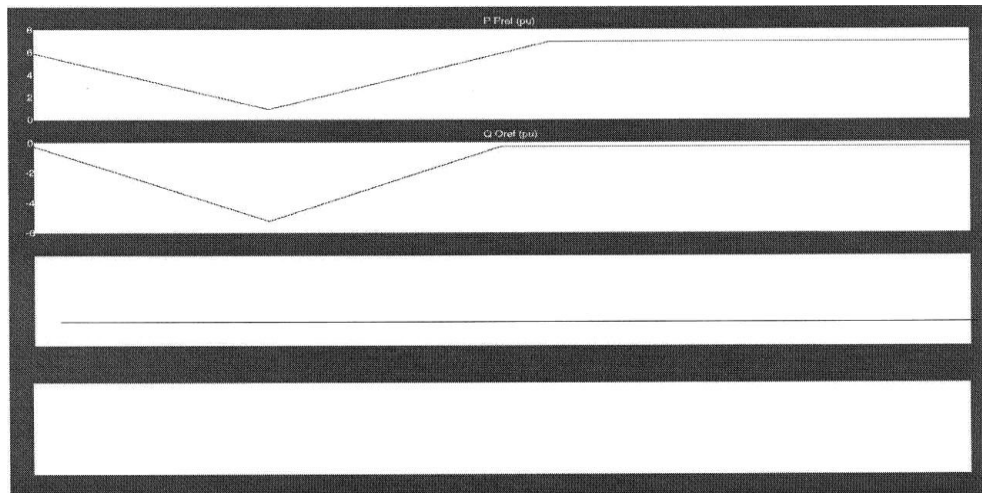


Figure 26. Simulation Result of UPFC.

7.7 With UPFC at height of 60m

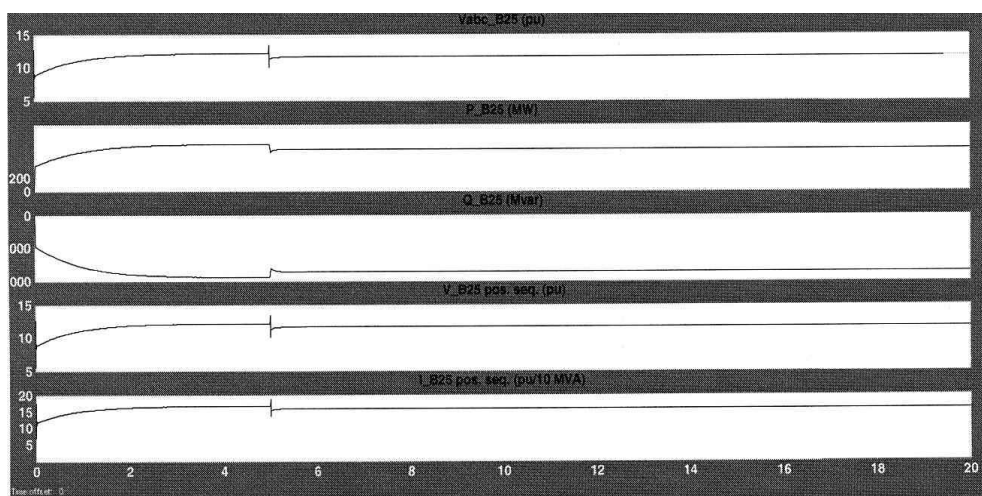


Figure 27. Simulation Result of Grid with UPFC at 60m Height.

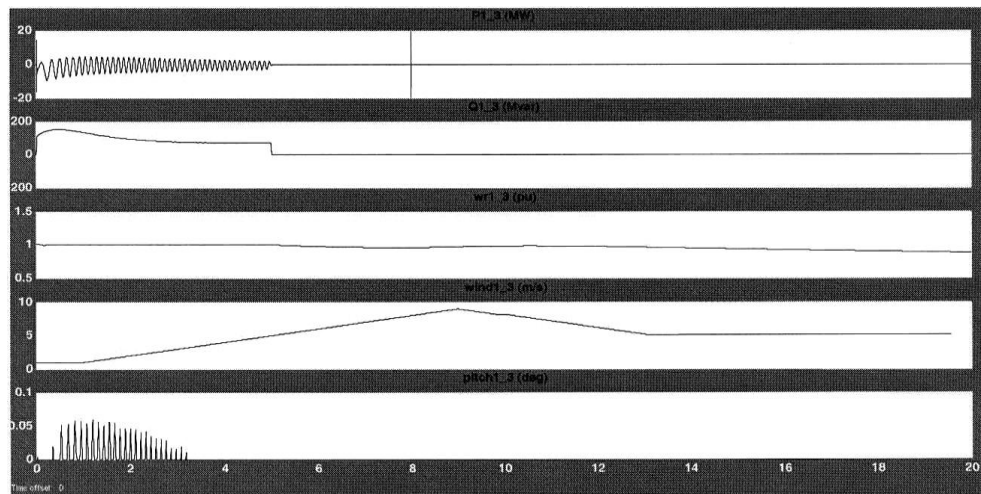


Figure 28. Simulation Result of Wind Turbine with UPFC at 60m Height.

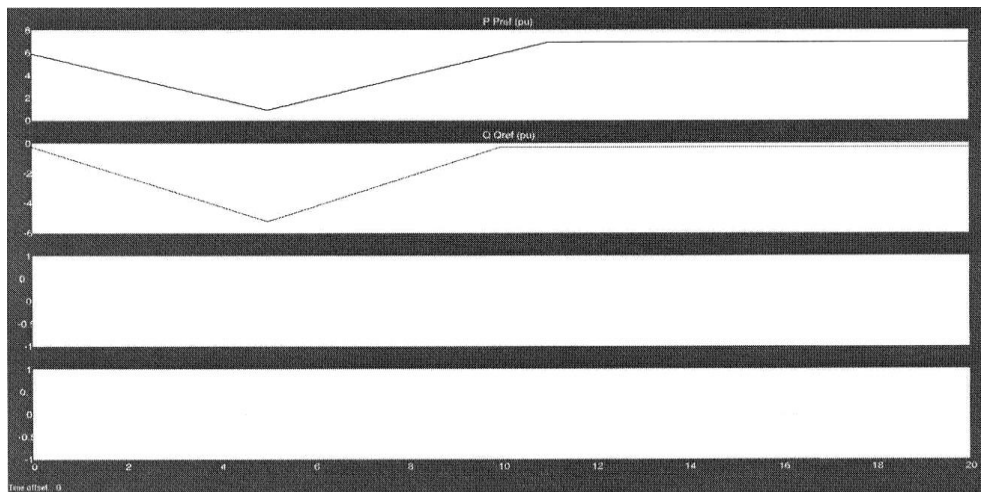


Figure 29. Simulation Result of UPFC.

The UPFC is versatile and multifunction power flow controller with capabilities of terminal voltage regulation, series line compensation and phase angle regulation. Besides the above mentioned functions, UPFC has additional features making it very popular among the available FACTS devices. But cost of FACTS devices varies proportionally with size, as size of UPFC is large in comparison to others. So it is expensive to use.

8. Discussion

The use of STATCOM is to control the voltage by exchanging reactive power with the grid, but their capability to exchange active power is very limited due to the small energy that can be stored in a conventional DC capacitor attached with it. A STATCOM can give additional benefits, such as increased capability to damp electro-mechanical oscillations increased power quality and reliability of supply. The results have shown that

the STATCOM device has the ability to significantly reduce the power fluctuations generated by a wind farm comprising induction generators, and the voltage profile has been improved, while also keeping the voltage at the PCC in limit. In addition, the Wind Farm's fault ride through capability can be greatly improved by the STATCOM. This would allow a comparison between a wind farm using fixed speed induction generators combined with a STATCOM, and wind farms using DFIGs which inherently generate fewer flickers due to the smoothing effect of the rotor with variable speed.

9. Conclusion

The basic operation of IG and FACTS controller has been discussed. A Wind Farm test case is simulated with integration of different FACTS controller namely SVC, STATCOM and UPFC at different wind altitudes.

It has been observed that Using SVC in wind power plant doesn't affect too much. The voltage and the reactive profile almost remains the same. So it is not recommended to use svc for voltage and reactive power regulation in wind power plant. The use of STATCOM is to control the voltage by exchanging reactive power with the grid. The results have shown that the STATCOM device has the ability to significantly reduce the power fluctuations generated by a wind farm comprising induction generators, and the voltage profile has been improved, while also keeping the voltage at the PCC in limit. The Unified Power Flow Controller (UPFC) is a second generation FACTS device, which enables independent control of active and reactive power besides improving reliability and quality of the supply. The UPFC is versatile and multifunction power flow controller with capabilities of terminal voltage regulation, series line compensation and phase angle regulation. But cost of FACTs devices varies proportionally with size, as size of UPFC is large in comparison to others. So use of STATCOM is recommended.

9. References

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