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Modeling and Stability Control of Wind Turbines Equipped with Synchronous Generator Using Static Synchronous Compensator

Reza Elmamouz [1], Saeed Barghandan [2], Mohsen Ebadpour [3]
Department of Electrical Engineering. Ahar Branch, Islamic Azad University, Ahar, Iran
Email: saeed_barghandan@yahoo.com [2] (Corresponding author)
Email: reza_almamooz@yahoo.com [1], m-ebadpour@iau-ahar.ac.ir [3]

Abstract

Nowadays, among the renewable energy resources, wind energy is more economically viable than other new sources. To achieve the maximum power at different wind speeds, the turbine speed must be variable over a wide range. Electricity generation from wind is performed by different models of wind turbines with different generators. Due to the capabilities and advantages such as relatively high power density, low noise, high efficiency, high reliability and low maintenance costs, wind turbines equipped with permanent magnet synchronous generator (PMSG) are in increasing use. This paper presents a method for modeling and controlling the stability of PMSG-equipped power systems using static synchronous compensator (STATCOM). STATCOM is a static synchronous generator that is installed in parallel with the power grid and is used as a reactive power compensator which plays an effective role in voltage stability. The main goal of this study is to develop a reliable control strategy for wind farms and STATCOM to investigate the effect of reactive power losses under constant and sub-fault conditions. Furthermore, to increase the attenuation of the synchronous generator of single-machine system with infinite bus, STATCOM with PID controller is connected to the studied system to rise the dynamic stability of the PMSG based wind turbine.

Keywords: Wind energy, permanent magnetic synchronous generator (PMSG), static synchronous compensator (STATCOM), reactive power, voltage stability.

1. Introduction

Concerns about the increasing effects of greenhouse gases from fossil fuel power plants make renewable energy sources, such as wind, a viable alternative to the world's electricity generation. Electricity generation from wind is performed by different models of wind turbines with different generators, such as wind turbines with permanent magnet synchronous generator (PMSG) [1]. In offshore wind turbines equipped with PMSG, it is difficult to control and supply the reactive power required by all turbines at the same time, and it is also necessary to have the desired power factor for the system. When the amount of reactive power required by the wind farm is not provided, the lines between the plant and the grid are damaged. One possible solution to this problem is to use an external compensator such as STATCOM [2].

STATCOM is basically a static synchronous generator that is installed in parallel in the network and is used as a reactive power compensator. STACTOM acts both capacitively and inductively and plays an effective role in voltage stability. STATCOM is built with the help of a voltage source converter (VSC) and a capacitor to store energy and can generate or absorb reactive power instantaneously and without dependence on its bus voltage. By adding a feedback control system, in addition to reactive power, it can also be used to dampen system fluctuations and increase system stability [3].

There are different methods for generating electric power with constant frequency voltage from a wind power plant, which in a general view rely on induction, synchronous and permanent magnet generators. In [4], a coupled direct modular PMSG for variable speed wind turbine is presented. This method provides a capacitive connection that can reduce the power limits of PMSG due to internal reactance and provide multiple single-phase output to obtain a smooth DC link voltage. In [5], a dynamic model based on small signal stability of PMSG wind turbine with power converters and controllers is presented. In [6], a new connection method for two or more PMSG wind turbines in a wind farm is studied, the presented design having only one inverter with a DC link. In [7], the control method of a hybrid wind farm includes several wind turbines with induction generator and synchronous generator is presented to provide the reactive power required by induction generators when faults occur and also to reduce power fluctuations.

Recently, a simple method of coordinating DC link voltage and PMSG wind turbine pitch angle to smooth wind power fluctuations has been presented, but it is not approved due to the mechanical nature of the pitch angle control method [8]. Numerous STATCOM capabilities such as improving power system stability, and mitigating power system fluctuations have been demonstrated in [9]. In [10], a linear feedback is investigated for STATCOM output to control mechanical power and voltage in different operating modes. In [11], the controller design and system modeling for rapid regulation of load voltage and elimination of voltage flicker using STATCOM are discussed.

This study provides reliable modeling and control for a PMSG-based wind farm with reactive power compensation by STATCOM at constant and under fault conditions. Since voltage instability in wind turbines due to reactive power imbalance is obvious, the use of a STATCOM in wind farms can play a key role in improving power quality and system stability. In the second part, the synchronous generator is modeled as a wind energy generator. The principles of STATCOM operation are described in Part III. In the fourth part, modeling and simulation of the studied system with its governing equations are presented. Finally, conclusions are drawn from the presented study.

2. Synchronous Generator Model

In a synchronous generator, the rotor is responsible for receiving direct current I_f (excitation current) by the brushes. The I_f creates an excitation flux in the rotor, which includes three windings in the stator. The stator windings are spaced 120 degrees apart, creating a three-phase voltage waveforms. The equivalent circuit of one phase of a synchronous generator is shown in Fig. 1.

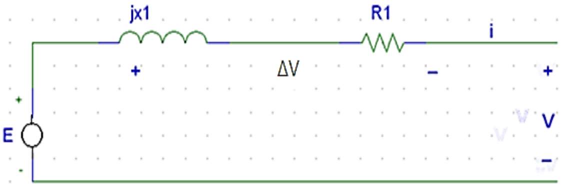


Fig. 1. The equivalent circuit of one phase of a synchronous generator.

The magnitude of the electromotive force of a synchronous generator is equal to

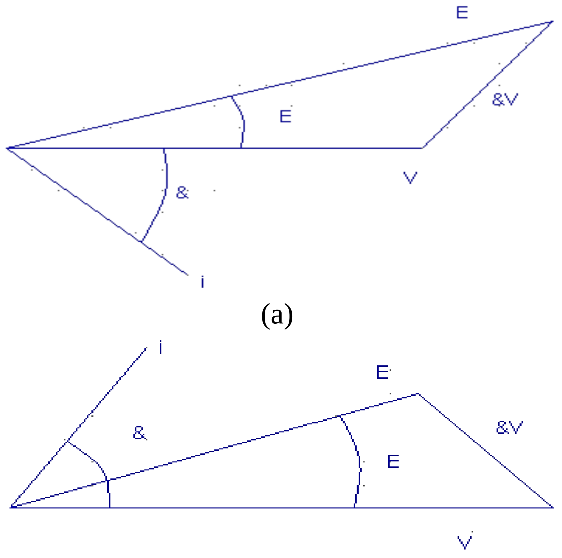
$$|E| = K_1 \omega \zeta \quad (1)$$

where $\omega = 2\pi f$ is the electrical angular frequency, ξ is the amount of flux at each pole and K_1 is a constant value that depends on the number of poles and the number of winding turns per coil. According to Fig. 1, the reactance X_1 is the synchronous reactance of the generator (X_s) in each phase. The reactance of the generator changes from steady state to transient state during operation. The resistance R_1 represents the resistance of the generator winding conductors (R_s), which is naturally less than X_s and is normally ignored except in efficiency calculations.

The synchronous frequency of the generator can be calculated from the following equation

$$f = \frac{P}{2} * \frac{n}{60} \quad (2)$$

where P is the number of generator poles and n is the rotor speed in terms of rpm.



(a)

(b)

Fig. 2. Phase diagram of one phase of a three-phase synchronous generator (a) super-excited (b) sub-excited.

The electromotive force of the machine (E) may differ from the terminal voltage (V) both in size and phase, while the output voltage and frequency must be constant when the generator is connected to the grid. This difference can be calculated as

$$\Delta V = E - V \frac{V}{phase} \quad (3)$$

This voltage difference will generate line current (I) with respect to the constant value of the machine. The relationship between I, E and V is shown in the phasor diagram of Fig. 2 [12].

Amplitude of E is proportional to the rotor flux ξ, which is also proportional to the current in the rotor. When the rotor current is relatively small, i.e. E is less than V, it is called the sub-excitation state. When E is greater than V, it is called the super-excitation state, where E is forward V by δ. The amount of θ and δ are as

$$\theta =< V - < I \quad (4)$$

$$\delta =< E - < V \quad (5)$$

The active and reactive powers that are generated in each phase can be expressed as follows.

$$P = \frac{|E||V|}{Xs} \sin\delta \frac{W}{phase} \quad (6)$$

$$Q = \frac{|E||V|\cos\delta - |V|^2}{Xs} \frac{Var}{phase} \quad (7)$$

Based on Equation (6), when the mechanical power increases, the electrical output power will increase up to $\delta = 90^o$. The maximum electrical power occurs at $sin \ \delta = 1$, which is called precipitation power. When the mechanical power increases further, the output power decreases, δ increases rapidly, and synchronism (stability) disappears. If a turbine is operated near nominal power in such a way that a strong wind increases the input power and this increase exceeds the precipice power, the nominal speed of the rotor will exceed its limit. In this case, in the generators, the protection factors of the generator are taken out of line. The rotor speed control system will also provide this safety, but the control system must be well designed.

Another characteristic of a synchronous generator is that the power will be negative when δ is negative. This means that the generator will act like a motor and will receive power from the grid and the turbine will act as a fan. Therefore, when the wind speed reaches an undesirable level, the generator should be disconnected from the grid to prevent the motor mode [13].

3. General Principles of STATCOM Operation

The electric circuit of STATCOM is illustrated in Fig. 3. Figure 3 shows that the transfer of active and reactive power takes place between the voltage V_1 and the voltage V_2. In this figure, V_1 represents the system voltage that must be controlled and the V_2 generated by the VSC.

In steady state operations, the voltage V_2 generated by a VSC is in phase with V_1 (i.e. $\delta = 0$). If amplitude of V_2 is less than V_1, reactive power Q flows from V_1 to the V_2 (STATCOM absorbs reactive power). If amplitude of the V_2 is greater than V_1, Q flows from the V_2 toward V_1 (STATCOM generates reactive power). The amount of exchanged reactive power is obtained as

$$Q = \frac{V_1(V_1 - V_2)}{X} \tag{8}$$

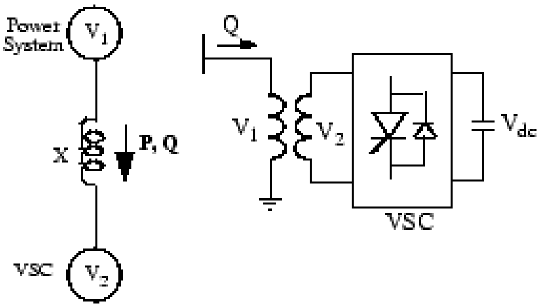


Fig. 3. STATCOM circuit and its operation.

In general, STATCOM consists of three main parts such as capacitors connected on the DC side, the transformer and the VSC. The capacitor on the DC side acts like a DC voltage source. In steady state conditions, the voltage V_2 should be slightly different from the voltage V_1 in order to compensate the both converter and transformer losses and keep the capacitor in charge.

Voltage source converters based on IGBT switches using width modulation (PWM) technique are used to generate a sine waveform from a DC voltage source with a frequency of about a few kHz. Harmonic voltages are eliminated by installing filters on the AC side of the voltage converter. In this type of converter, the voltage source uses a constant DC voltage V_{dc}. The voltage V_2 is changed by changing the modulation index of the PWM modulator.

STATCOM performance is similar to a PMSG, however, at low voltages over the normal voltage range, STATCOM can produce more reactive power than PMSG because the maximum reactive power produced by PMSG is proportional to the square of the system voltage (with fixed suspension), while the maximum reactive power generated by STATCOM decreases linearly with voltage (assuming constant current). This ability to generate more reactive power by STATCOM along with the line is an important advantage of STATCOM over PMSG that has been explored in the simulation. In addition, STATCOM has a faster response than PMSG because unlike PMSG, STATCOM has no delay due to thyristor fire, which is about 4 m/s for PMSG.

4. Modelling and Simulation Results

4.1. STATCOM modeling in a simple radial system

In the first part, a simple radial system according to Fig. 4 is examined. As depicted in Fig. 4, at the beginning of the line a generator is connected to the B_1 bus and this bus is connected to the B_2 bus by a 300km transmission line. The B_2 bus is connected to the B_3 bus by a 230/33kV transformer and the B_3 bus is connected to a variable load according to Table 1. The purpose is to set the B_2 bus voltage to a constant value, using STATCOM. In fact, STATCOM connects to the B_2 bus in parallel and keeps the voltage across the bus constant by changing the load to a constant value of 1p.u.

According to the load profile in Table 1, the B_2 bus voltage curves and reactive power changes in STATCOM are shown in Figs 5 and 6. As it can be seen from curves, at the moment of load change, i.e. times 1s, 2s, 3s and 4s, the amount of reactive power absorbed by STATCOM changes and the B_2 bus voltage passes through the transient conditions in the system and fixed at a constant value of 1p.u.

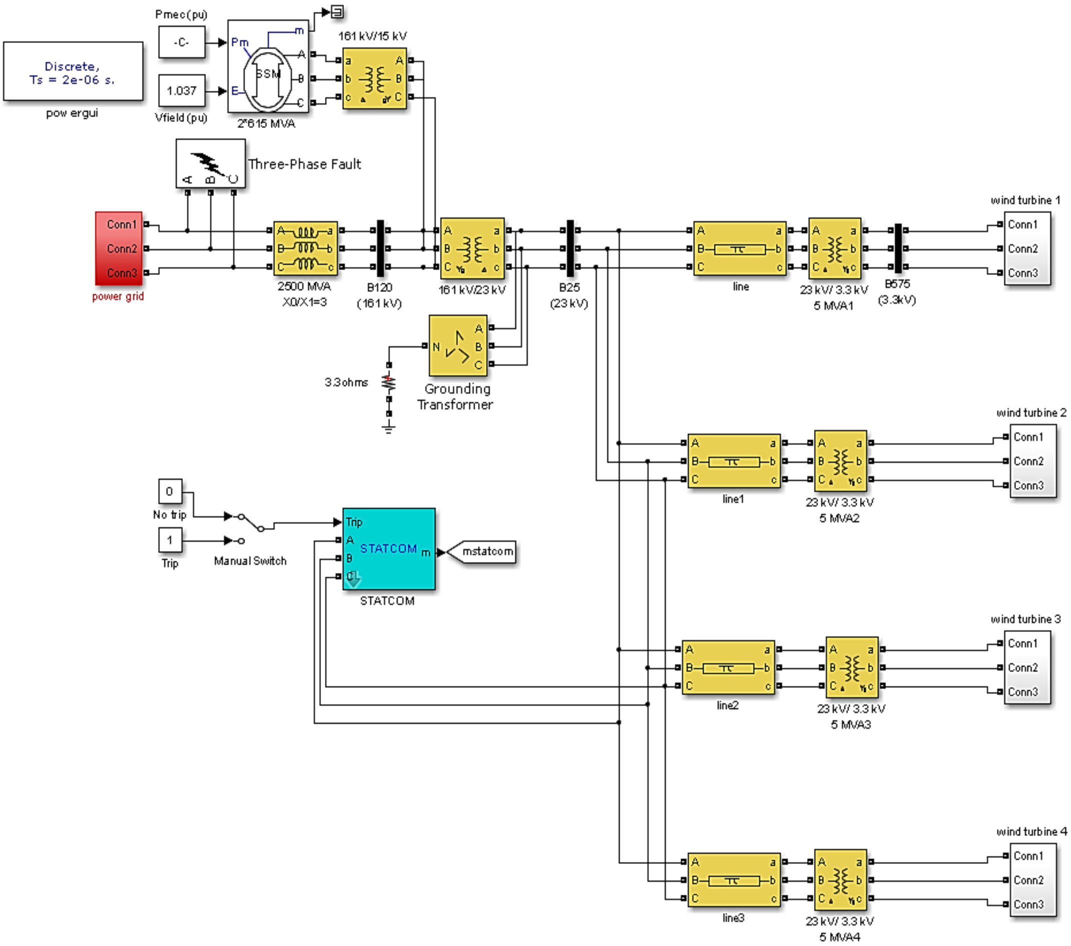


Fig. 4. modeling of STATCOM in a radial system.

Table 1.load profils in B_3 bus.

Time (s)	Power
1	5000MW
2	5000+5000j MVA
3	5000-5000j MVA
4	5000MW

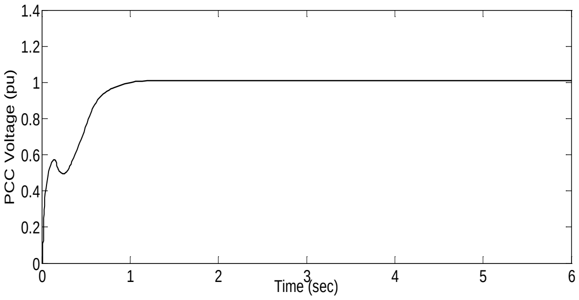


Fig. 5. Bus voltage in normal system operation mode.

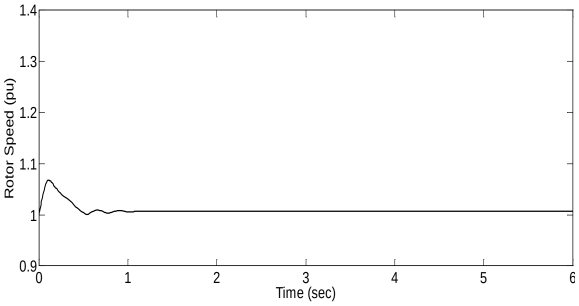


Fig. 6. Generator speed in normal system operation mode.

4.2. Simulation in a Symmetric System

In the second part of the simulation, a symmetric system is studied. The purpose is to regulate the voltage across the B_2 bus. System specifications are listed in Table 2.

First, the simulation of applied STATCOM in B_2 bus to regulate the voltage is examined and the purpose is regulation of bus voltage in accordance with Table 3.

According to the determination of V_{ref} based on Table 3, the B_2 bus voltage variations curves and STATCOM reactive power changes are illustrated in Figs 7 and 8. When the desired voltage level is less than 1p.u, STATCOM absorbs reactive power and stabilizes the voltage level at the desired value, and when the desired voltage level is higher than 1p.u, STATCOM generates reactive power to maintain the voltage level in the required amount.

Table 2. Characteristics of symetric system.

System nominal voltage (V_{rms})	500 kV
frequency	60 Hz
Converter rating	100 MVA
DC link nominal voltage	40000 V
DC link capacitancs	350µf
Droop	0

Table 3.voltage profile in B_2 bus.

$V_{ref}\ (pu)$	Time (s)
1	1
0.97	2
1.03	3
1	4

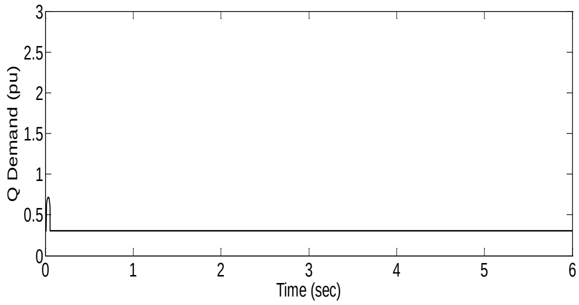


Fig. 7. Demanded reactive power in normal system operation mode.

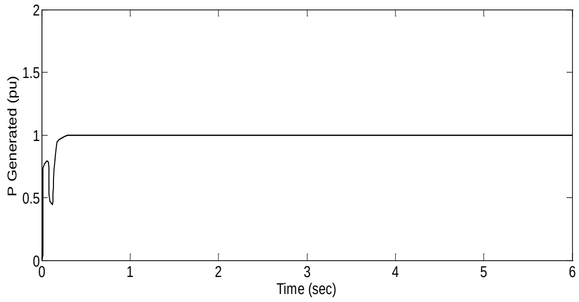


Fig. 8. Generated active power from wind farm in normal system operation mode.

STATCOM can be used in reactive power setting mode to adjust the amount of reactive power absorbed or injected to the grid. According to the set reactive power value for STATCOM, the corresponding bus voltage will be set to a certain value. By setting the STATCOM reactive power value to 0.5 p.u, curves (9) and (10) are obtained.

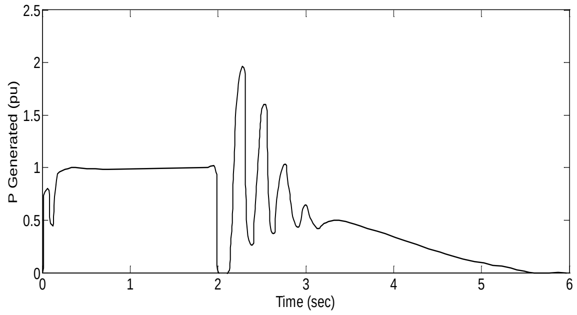


Fig. 9. Generated active power from wind farm in fault mode without STATCOM.

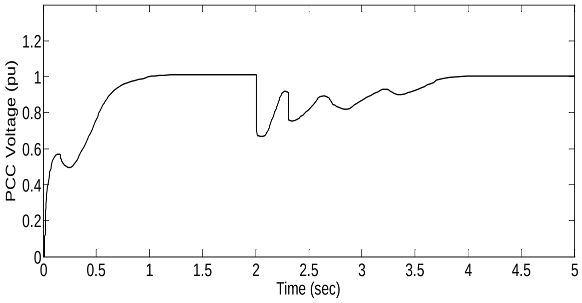


Fig. 10. Bus voltage in fault mode with STATCOM.

4.3. Comparison Studies

In this subsection, the simulation results of the studied system in two modes with and without STATCOM application are simulated when a three-phase fault occurs in the system. The wind speed in this simulation starts from 12 m/s and reaches a slope speed of 14 m/s. The cut-out speed is considered to be 24 m/s. The comparison results of voltage, reactive power and generator speed are illustrated here.

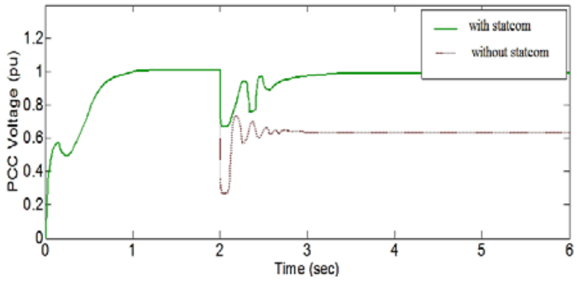


Fig. 11. Comparison of voltage during fualt.

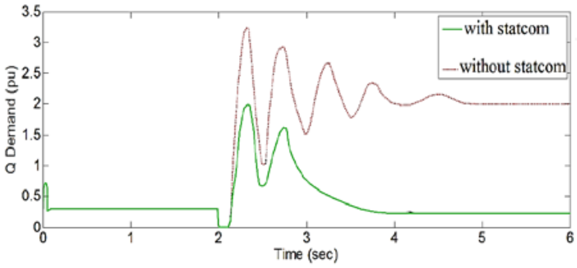


Fig. 12. Comparison of demanded reactive power during fualt.

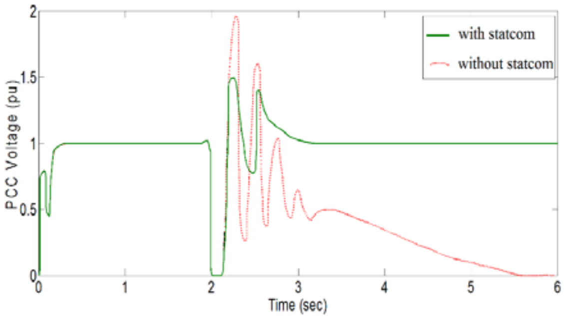


Fig. 13. Comparison of wind active power during fualt.

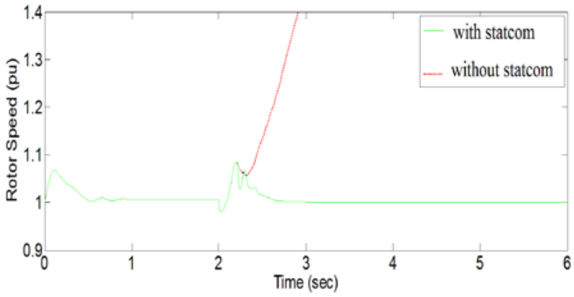


Fig. 14. Comparison of generator speed during fualt.

5. Conclosions

In this paper, the application of STATCOM with PID controller in wind turbines equipped with PMSG connected to the grid is investigated. According to the studies, by using STATCOM compensator, changes in voltage and power of the system are not gradual and sudden and the response is very soft. Moreover, the response time to transient faults is greatly reduced and the voltage stability is significantly improved, all of which increases the reliability of wind farms. Base on the simulation results in both cases with and without applying STATCOM to the system in the event of an fault, it is clear that the use of STATCOM in wind farms equipped with PMSG seems inevitable.

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