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*Research Article*

# THE EFFECT OF STATCOM CONTROLLER FOR IMPROVING DYNAMIC PERFORMANCE OF WIND FARM IN POWER SYSTEM

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**ABSTRACT.** In this paper the effect of static synchronous compensator **(**STATCOM) for improving dynamic performance of wind farm in power system is presented. The effectiveness of the STATCOM is validated through simulation results obtained on three pairs of 1.5 MW wind-turbines system model built in Matlab Simulink. The pitch angle control was applied to all wind turbines. The simulation results are validated with time domain simulations using Simulink MATLAB. The results show the capability of STATCOM controller for dynamic performance improvement under various disturbances. Output power, reactive power and voltage presented under different cause and discussions are mentioned therein.

**Keywords:** *dynamic performance, FACTS devices, STATCOM, wind farm*

## INTRODUCTION

One of the most important new sources of energy is wind power. Wind energy itself is both renewable and sustainable. The wind farm has a positive influence on power system stability. The power converter in a wind farm can be used as a local reactive power source. In recent years, use of the new sources of energy are incr- eased. The supply of electricity to remote locations is important in developing countries [1, 2]. The use of renewable energy in order to improve energy efficiency is essential. Wind energy is a kind of stochastic energy. Wind power generation has shown rapid developed during the past few years [3, 4]. Wind power plant output and the total load vary continuously during day. Wind energy is one of the most environmentally friendly energy sources available today. Electricity generated by wind turbines provide a secure and sustainable energy supply [5, 6]. Wind power involves conversion energy from the wind into other types of useful energy [7, 8].

The planning and operation condition of electrical power systems are changing due to a variety of causes [9]. A model of the power system can be structured as several interconnected subsystems, their associated control and their functional relationships as shown in Fig. 1.

Flexible ac transmission system (FACTS) controller and power system stabilizer (PSS) can help in raising dynamic stability limit and provide better power flow control [10, 11]. Generally, from control of view, FACTS controllers can be divided into four major groups as shown in Fig. 2 [12]. Shunt FACTS controller are classified to static VAR compensator (SVC) and STATCOM. They are used at any location without any coordination with other voltage control devices and without any reciprocal coordination.

The STATCOM performs the same function as the SVC. A comparative study between SVC and STATCOM is given in the Table I.

The performance of an electrical power system with wind energy penetration could be improved with the installation of FACTS controllers. FACTS devices can be used to regulate the real and reactive power output and improve power quality of the wind energy conversion system (WECS) [13].

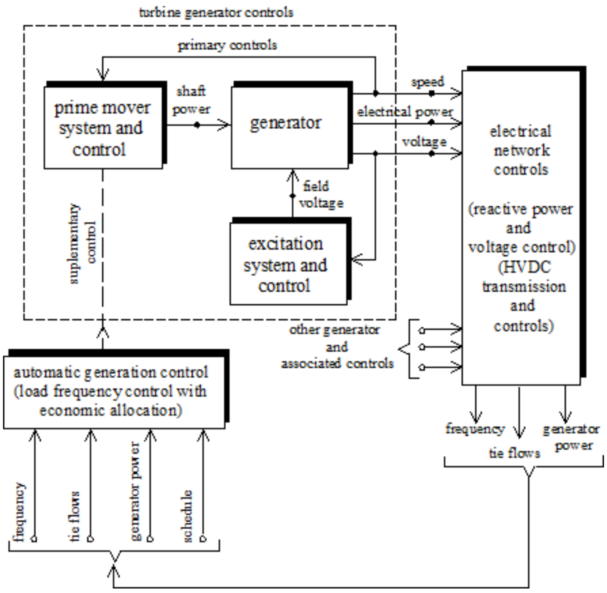


***Fig. 1.*** *Power plant and network primary and supplementary power system controls*

Several recent research in technical literature can be found on the application of FACTS devices for improving dynamic performance of wind farm in the overall power system [14, 15]. The stability improvement and power-flow control results of a doubly fed inductor generator (DFIG) based offshore wind farm connected to a one-machine infinite-bus system using a static synchronous series compensator (SSSC) is presented in [16], which an oscillation damping controller is designed by using modal control theory. The impact of frequency sensitive loads on system frequency when wind farm is integrated with the conventional power system by using small-signal linearized model of variable speed wind turbine generator is presented in [17].

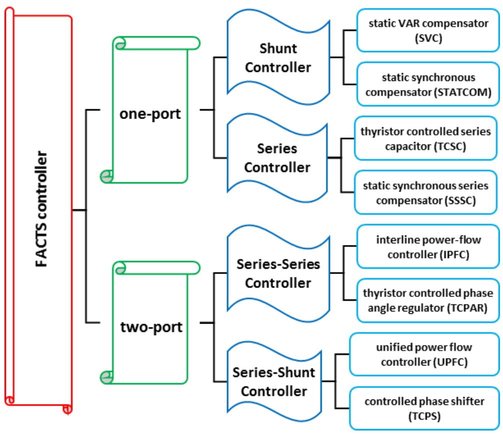


***Fig. 2.*** *Classification of FACTS devices*

***Table 1.*** *Comparison of STACOM and SVC*

| **Components** | **STATCOM** | **SVC** |
|---|---|---|
| Performance and actions | Voltage source behind a reactance | Variable susceptance |
| Transmission system harmonics | Insensitive | Sensitive |
| Dynamic range | Large | Smaller |
| Generates harmonics | Fewer | More |
| Devices principle | Reactive source | Varying reactance |
| Regions of operation | Both inductive and capacitive | Mostly in capacitive |
| Operating in very weak ac network | Maintain a stable voltage | Difficulty in operating |
| During transient | Faster response | Slow response |
| Basic control | Bus voltage | Bus voltage |
| Maximum capacitive power generated | Linearly with voltage | Proportional with voltage square |
| Reactive power capability | Leading/lagging | Leading/lagging indirect |
| Losses | Very good but increase with switching frequency | Good but increase in lagging (or leading) mode |

A method to compensate the network voltage unbalance at the point of common coupling using the DFIG wind turbine is proposed in [18], which a dynamic voltage restorer based on a voltage-source converter is connected in series between the generator and the grid. A systematic procedure to design a decentralized wide area damping controller for the wind farms and FACTS controllers in a smart grid considering uncertainties in the load parameters is presented in [19], which the input signals are wide area signals obtained from the phasor measurement units and the output signals are fed to wind farm generators and the FACTS controllers.

There are a number of researches about application of STATCOM in power system with wind farm [20]. An interface neuro-controller base on the heuristic dynamic programming method and radial basis function neural networks for the coordinated reactive power control between a large wind farm equipped with DFIG and a STATCOM for improves power oscillation damping of the system after grid faults is proposed in [21]. The use of parallel FACTS controller such as STATCOM for providing reactive power for DFIG under normal working circumstances and transient state have been proposed in [22], which the proposed control method has been simulated for IEEE 9-bus test grid and the achievability to the desired targets in STATCOM efficiency for its reactive power has been investigated. A voltage control method based on one-cycle control principles for hexagram-converter-based STATCOM is proposed in [23] and proven by a wind farm power system simulation showing the improvement of voltage variations caused by wind speed changes. A STATCOM with a voltage controller to mitigate the potential of sub synchronous resonance in a series compensated induction-generator based wind farm is proposed in [24], which it is shown that a three-phase fault close to the wind farm may cause severe oscillations in the voltage, electromagnetic torque, and shaft torque of the wind turbine generator. The change of the voltage and power of load bus were examined by FACTS devices of DFIG based wind farm in grid-connected is show in [25]. The simulation results of using a STATCOM to achieve damping improvement of an offshore wind farm fed to a multi-machine system is presented in [26], which a controller of the proposed STATCOM is designed to contribute adequate damping characteristics to the dominant modes. A method to enhance the stability of a grid-connected wind farm composed of a fixed-speed wind turbine generator system using a combination of a STATCOM and small

series dynamic braking resistor is presented in [27]. A modified fruit fly optimization algorithm combined with a probabilistic approach to coordinate and optimize the parameters of PSS and SVC damping controller for improving the probabilistic small-signal stability of power systems is proposed in [28]. The optimal rating and location of STATCOM for enhancing transient voltage stability of a real distribution network with fixed and variable speed wind turbines is proposed in [29], which loads play significant role in voltage stability analysis. A multi-objective predictive control technique for the stability improvement of a power system in the presence of wind farms using STATCOM is presented in [30].

The reactive power compensation is required to maintain level of the normal voltage in the power system. Reactive power imbalances can be minimized by reactive power compensation devices. A STATCOM provide continuously variable reactive power at its point of connection with the power system. The effect of STATCOM for improving dynamic performance of wind farm in power system is presented in this paper. The complete digital simulation is performed in the Matlab Simulink environment. Effect of parameter variations is represented in graphical form. This paper is organized as follows. The wind turbine model and STATCOM controller model are explained in sections 2 and 3, respectively. The system under study and its implementation into Matlab Simulink is discussed in sections 4. Further, the simulation results and analysis is established in section 5 and section 6 provides important conclusions.

In the text, references should be cited in by number as [1]. If you need more than one citation, you should place the references as [2, 3, 4]. If you need to cite without parenthesis, use this example: As previously reported by Alexandrova et al. [5].

## WIND TURBINE MODEL

Wind power is a rapidly growing technology among renewable energy resources. The use of wind turbine to generate electricity from renewable resources is growing in the industrial activities development. Wind turbines have a relatively small land footprint. There are several different topology options for wind turbines, each with its particular advantages and disadvantages. The wind turbines can be divided into fixed speed and variable speed as shown in Fig. 3 [31, 32]. The comparison of fixed and variable speed-based WECS are show in Table 2. The most common type of wind turbine is the fixed-speed wind turbine with the induction generator directly connected to the grid [33].

***Table 2.*** *Comparison of different wind turbine*

| WECS | Advantage | Disadvantage |
|---|---|---|
| Fixed speed wind turbine | Simple strcutre Low cost<br>Low maintenance | High mechanical stress Relaively low energy conversions<br>High power fluctuations to the grid |

| | | |
|---|---|---|
| Variable speed wind turbine | Simple pitch control Improved power quality Reduced acoustic noise Maximized captured power<br>Reduced mechanical stress Increasing the annual energy output significantly Provided dynamic compensation for torque and power pulsation | High cost Complex control system The power rating of the generator should be five times greater than that of the optimal version of the constant speed case. |

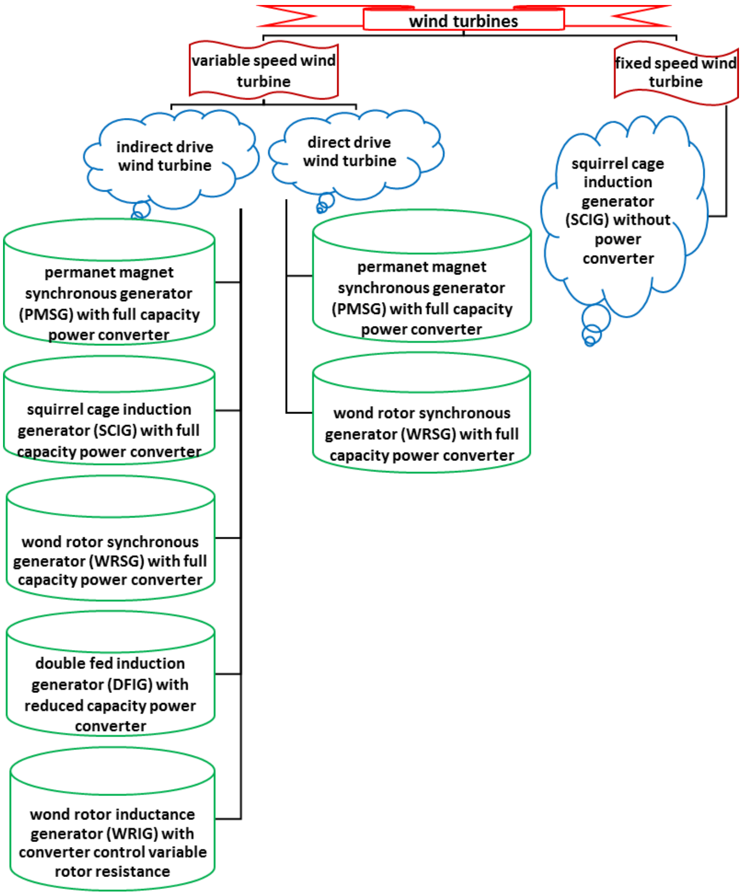


***Fig. 3.*** *Classification of generator for wind energy system application*

In this study wind turbines uses squirrel-cage induction generators. The stator winding of squirrel cage induction generator is connected directly to the grid and the rotor is driven by a variable pitch wind turbine.

A wind turbine is characterized by the curves of the dimensionless power coefficient (CP) which is a nonlinear function of both tip speed ratio (□) and blade pitch angle (□) [34, 35]. Power coefficient known as performance coefficient calculates the fraction of power a wind turbine can extract from the wind. Fig. 4 shows the graph of the power coefficient versus pitch angle and tip speed [36]. Also, it shows the typical power curve of a variable-speed variable-pitch wind generation system. It can be observed that there are four different operational regions ,that apply both to constant speed and variable speed turbines: the low speed region, the mode rate speed region (bounded by the cut-in speed at which the turbine starts working, and the rated speed, at which the turbine produces its rated power), maximum power tracking region, and the high speed region. When wind speed is lower than rated wind speed, □=0. When wind speed is upper than rated speed, the pitch-angle control system activates and □ increases accordingly [37, 38].

A wind farm can utilize the wind resources from a certain area efficiently. In a real electrical power system, a large wind farm generally consists of hundreds of individual wind turbines. Wind farms want to sell into the power system whenever wind power production is possible. The reactive power production in the wind farm has an impact on the voltage, that it is dependent on the local load and on the feeding grid im- pedance. The total power output of the wind farm is obtained by summing up the power from individual wind turbines [39, 40].

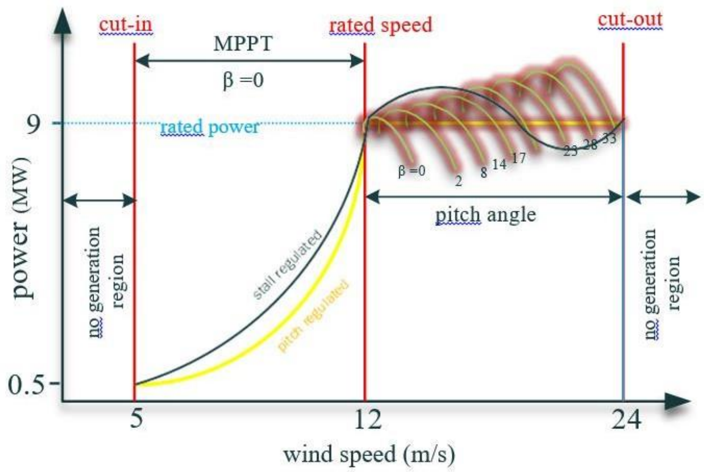


***Fig. 4.*** *Ideal power curve of a wind turbine operation zone*

## STATIC SYNCHRONOUS COMPENSATOR

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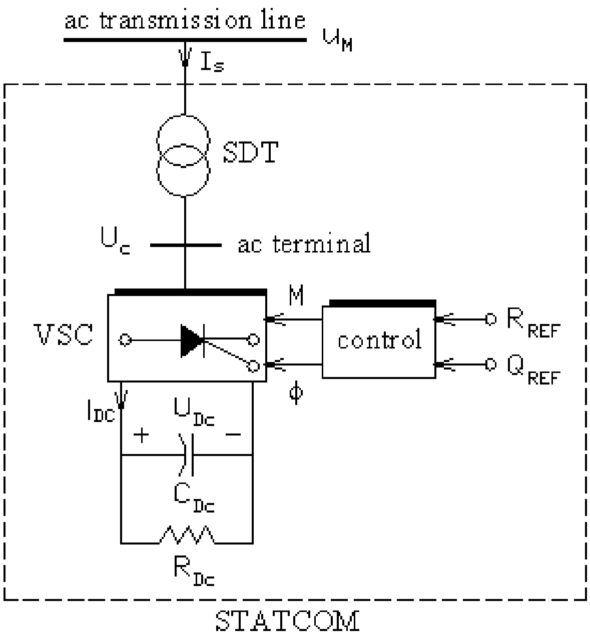
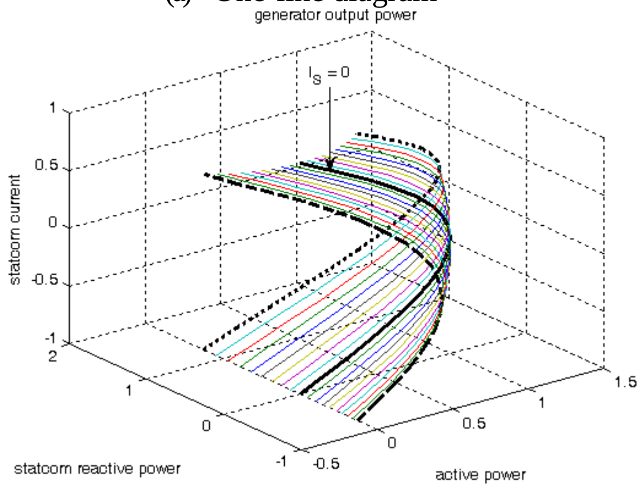
When shunt FACTS devices are connected to a long line, the power transfer capability will be increased. A STATCOM is capable of injecting independently controllable reactive power into the system. It provides continuously variable reactive power at its connection point with the grid [41, 42]. The STATCOM can be set to operate at constant voltage or at constant reactive power. In general, a STATCOM system can be div- ided into three key parts: the converter power stage, the passive components and the control system [43, 44]. The configuration of a STATCOM connected to bus M of a transmission line is shown in Fig. (5-a). The reference signal QREF and PREF can control the amplitude and phase angle of output voltage, respectively. The STATCOM consists a dc capacitor that keeps dc voltage constant, a three-phase voltage source converter (VSC) that generates the sinusoidal ac voltage with minimal harmonic distortion and a step-down transformer (SDT) with a leakage reactance XSDT. The dc capacitor (CDC) has function of establishing an energy balance between the input and output during the dynamic change of the VAR output. The DC bus voltage will always be kept constant. A typical variation of reactive power supplied by the STATCOM (when it operates at full inductive and capacitive ratings) is shown in Fig. (6-b). In practice, the STATCOM can operate anywhere between the two curves. The block diagram of control system for a STATCOM is show in Fig. 6 [45]. The output of the phase-locked loop is used to compute the d and q components of the ac three-phase voltage and currents. The d and q components of ac positive-sequence voltage and currents are measuring by mea- surement systems. The control system consists two loops: outer voltage regulation loop and inner current regulation loop. The voltage regulator outputs are Iqref and Idref which are the reference currents in the dq coordinates for the current regulator.




(a) One-line diagram




(b) Current effect on output power

***Fig. 5.*** *Structure and current of STATCOM*

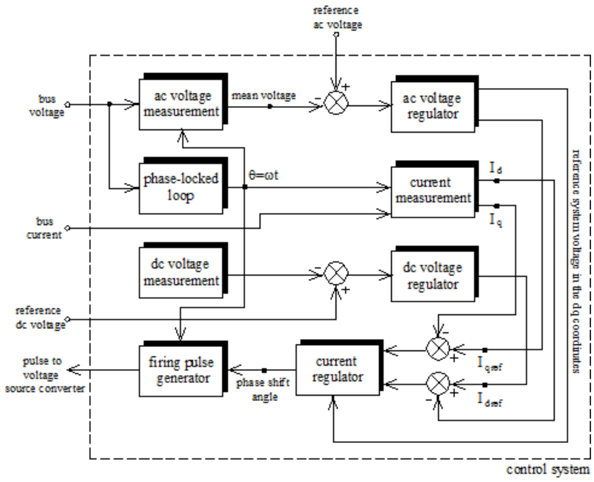



***Fig. 6.*** *Control system block diagram for STATCOM*

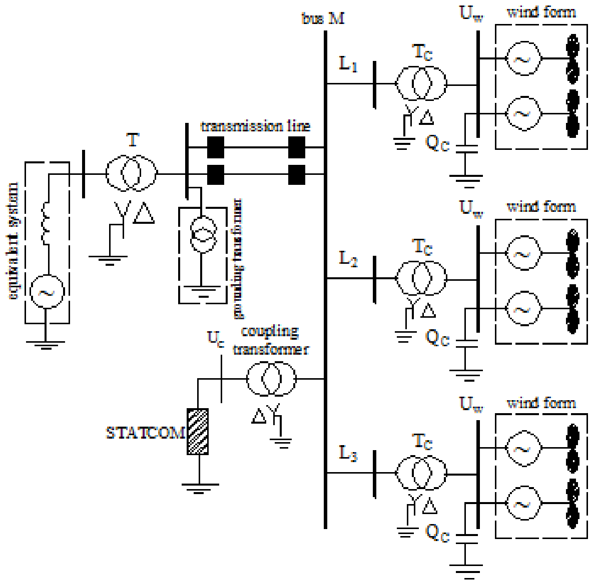
## SYSTEM UNDER STUDY

Fig. 7 shows the single-line diagram and Simulink model of power system used for the simulation and analysis. The model system consists of one the synchronous generator (2500 MVA) and a wind farm (9 MW). Three pairs of 1.5 MW wind turbines simulate the wind farm. Wind farm is connected to a 25 KV (bus M) distribution system through an individual transformer (TC) and a common transmission line (L1,L2,L3).

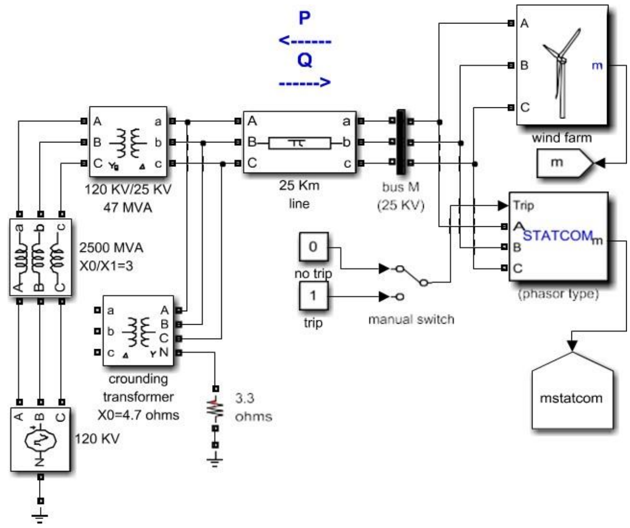
Each wind turbine is equipped with protection system monitoring voltage, current and machine speed. At the point connection of the wind turbine in low voltage bus (bus W), a capacitor banks (QC) has been used for compensated reactive power absorbed by the induction generators. A STATCOM can be placed at the point of common coupling (PCC) between the wind farm and the power network via a coupling transformer (0.4KV/30KV). By applying a STATCOM system at the PCC, the wind farm is able to control the amount of reactive power automatically. The wind farm model built in Matlab Simulink is shown in Fig. 8. The values and ratings of system components are presented in the Table 3.

***Table 3.*** *System parameters*

| Component | Parameters | Value |
|---|---|---|
| Transmission line (L) | Resistance | 0.1153 Ω/Km |
| | Inductance | $1.05\times10^{-3}$ H/Km |
| | Capacitance | $11.33\times10^{-9}$ F/Km |
| | Length | 25 Km |
| STATCOM | Converter rating | 3 MVAR |
| | Converter impedance | 0.0073+j82.93 (pu) |
| | DC link capacitance | $375\times10^{-4}$ F |
| | Droop setting | 3% |
| | DC link nominal voltage | 4 KV |
| Wind turbine | Nominal wind speed | 9 m/s |
| | Capacitor bank (QC) | 400 KVAR |
| | Low voltage bus (UW) | 575 |
| Transformers | TG | 47 MVA, 120KV/25KV |
| | TC | 4 MVA, 25KV/575V |




(a) Single-line diagram




(b) Simulink model

***Fig. 7.*** *Model of power system under study*

## SIMULATION RESULTS AND ANALYSIS

To evaluate improve dynamic performance of wind farm in power system by using a STATCOM which is connected to a weak grid, the digital simulations have been performed in Matlab Simulink toolbox. Initially, the pitch angle of the turbine blades is $0^o$. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding rated speed. The maximum pitch angle and the maximum rate of changes of pitch angle are $45^o$ and $2^o$/s, respectively. The simulation results of system are observed during 25 s. The system base power is 100 MVA. The power system is studied to evaluate the system perfor- mance under different transient conditions, such as a wind speed change, three phase fault, fault location effect and temporary tripping of a wind turbine in a wind farm. The base wind speed is 9 m/s.

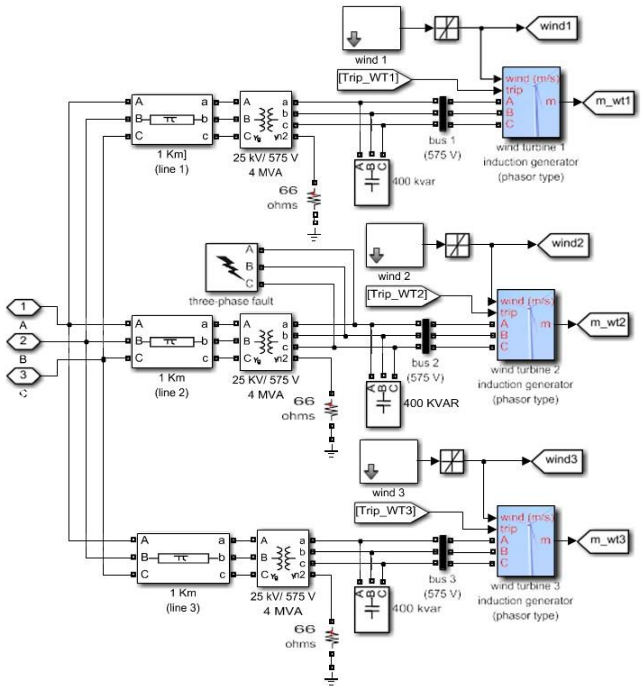


***Fig. 8.*** *Simulink model of wind farm*

### *Wind Speed Change*

Initially, wind speed is set at 8 m/s, then starts at t=2 s for wind turbine 1, wind speed is rammed to 12 m/s in 4 s. The same gust of wind is applied to turbine 2 and turbine 3, respectively with 3 s and 6 s delays. The wind speed of wind turbines 2 and 3 are rammed to 11 m/s in 2 second and rammed to 10 m/s in 2 second, respectively. Fig. 9 shows the change in wind speed of turbines. The change in turbines pitch angle for with and without STATCOM is shown in Fig. 10.

Fig. 11 shows the variation of the generated active power and absorbed reactive power for wind farm without controller. As it is seen, the absorbed reactive power increases as the generated active power increases. Wind turbine 2 is tripped at t=16.3 s, but turbines 1 and 3 continue to generate 3 MW each one. After that, the pitch angle in turbine 2 at t=20.2 s reaches to zero.

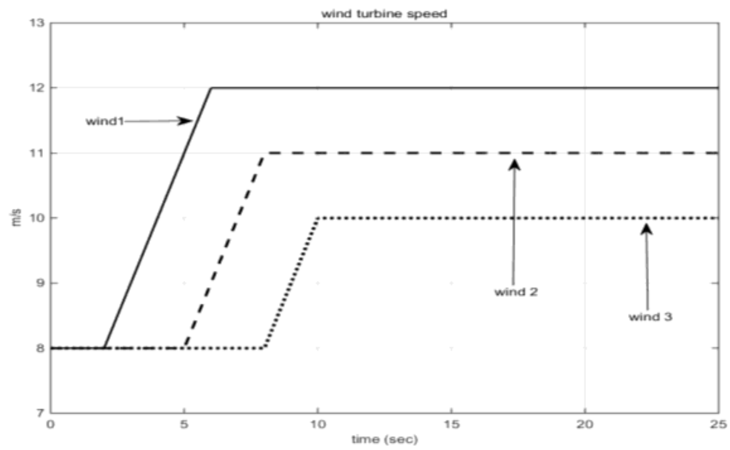
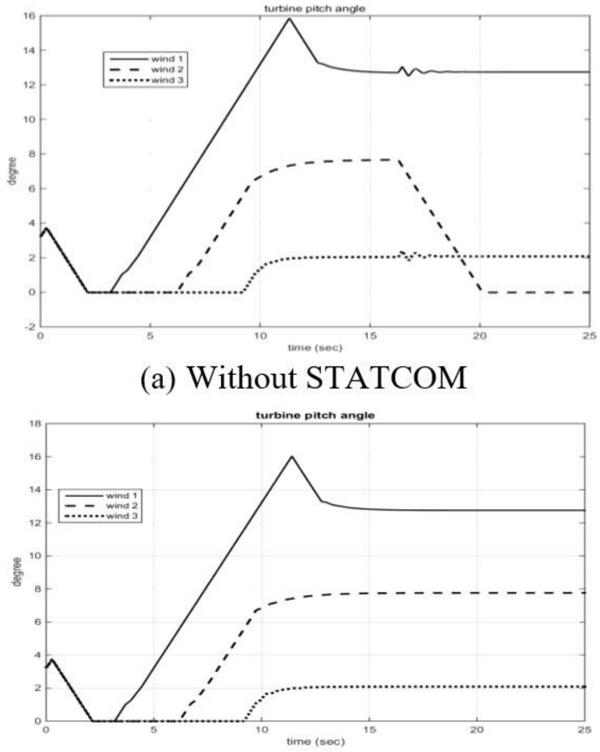


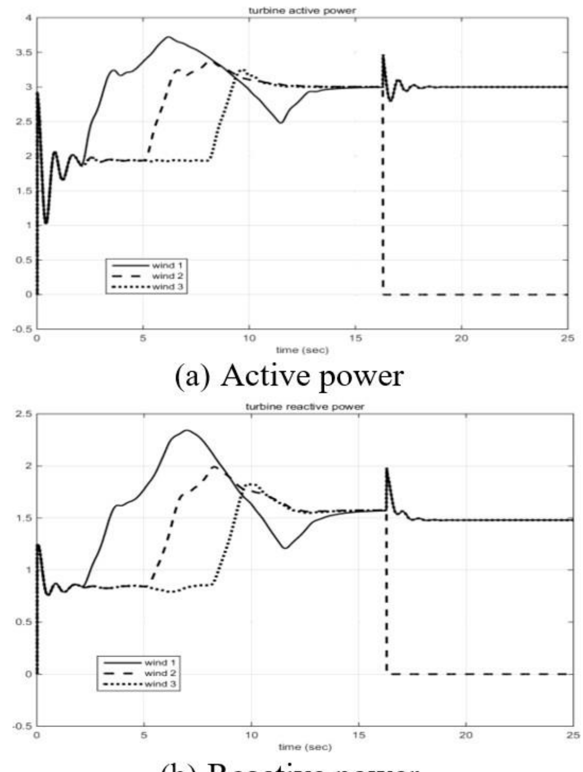

***Fig. 9.*** *Change in wind speed in turbines*




(a) Without STATCOM

(b) With STATCOM

***Fig. 10.*** *Change in pitch angle for turbines without STATCOM*

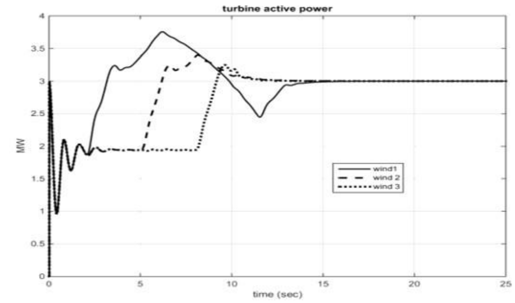



(a) Active power

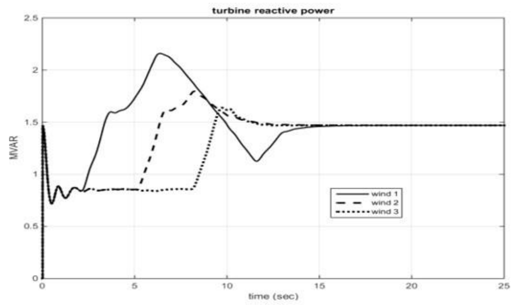
(b) Reactive power

***Fig. 11.*** *Turbine power without STATCOM*

Fig. 12 shows the variation of the generated active power and absorbed reactive power for wind farm with controller. For each pair of turbines the generated active power starts increasing smoothly to reach its rated value of 3 MW in approximately 15 s. At nominal power, each pair of wind turbine absorbs 1.47 MV-AR. When the output power exceed 3 MW, the pitch angle is increased from 0º to 12.5º, 8º and 2º for wind turbines 1, 2 and 3, respectively, in order to bring output power back to its nominal value.




(a) Active power




(b) Reactive power

***Fig. 12.*** *Turbine power with STATCOM*

Figs. 13 and 14 shows the voltage magnitude, active power and reactive power in bus M (25 KV) with the presence of the STATCOM controller. The required reactive power supplied by the STATCOM is shown in Fig. 15. The drop in the bus voltage determines the amount of reactive power necessary. For steady wind speed, the total exported power measured at the bus M (25 KV) is 9 MW and the STATCOM maintains voltage at 0.984 pu by generating 1.62 MVAR. In power system without controller, the voltage at bus M is dropped to 0.978 pu. The STATCOM improves the voltage characteristic system during and after the speed change.

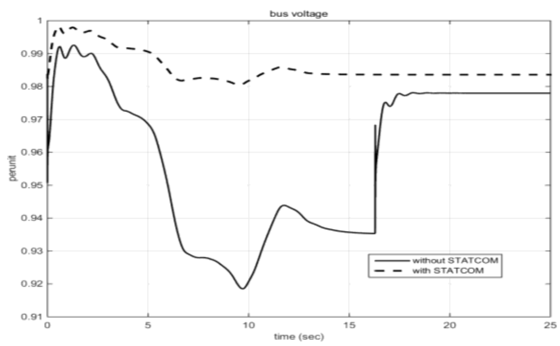
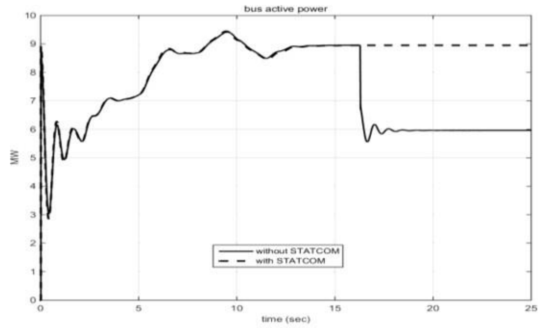
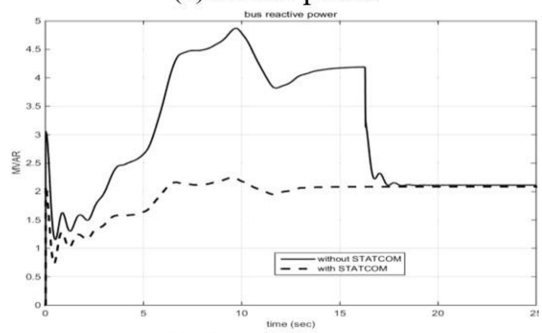



***Fig. 13.*** *Simulation results in bus M (25 KV) for change in wind speed*




(a) Active power




(b) Reactive power

***Fig. 14.*** *Simulation results in bus M (25 KV) for change in wind speed*

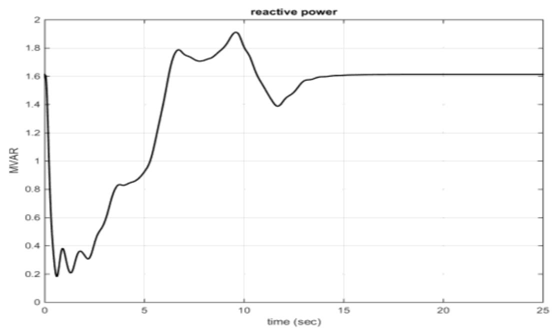


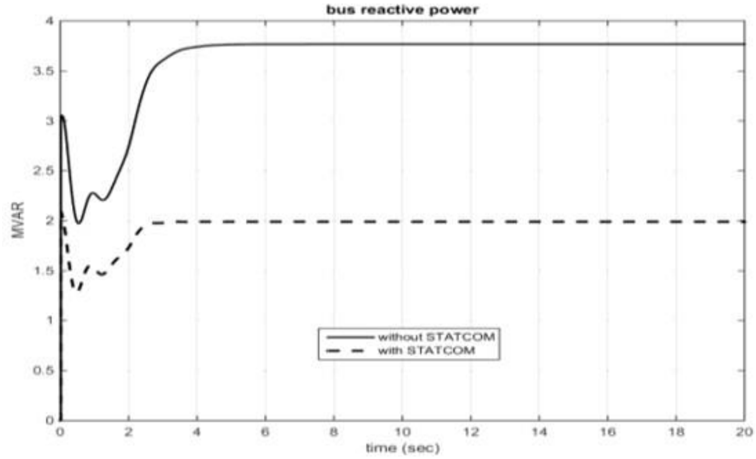

***Fig. 15.*** *Generated reactive power by STATCOM*

***Fault Condition***

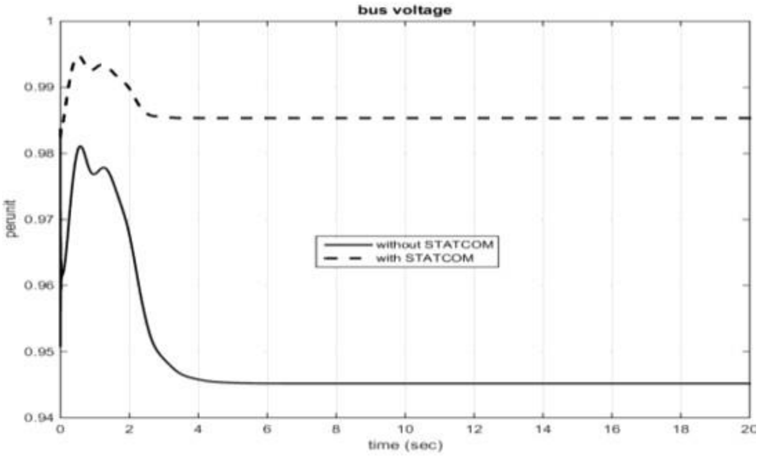
This section investigated the performance of wind farm behavior during a double line to ground fault presence of within STATCOM controller. During fault period, the wind turbines operate at nominal values and not change. To study the effect fault condition, the simulation is performed when the fault occurs at second wind turbine terminals.

Fig. 16 shows the voltage magnitude and reactive power in bus M (25 KV) at nominal wind speed (9 m/s) with and without STATCOM controller. The voltage, active power and reactive power at low voltage bus (bus M) before any fault are shown in Table 4. The voltage and reactive power at bus STATCOM with controller are 0.9853 pu and 1.445 MVAR, respectively. At t=15 s, a fault is applied at second wind turbine terminals, causing the turbine to trip at t=16 s.

Fig. 17 shown the voltage magnitude and reactive power in bus M (25 KV) for a phase to phase fault with the presence of the STATCOM controller.




(a) Reactive power




(b) Bus voltage

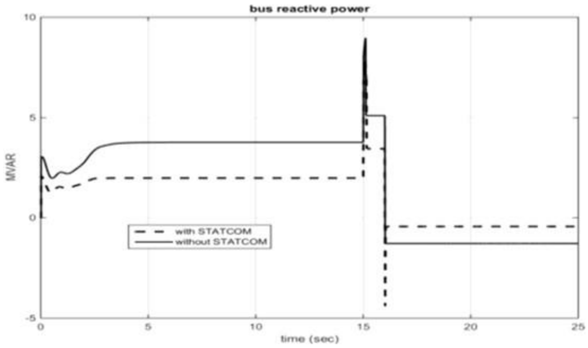
***Fig. 16.*** *Simulation results in bus M (25 KV) at nominal wind speed before fault*

***Table 4.*** *Voltage and power in low voltage bus at turbines nominal speed*

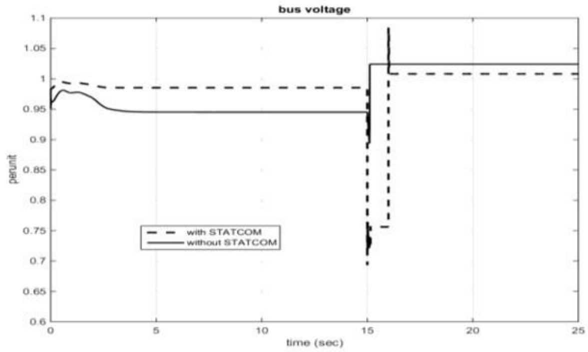
| Controller | Voltage (pu) | Active power (MW) | Reactive power (MVAR) |
|---|---|---|---|
| Without controller | 0.9452 | 8.649 | 3.768 |
| With controller | 09853 | 8.665 | 1.988 |

Finally and after clearing the fault, the reactive power value for the system without and with controller is - 1.28 and -0.43 MVAR, respectively.

Fig. 18 shows the voltage magnitude and reactive power in bus M (25 KV) for a single phase to ground fault with the presence of the STATCOM controller.

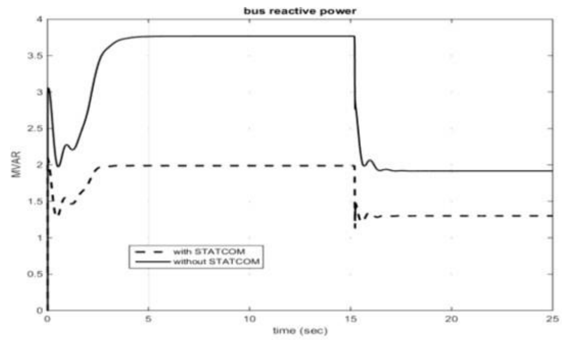



(a) Reactive power

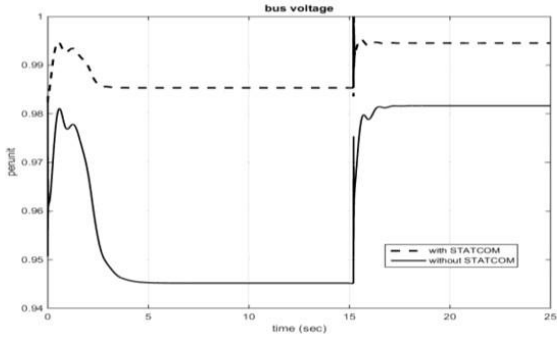



(b) Bus voltage

***Fig. 17.*** *Simulation results in bus M (25 KV) for a phase to phase fault*




(a) Reactive power

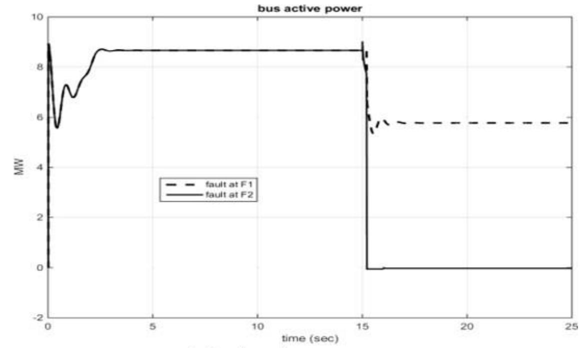



(b) Bus voltage

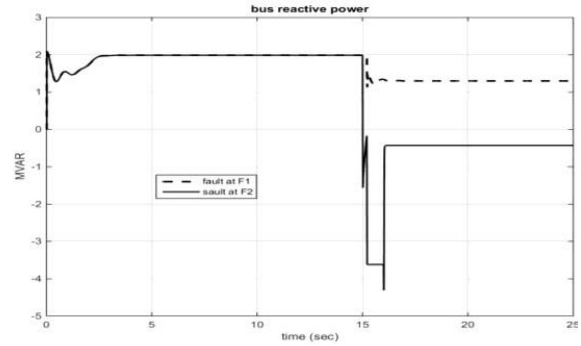
***Fig. 18.*** *Simulation results in bus M (25 KV) for a single phase to ground fault*

### *Fault Location Effect*

During a grid fault, the voltage sags at the PCC can cause a high current in the rotor circuit and the converter. In this section, the operation of the wind farm for different fault locations are studied. Fig. 19 shows the simulation results when a single phase to ground fault occurs at F1 (terminal turbine 2) and F2 (bus M). Fig. 20 shows the simulation results when a two phase to ground fault occurs at F1 (terminal turbine 2) and F2 (bus M) and F3 (bus N).

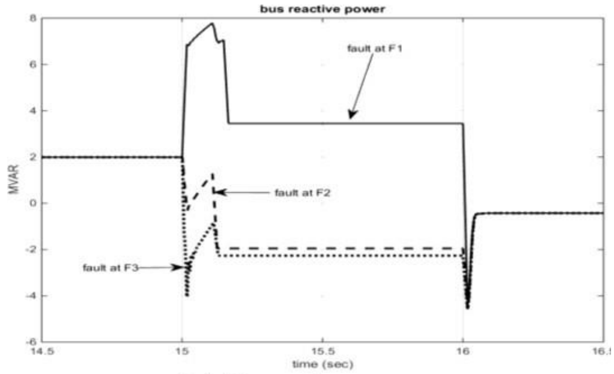



(a) Active power

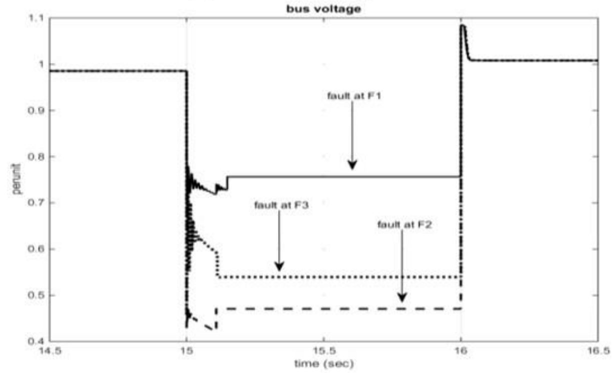



(b) Reactive power

***Fig. 19.*** *Simulation results at different fault locations*




(a) Reactive power




(b) Bus voltage

***Fig. 20.*** *Ractive power and bus voltage at different fault locations*

## CONCLUSION

Wind is a highly variable resource energy. A wind farm contains a group of wind turbines in the same location used to produce electricity. The dynamic performance of a power system with wind farms could be improved with the installation of FACTS controllers. A Matlab Simulink model of a wind farm in power system for analyzing the effect of STATCOM in dynamic performance is developed in this paper. A wind farm with 6 wind turbines was used to simulation and verify the effect of STACOM on dynamic performance of wind turbine. The power and voltage of the wind turbine farm are monitored in different conditions.

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