Stability Improvement of a Two-Area Power System Connected With an Integrated Wind Farm Using FACTS Devices

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(Electrical Power Systems)

By

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Abstract

With the increased focus on renewables, the installation of wind power generation systems or wind farms have been rapidly grown all over the world. However, due to the inherent intermittent characteristics it has introduced number of testing issues such as protection and stability issues. Another problem is the inter-area oscillations affected by interactions among generators. So as to examine the execution of a practical power system, a two-area power system coupled with a coordinated DFIG-based offshore wind farm is considered in this work. In order to improve the damping of considered power system connected with an coordinated offshore wind farm, presented work make use of STATCOM (Static Synchronous Compensator) for compensating the reactive power and keeping voltage profile at the coupled bus. The principle commitment is to analyze a STATCOM linked with a lead-lag power-oscillation damping controller (PODC), which is composed by utilizing phase-compensation method to reduce oscillations of the studied two-area. By simulation results it can be concluded that the proposed FACTS device will be able to enhance stability of the considered system under various disturbance conditions.

List of Figures

1.1 Classification of power system stability . . . 3
1.2 Oscillatory instability . . . 4
1.3 A periodic instability . . . 4
1.4 Phasor representation of sinusoidally varying angle, speed and torque deviations . . . 12

2.1 Schematic Diagram of Doubly Fed Induction Generators . . . 20

3.1 General feedback control system . . . 24
3.2 Scheme of the POD controller . . . 24
3.3 Simplified time-constant regulator model of SVCs . . . 26
3.4 Control block diagrams of the proposed STATCOM including the designed PODC . . . 26

4.1 Two-area test system with DFIG connected to Area 1 . . . 29
4.2 Two-area test system with DFIG connected to Area 1 . . . 30
4.3 Active power of Generator 1 . . . 31
4.4 Active power of Generator 2 . . . 31
4.5 Reactive power of Generator 1 . . . 31
4.6 Reactive power of Generator 2 . . . 32
4.7 Voltage at Bus 7 . . . 32
4.8 Voltage at Bus 8 . . . 32
4.9 Rotor speed of Generator 1 and 2 . . . 33
4.10 Rotor-angle difference G1 and G2 . . . 33
4.11 Rotor-angle difference G1 and G3 . . . 34
4.12 Two-area test system with DFIG connected to Area 1 . . . 35
4.13 Active power of Generator 1 . . . 35
4.14 Active power of Generator 2 . . . 35
4.15 Reactive power of Generator 1 . . . 36
4.16 Reactive power of Generator 2 . . . 36
4.17 Voltage at Bus 7 . . . 37
4.18 Voltage at Bus 8 . . . 37
4.19 Rotor Speed of Generator 1 and 2 . . . 37

List of Tables

1.1 Comparison among FACTS Conrtrollers 14

2.1 Oscillation effect due to wind penetration 20

Abbreviations

FACTS	Flexible Alternating Current Transmission System
WFs	Wind Farms
VSWTs	Variable-Speed Wind Turbines
HVDC	High-Voltage,Direct Current
PSS	Power System Stabilizers
SVC	Static VAR Compensator
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
UPFC	Unified Power Flow Controller
TCSC	Thyristor Controlled Series Capacitor
GTO	Gate turn on/off
DFIG	Double Fed Induction Generator
MATLAB	Matrix Laboratory
WSCC	Western Systems Coordinating Council
PWM	Pulse Width Modulation
RSC	Rotor Side Converter
GSC	Grid Side Converter
SCIG	Squirrel Cage Induction Generators
IEEE	Institute of Electrical and Electronics Engineers
POD	Power Oscillation Damping
PSAT	Power System Analysis Toolbox
W/O	Without

Contents

Acknowledgement **i**

Abstract **ii**

List of Figures **iii**

List of Tables **iv**

Abbreviations **v**

Contents **vi**

1 Introduction **1**
- 1.1 Power System Stability Problem . . . 1
- 1.2 Classification of Stability . . . 2
- 1.3 Small-Signal Stability . . . 3
  - 1.3.1 Power System Oscillations . . . 3
  - 1.3.2 Classification of Power System Oscillation . . . 5
- 1.4 Techniques for Analysis of Small Signal Stability . . . 7
- 1.5 FACTS Controllers . . . 13
  - 1.5.1 Static VAR Compensator (SVC) . . . 14
  - 1.5.2 STATCOM (Static Synchronous Compensator) . . . 15

2 Literature Survey **17**

3 Control Scheme and Design **23**
- 3.1 Power Oscillation Damping Controller . . . 23
- 3.2 POD design . . . 24
- 3.3 SVC and POD Modeling . . . 25
- 3.4 STATCOM and POD Modeling . . . 26

4 Simulation and Results **29**
- 4.1 Two-Area Model With Wind Farm . . . 29
- 4.2 PSAT Simulaion of Two Area Model With Wind . . . 30
  - 4.2.1 Case 1: When SVC and STATCOM are connected in system . . . 30
  - 4.2.2 Case 2: When STATCOM with PODC connected in system . . . 34

5 Conclusion and Future Scope **39**
- 5.1 Conclusion . . . 39
- 5.2 Future Scope . . . 39

References **41**

Chapter 1

Introduction

For the purpose of improvement, electric supply industries has undergone number of changes in past few decades. One among them is to shift focus on renewables based generation from conventional methods of generation of electrical energy. This shift is mainly caused due to increased load demand and environmental constraints.

In past few years, wind energy has been one of the rapidly grown renewable energy resources in the whole world. Currently, mature variable-speed wind turbines (VSWTs) have turn out to be more attractive owing to their inherent advantages. However, due to the inherent intermittent characteristics it has introduced number of challenging testing issues such as protection, voltage stability, transient stability, etc.

1.1 Power System Stability Problem

Power system stability is important facet for transferring continual electric power. It is characterized as that property of a power system that allows it to persist in a state of operating equilibrium under common operating conditions and to re-claim a suitable state of equilibrium after being subjected to a faults [1]. Unsteadiness of power system can rise in several different situations liable on the system configuration and operative mode. One of the stability problems is keeping synchronous process or synchronism mainly that power system support on synchronous machines. This aspect is influenced by the dynamics of generator's rotor angle and power-angle relations. Additional instability challenges that may be saw is voltage collapse that is typically related to load behavior and not synchronous speed of generators.

Small signal stability can be termed as the conduct of the power system to be remained at stable operating point when subjected to small instabilities. This is generally considered as a trouble of inadequate or weakly damping of system fluctuations. Such oscillations are unwanted at low-frequencies, as they tend to decrease the power being transferred in the transmission line and many a times present stress in the system. Many of these low frequency oscillations could be initiate in the electrical power system, but the two greatest serious types that are of concern are the local mode and the inter-area mode. The local mode is connected with a single Unit as for the entire system, then again the inter-area mode is connected with a few units in an area concerning different units in various area. The objective this project is having is to test such small frequency disturbances by having fast and powerful computational tools in the stability evaluation.

1.2 Classification of Stability

Figure 1.1 [1] gives a far reaching classification of power system stability. As depicted by figure 1.1, there are two primary classes of stability: voltage stability and Angle stability. Angle stability has two primary sub classes: small-signal (steady-state) stability and transient stability. A power system is thought to be steady state stable if, after any little unsettling influence, it achieves a consistent state working condition which is identical or close the pre-disturbance working . A power system is transient stable for a huge disturbance or sequence of disturbances if subsequent disturbance it reaches an adequate steady-state operating state. not at all like steady-state stability which is a capacity just of the working state, transient stability is more complex since it is a component of both working condition and the unsettling influence [2]. Voltage stability additionally has two fundamental sub classes: Large disturbance voltage stability and small-disturbance voltage stability.

For transient stability, it is typically when the power system encounters large disturbance caused by inequality between the mechanical input and the electrical output powers. In order to consider this kind of stability, the focus is just on the first swing periodic drift.Therefore, just a small amount of a moment is sufficient to saw the transients and a few simulation time seconds to study the system. As of the small-signal stability, it happens when the system needs synchronizing torque or when a precarious control activity occurs.This kind of Stability requires an investigation of over a moment to a few hours.

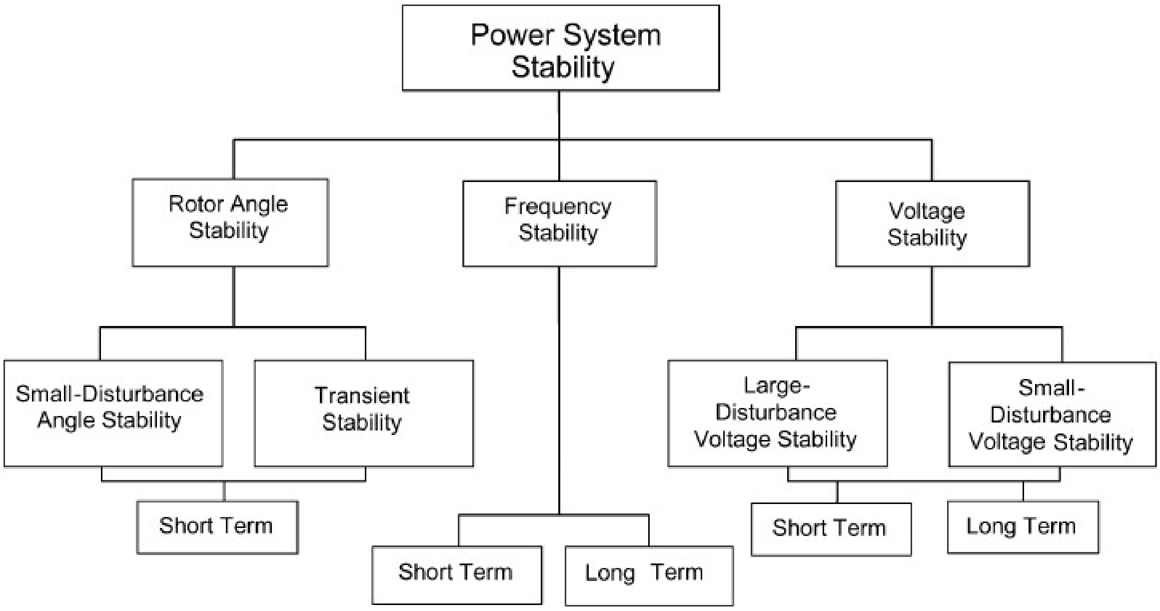


Figure 1.1: Classification of power system stability

1.3 Small-Signal Stability

Small-disturbance angle stability (small-signal stability) is another subcategory of rotor angle stability (Figure 1.2) and consists of the ability of the power system to maintain angle stability after being subjected to a small disturbance. A disturbance is considered to be small if the linearized system still represents the dynamics of the original system under this disturbance [3,4]. Once the system is linearized, modal analysis methods could be applied. Modal analysis allows for the computation of the characteristics of modes (mode shapes, participation factors and transfer functions) that can be useful for damping enhancement [4,14]. Time-domain simulations can be used to validate the results [15]. Bifurcation method is another alternative which, unlike modal analysis that considers all system parameters to be fixed, evaluates the impact of large changes on the small-signal stability [16,17]. As discussed previously, two forms of rotor angle instability may arise. The presence of complex conjugate eigenvalues with positive real parts incites an oscillatory instability (Figure 1.2). If the eigenvalue is positive and real, the instability is an aperiodic type (Figure 1.3). Small-signal stability is not in the scope of this thesis.

1.3.1 Power System Oscillations

A study of power system oscillations is of awareness in a system where more than one generator is operate in parallel to distribute a shared load. In small systems, there

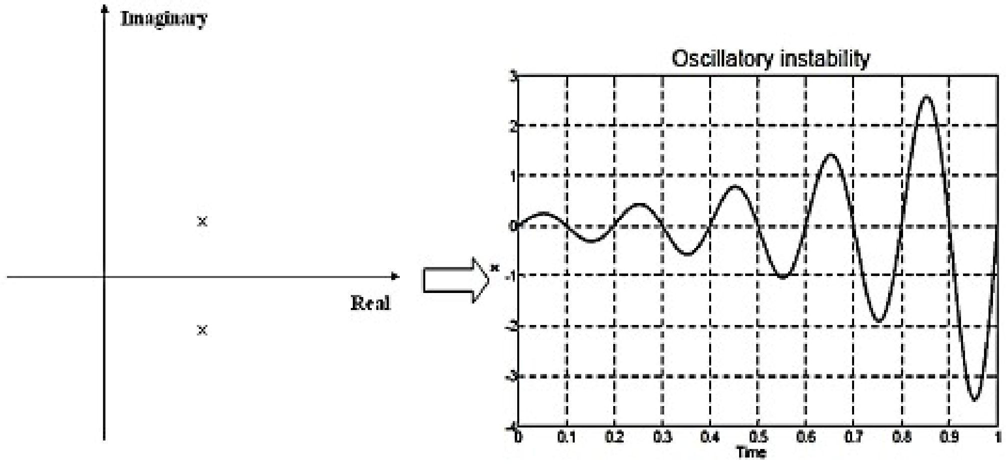


Figure 1.2: Oscillatory instability

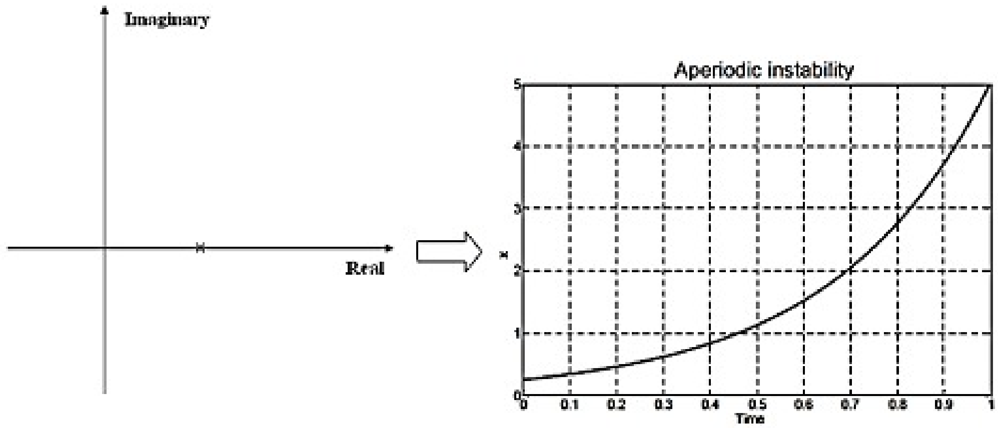


Figure 1.3: A periodic instability

might be just several generators and in large systems there might be a many generators working in parallel. In such a condition synchronous machines produce torques that be subject to on the relative angular movement of their rotors. These torques performance to keep the generators in synchronism (synchronizing torque) so, if the angular displacement between generators rises, an electrical torque is formed that efforts to reduce that angular displacement, results in oscillations, the instant of inertia of rotors and synchronizing torques cause the angular movement of the generators to oscillate subsequent the rate of a disturbance when it is operating under stable condition.Under these conditions, the generators go about as rigid forms and oscillate concerning each other utilizing the electrical transmission way among them to exchange energy. If a system is small-signal unstable, oscillations can develop in magnitude over the traverse of numerous seconds and, can in the end result in blackouts of significant segments of the power system. Further, a power system is constantly subjected to random disturbances as load or generation changes in controller settings. Hence it never resolves to a steady state at any given point of time.Henceforth it never resolves to steady-state at any given purpose of time. Thus having satisfactory damping of all system oscillations is oscillations to system stability and in this manner, to system security and reliability. In a very much composed and operated system, these oscillations of the rotor angle movement decay and settle to a value that won't limitation Power flow through the transmission network. Such a system is said to be small-signal stable. In the following conditions, the system might be small-signal unstable.[1][2][3]

1. Utilization of high high gain fast-acting exciters.
2. Bulk power transfer over faraway transmission lines from faraway generating plants
3. Power transfer over weak ties among systems which may efects due to line outages.
4. Insufficient changes of controls of equipment such as generator excitation systems, HVDC converters, static var compensators.
5. Adverse contact of electrical and mechanical systems affecting instabilities of torsional mode fluctuations.

In an over loaded system, rather small inherent damping and a low magnitude of synchronous torque coefficient may constrain the system operation by restraining power transmission.

1.3.2 Classification of Power System Oscillation

The power system oscillations are basically worried about little outings of the system conditions about a steady-state working point following a small disturbance. For an convenience of examination, the oscillations related with a power system is delegated takes after[1][2].

1. Swing mode oscillations
2. Control mode oscillations
3. Torsional mode oscillations

Swing Mode Oscillations

In this mode denoted to as electro-mechanical oscillations. For n generator system, here are (n - 1) swing (oscillatory) modes related with the generator rotors. A swing mode oscillation is ordered by a high relationship of the generator rotor in that mode, where generators in two coherent groups swaying against each other with estimated phase difference of 180 ° amongst the groups. that is shown further in the eigenvalue analysis, a high association is signified by participation factors and formation of rational groups is identified by right eigen vectors related with rotor slip. The location of generators in the system defines the type of swing mode. Swing mode oscillations can be more gathered into four broad classes:

1. Local machine-system oscillations
2. Inter unit (Intra-plant) mode oscillations
3. Local mode oscillations
4. Inter-area mode oscillations

1. **Local Machine-system oscillations:-** These oscillations by and large include one or more synchronous machines at a power station swinging together against a relatively substantial power system or load center at a frequency in the scope of 0.7 Hz to 2 Hz.These oscillations become particularly troublesome when the plant is at high load with a high reactance transmission system. The term local is used because the oscillations are localized at one station or a small part of the power system.
2. **Inter unit (Intra-plant) mode oscillations:-**these oscillations commonly include at least two or more Synchronous machines at a power plant swing against each other, usually at a frequency of between 1.5 Hz to 3 Hz.
3. **Local mode oscillations:-** These oscillations generally involve nearby power plants in which coherent groups of machines within an area swing against each other. The frequency of oscillations are in the range of 0.8 to 1.8 Hz.
4. **Inter-area mode oscillations:** These oscillations usually involve combinations of many synchronous machines on one part of a power system swinging against

machines on another part of the system. Inter-area oscillations are normally of a much lower frequency than local machine system oscillations in the range of 0.1 to 0.5 Hz. These modes normally have wide spread effects and are difficult to control.

Control Mode Oscillations:-

Control modes are associated with generating units and other controls. Poorly tuned exciters, speed governors, HVDC converters and static var compensators are the usual causes of instability of these modes.

Torsional Mode Oscillations

These oscillations include relative angular movement between the pivoting components of a unit, with frequencies running from 4Hz or more. This mechanical system has next to no innate normal damping. The source of torque for instigating torsional oscillations with the excitation system originates from a blend of balance of excitation system yield power, and regulation of synchronous machine power because of changes in generator field voltage. Close to the excitation systems, there are different mechanisms that can energize torsional oscillation.

A wide transfer speed excitation system may have the capacity to give enough negative damping at any of these torsional characteristic frequencies to destabilize at least one of these torsional modes, especially with the utilization of a power system stabilizer of these oscillations, local machine-system mode, local mode, intra-plant mode, control mode and torsional mode are generally categorized as local problems as it involves a small part of the system.

1.4 Techniques for Analysis of Small Signal Stability

1. Eigenvalue analysis [4]

2. Damping and synchronizing torque analysis [1, 5]

3. Frequency response and residue based analysis [6, 7]

4. Time-domain solution analysis [2, 1, 8, 10]

1. **Eigenvalue Analysis**

   <u>**Eigenvalues:**</u>

   The eigenvalue of matrix are given by value of the scalar parameter λ for which there be non-trivial solution (i.e.u = 0) to the equation

   $$Au = \lambda u \tag{1.1}$$

   In A is an (n × n) matrix and u is an (n × 1) vector referred to as eigen vector. To find the eigenvalue, (1.1) may be written in the form

   $$(A - \lambda I)u = 0 \tag{1.2}$$

   Where I is an identity matrix of dimension (n × n).

   For a non-trivial solution,

   $$det(A - \lambda I) = 0 \tag{1.3}$$

   Growth of the element gives the characteristic equation. and the n solutions of $\lambda = \lambda 1$, $\lambda 2$, ... , λn is denoted to as the eigenvalues of the A matrix. The eigenvalues may be real or complex, and a complex eigenvalue always ensue in conjugate pair.So $\lambda_i = \sigma_i +$ jω_i, where σ_i is referred to as neper frequency (neper/s), and w_i isreferred to as radian frequency (rad/s).

Eigenvectors:

In any eigenvalue λ_i, the n column vector ui, which in (1.1) is called the right eigenvector of matrix A a with eigenvalue λ_i, Therefore we have

$$Aui = \lambda_i ui \tag{1.4}$$

$$Aui = \lambda_i ui \tag{1.5}$$

where i = 1, 2,......, n

The eigenvector ui has the form

$$ui = \begin{bmatrix} u1i \\ u2i \\ . \\ . \\ uni \end{bmatrix}$$

In eq. (1.4) is homogeneous, k ui (k is scalar) is a solution. Thus, the eigenvector is determined only to within a scalar multiplier. So the n element row vector wj

$$WjA = \lambda_j wj \tag{1.6}$$

The left eigenvector denoted with the eigenvalue λ_j, and has the form of

$$Wj = [Wj1Wj2.\ldots\ldots Wjn] \tag{1.7}$$

where j = 1,2,. . . . . . .,n

Left & right eigenvector corresponding to different eigenvalues are orthogonal. In other words, if λ_i is not equal to λ_j, we have,

$$W_j u_i = 0 \tag{1.8}$$

In the case of eigenvectors corresponding to same eigenvalue λ_i, we have,

$$W_i u_i = C_i \tag{1.9}$$

Where C_i is a non-zero constant.

Since, as noted above, the eigenvectors are determined only to within a scalar multiplier, it is common practice to normalize these vectors so that

$$W_i u_i = 1 \tag{1.10}$$

Eigenvalues and Stability:

Time-dependent characteristic of mode corresponding to an eigenvalue λ_i is given by $e^{\lambda_i t}$. Therefore, the stability of the system is determined by the eigenvalues as follows:

1. Real eigenvalue relates to a non-oscillatory mode. A negative real eigenvalue shows to a decaying mode. The bigger its magnitude,the fast decay. A positive real eigenvalue shows to aperiodic monotonic insecurity.

2. Complex eigenvalues are in conjugate pairs and each combine relates to an oscillatory mode. The real part of the eigenvalues gives the damping and imaginary component gives the frequency of motions. A negative real part shows to a damped motions where as a positive real part shows to oscillation of expanding amplitude. In this way, for a complex pair of eigenvalues given by,

$$\lambda = \sigma \pm jw \tag{1.11}$$

The frequency of oscillation in Hz is given by,

$$f = \frac{\omega}{2\pi} \tag{1.12}$$

The damping ratio is given by,

$$\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{1.13}$$

The damping ratio determines the rate of decay of the amplitude of the oscillation. The time constant of amplitude decay is $\frac{1}{|\sigma|}$. In other words, the amplitude decays to 1/e or 37% of the initial amplitude in $\frac{1}{|\sigma|}$. Seconds or in $\frac{1}{2\pi}\frac{\sqrt{1-\zeta^2}}{\zeta}$ cycles of oscillations. This also corresponds to $(\frac{f}{|\sigma|})$ cycles. For example, a damping ratio of 5% means that in 3 oscillation periods the amplitude is damped to about e$^{-|\sigma|t}$ $= e^{\frac{|\sigma|}{f}(cycles)}$= e-0:3146×3 = 0.3892 of its initial value. The small-signal stability analysis program determines the dynamic performance of the system by computing the eigenvalues and eigenvectors of the state matrix of the linearized power system model.

2. **Damping and Synchronizing torque**

In electric power system, the change in electrical torque of a synchronous machine following a disquiet can be solved into two components as:

$$\Delta Te = T_S \Delta\delta + T_D \Delta S_m \tag{1.14}$$

where,

T$_S\Delta\delta$ is the component of torque change in phase with the rotor angle perturbation and is referred to as the synchronizing torque component; T$_S$ is the synchronizing torque coefficient.

T$_D$ ΔSm is the component of torque in phase with speed deviation and the damping torque component; T$_D$ is the damping torque coefficient. System stability depends on both components of torque for each of the synchronous machine. This analysis assumes that the rotor angle and the speed deviations oscillate sinusoidally. Hence, phasor notations can be used to analyze the stability performance of power systems. Figure (1.4) is drawn based on the observation that

$$\frac{d\delta}{dt} = Sm\omega b \tag{1.15}$$

$$\frac{d\delta}{dt} = \Delta Sm\omega B \tag{1.16}$$

$$j\omega\Delta\delta(j\omega) = \Delta Sm(j\omega)\omega B$$

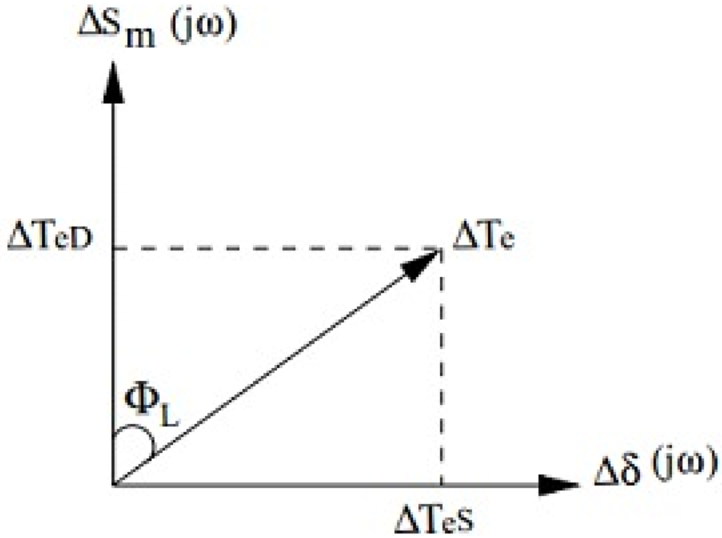


Figure 1.4: Phasor representation of sinusoidally varying angle, speed and torque deviations

From the figure 1.4 the damping torque component can be written as,

$$\Delta TeD = \ \Delta Te\ \cos\phi_L \tag{1.17}$$

The synchronizing torque component can be written as

$$\Delta TeS = \ \Delta Te\ \sin\phi_L \tag{1.18}$$

If either or both damping and synchronizing torques are negative, i.e., if ΔTeD < 0 and/or ΔTeS < 0, then the system is unstable. A negative damping torque implies that the response will be in the form of growing oscillations, and a negative synchronizing torque implies monotonic instability.

3. **Frequency Response and Residue Based Analysis**

Frequency response is just another characterization of a system's transfer function between a given input and output. Frequency response methods allow a deeper insight into small-signal dynamics and have widespread use in the design of power system controllers. Frequency response can also be measured directly, even in a power system. It is thus an excellent method to validate mathematical models that are to be used in control design and stability analysis [6, 7]. Residues give the contribution of a mode to a transfer function. They also give the sensitivity of the corresponding eigenvalue to a positive feedback between the output of the transfer function and its input [5]. Thus, residues are useful to get an idea of which modes will be affected most by feedback. This concept has been used in [11] to determine the suitable location of power system stabilizers. An advantage of using residues in such analysis is that it takes into account the transfer function structure of the excitation system unlike participation factors. However, evaluation of residues dependent on the specific input/output combinations and may be computationally intensive for large systems.

4. **Time-Domain Solution**

   Conventional method solves the non-linear differential algebraic system of equations numerically, employing numerical techniques to provide solution to each variable at rectangular intervals of time and thus, they basically provide time domain solutions. Time domain techniques provide an exact determination of stability of non-linear systems both for small and large disturbances. However, the use of time response alone to look at small disturbance damping can be misleading. The choice of disturbance and selection of variables to be observed in time response are critical. The input, if not chosen properly, may not provide substantial excitation of the important modes. The observed response may contain many modes and the poorly damped modes may not be dominant. Number of modes depends on modeling details employed for different dynamic components. Larger systems may have a number of inter-area modes of similar frequencies, and it is quite difficult to separate them from a response in which more than one is excited. Therefore, for a large power system it is not possible to identify any desired mode and study their characteristics.

   Of all these methods, eigenvalue or modal analysis is widely used for analyzing the small-signal stability of power system [7] [12] [14].

1.5 FACTS Controllers

The traditional approach employs power system stabilizers (PSS) on generator excitation control systems in order to damp those oscillations. PSSs are effective but they are usually designed for damping local modes. In large power systems, they may not provide enough damping for inter-area modes. So, more efficient substitutes are needed other than PSS. FACTS are defined as "a power electronic based device and other static equipment that provide control of one or more AC transmission system parameters to increase controllability and enhance power transfer capability". Generally, FACTS controllers can be divided into four categories [16].

1) Series Controller

2) Shunt Controller

3) Combined series-series Controller

4) Combined series-shunt Controller

Table 1.1: Comparison among FACTS Conrtrollers

Name	**Type**	**Purpose**
SVC	Shunt	Voltage Control
SSSC	Series	Power Flow Control
STATCOM	Shunt	Voltage Control
UPFC	Shunt and Series	Voltage and Power Flow Control
TCSC	Series	Power Flow Control

1.5.1 Static VAR Compensator (SVC)

The Static VAr Compensator (SVC) is a shunt-connected device whose main functionality is to regulate the voltage at a chosen bus by suitable control of its equivalent reactance. A static VAR compensator has a set of electrical devices for providing fast-acting reactive power on high-voltage electricity transmission networks. SVCs are part of the Flexible AC transmission system device family, regulating voltage, power factor, harmonics and stabilizing the system. A static VAR compensator has no significant moving parts (other than internal switchgear). Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers or switched capacitor banks. The SVC has an automated impedance matching device, designed to bring the system closer to unity power factor. SVCs are used in two main situations:

- Connected to the power system, to regulate the transmission voltage (Transmission SVC)
- Connected near large industrial loads, to improve power quality (Industrial SVC)

In transmission applications, the SVC is used to regulate the grid voltage. If the power system's reactive load is capacitive (leading), the SVC will use thyristor controlled reactors to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. By connecting the thyristor-controlled reactor, which is continuously variable, along with a capacitor bank step, the net result is continuously variable leading or lagging power.

1.5.2 STATCOM (Static Synchronous Compensator)

Wind farm and the connected power system has given rise to following challenging problems such as protection, voltage stability, transient stability, etc. Hence, the reactive-power control in normal operation conditions necessary. Another problem is the interarea oscillations caused by interactions among synchronous generators (SGs), and it will limit power transmission in power systems.

In this project, a static synchronous compensator(STATCOM) is considered for this application because the STATCOM can provide superior voltage-support capability using a voltage-source inverter. The STATCOM is one of the shunt devices of flexible ac transmission systems family using power electronics converters to control power flow and improve dynamic/transient stability of power systems. The STATCOM was connected at the point of common coupling to maintain stable voltage and improve power quality by protecting DFIG-based WF (Wind Farm) connected to a weak grid. STATCOM is used as damping controller which is use to damp out oscillations of a power system. For the purpose of improving damping of the studied power system connected with WF, The STATCOM is for compensating the reactive power and maintaining voltage profile at the connected bus.

Chapter 2

Literature Survey

H. N. Vijiyan, A. K. Ramasamy, Au Mau Teng and Syed Khaleel Ahmed, "Effects of Variations in Generator Inputs for Small Signal Stability Studies of a Three Machine Nine Bus Network," World Academy of Science, Engineering and Technology International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol:5, No:2, 2011

- This paper examines the effects of generator input variations on power system oscillations for a small signal stability study.
- Eigenvalues and eigenvectors are used to examine the stability of the power system. The dynamic power system's mathematical model is constructed and thus calculated using load flow and small signal stability toolbox on MATLAB.

The reason this test network was modified such, was so that the effect of variations on its generation could be significantly detected.

- The effect of generation input was analyzed by increasing the generation value of one machine methodically from 0%- 150% of the original value.
- At each change in the generation value the state variables were re-calculated after running a load flow program and linearization of the system equation was performed and the state matrix A.
- Analysis of the system can then be carried out by acquiring the eigenvalues of the state matrix, A and the associated participation factors. The eigen vectors are then used check for stability of swinging characteristics of the system.

Machine 3's (machine connected to bus 3) generation output into the system is increased proportionally from 0% to 150%.

Each increment value of generation is then run through the program and its eigenvalues are displayed.

- As the generation increases, machine 1's both parameters (angle and speed) remain fairly constant, this is because it is the slack bus of the system.
- The participation factors for rotor angle of machine 2 and machine 3 are opposing each other.
- As the generation output for machine 3 increases, the prominence of machine 2, or its influence in instability of the system reduced.

Bin Sun, Zhengyou He, Y. Jia, K. Liao "Small-Signal Stability Analysis of Wind Power System Based on DFIG,"Energy and Power Engineering, 2013, 5, 418-422

- In this paper, they build the model of DFIG for small signal stability analysis and modify the 3 generator 9-bus WSCC test system to study the impact of large scale integration of wind power on power system small-signal stability first. Then, different oscillatory modes are got by us with their eigenvalue, frequency and damping ratio.

The total capacity of this wind farm is 75 MW.

- The output of synchronous generator G3 should be adjusted at the same time when increasing the output of wind farm.
- By calculating the eigenvalues of the linearized model, the small-signal stability characteristics of the system can be evaluated.

In this paper got 8 oscillatory modes, most of their oscillatory frequencies are between 0.1 Hz and 2.5 Hz

- The low-frequency oscillation is of great harm to the safe and stable operation of the power system so these low-frequency oscillation modes must be suppressed or eliminate by taking some efficient measures.

The eigenvalues will change with the increase of the output of wind farm.

- With the increase of the output of wind farm, the eigenvalues move to the left on the complex plane, the damping ratios become bigger and bigger.

- The small-signal stability of the power system is constantly enhanced. When the wind farm output at rated power, the system is the most stable. When the wind farm output below rated power, the larger the difference between output power and rated power, the system is unstable.

H. Banna, Alvaro Luna, Shaoqing ying, H. Ghorbani and Pedro Rodriguez "Impacts of Wind Energy In-Feed on Power System Small Signal Stability," 3rd International Conference on Renewable Energy Research and Applications, Milwakuee, USA 19-22 Oct 2014

- In This paper presents the impacts of large amount of wind power in feed on the rotor oscillatory stability.

- Wind turbine generator types currently employed in wind farms, optimal location of the wind farms in the interconnected power system.

- Kundur's two area network model has been utilized to study the mentioned impacts on the overall system using MATLAB/Simulink.

For Simulation and analysis purpose only DFIG turbine technology is used in this paper.

Doubly Fed Induction Generator

It is a variable speed pitch control turbine consisting of a wind turbine, drive train, gear box, induction generator and back to back voltage source Pulse Width Modulation (PWM)converter. The rotor is connected to the grid through PWM converter and the stator is directly connected to the grid as shown in the fig. The active and reactive power of DFIG is controlled through Rotor Side Converter (RSC) and Grid Side Converter (GSC)

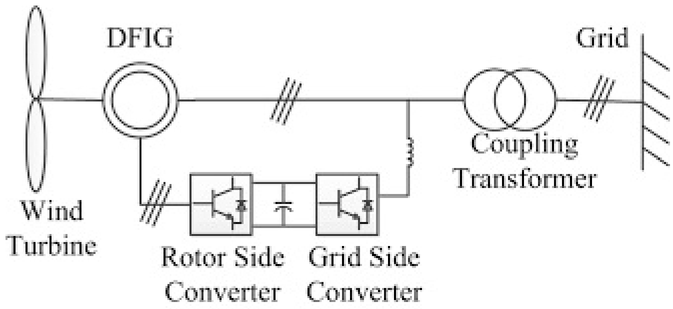


Figure 2.1: Schematic Diagram of Doubly Fed Induction Generators

System Study :

Table 2.1: Oscillation effect due to wind penetration

Cases	1	2	3	4
Penetration %	0 %	25 %	50 %	75 %
Oscillation	Negligible Oscillation & Same frequency	Negligible Oscillation & Same frequency	Increase in Interarea Oscillation while frequency also increase	Increase in Interarea Oscillation while frequency is high

Aditya P. Jayam, Nikhil K. Ardeshna and Badrul H. Chowdhur,"Application of STATCOM for Improved Reliability of Power Grid Containing a Wind Turbine," IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in, August 2008[23]

Test System

The proposed test system has two generators; one source is the wind turbine which is a Doubly-fed Induction Generator (DFIG) and the other is a synchronous generator. The total system has a typical load connected to the system at bus 3. The active voltage supporter, STATCOM is connected to the load bus. Grid represents an external system which is connected to the system of interest through a weak link .and a very weak grid and hence requires a compensating device of a higher rating.

Results

The simulation results for the voltages of the fault bus and the wind turbine, for the system cases without and with the STATCOM respectively. It can be observed that the voltage drop at the fault bus during the period of fault is to 0.4p.u and the system oscillates at a voltage of about 0.8p.u after the fault has been removed. The wind turbine voltage also reacts in the same way as the load bus and there is a great possibility that this might trip and hence go offline. With addition of a STATCOM at the load 4 bus, the voltage is increased to about 0.9p.u during the fault and is restored to 1.0p.u when the fault is cleared at 0.7sec. The voltage is quickly restored as there are minimum oscillations after the clearance of the fault in the system with a STATCOM.

D.Rakesh Chandra, M. Sailaja Kumari and M. Sydulu, "Impact of SCIG, DFIG Wind Power Plant on IEEE 14 Bus System with Small Signal Stability Assessment,"Power Systems Conference (NPSC), 2014 Eighteenth National,May 2015.

In this paper two small signal stability problems have been discussed and they are rotor angle stability, voltage stability and their simulations results have shown above. In case of SCIG power angles (rotor angles) are deviated, by which the system is said to be near to instability. Where as in case of DFIG rotor angles are almost constant with time by which we can conclude that system is completely stable. Coming to voltages at individual buses, SCIG based systems having fluctuations but DFIG based systems voltage almost remains constant From the simulation results it is clear that DFIG based system is more suitable to integrate into power system for wind power generation when compared to SCIG based system as power system stability is consider.

Simulation results show that SCIG based system is marginally stable where as DFIG based system is completely stable and rotor angle stability, voltage stability of DFIG is more predominant than SCIG. SCIG consisting of a fixed capacitor which may not sufficient to meet reactive power demand by the system. Where, DFIG consists of power electronics based controlling system by which it can supply reactive power to the system if necessary and thereby it can enhance small signal stability of the system.

Simon P. Teeuwsen "STATCOM with optimized POD Controller for efficient Inter-Area Oscillation Damping"Power and Energy Society General Meeting (PES), November 2013 IEEE

In this paper the purpose of installing a new STATCOM device might be a steady-state issue, dynamic problems, or even both. In the steady-state, the STATCOM can be used to slowly control the network voltage and prevent a voltage collapse, avoid overloading of transmission lines, balancing loads, etc. Dynamic support is provided by any STATCOM by nature and in some cases, this might be the main reason to install one. Since the control is extremely fast, the dynamic reactive power support is highly beneficial for the voltage recovery after fault clearing. The voltage recovery is highly influenced by loads and their characteristics, but also by generators nearby and other voltage controlling equipment in the area. Another reason of installing a STATCOM could be the limitation of temporary Over voltages, which can be observed during load rejection of thyristor based HVDC systems.

The utilized STATCOM (without POD controller) cannot improve the damping in the power system regardless to the studied location. In this paper shows that a properly tuned damping controller can provide a significant contribution to the power system.

The parameters of the POD are tuned utilizing parameter identification. The simulation results for the STATCOM connected to Bus 6 with optimized POD controller provides significant damping to the power system for all 4 fault cases.

Mahyar Zarghami, Mariesa. L. Crow, "Damping inter-area oscillations in power systems by STATCOMs,"Power Symposium, 2008. NAPS '08. 40th North American,November 2009 [25]

In this paper validate the proposed controller in IEEE 118 bus test system, a solid symmetrical fault has been applied on bus 43 of at 0 s and has been cleared at 0.2 s. Two cases have been considered for simulations. Case I is uncontrolled and case II is decentralized controlled (when control is implemented using estimated data with local observers). the proposed control can damp out oscillations effectively. voltage angles are controlled in order to damp oscillations and variations of voltage magnitudes are rather small.

Further investigation could be made on designing nonlinear controllers based on the proposed nonlinear modeling. Robustness and dependency of the designed controllers on topology changes of the power system is also a matter of concern. It is also possible to see how a bunch of FACTS devices (such as STATCOMs, UPFCs, SSSCs, etc.) existing in a network could work together to damp out inter-area oscillations.

Chapter 3

Control Scheme and Design

3.1 Power Oscillation Damping Controller

The design of POD controller in based on linear system techniques. in the wake of taking care of the power flow issue, a modal analysis is completed by figuring the eigenvalues and the participation factors of the state matrix of the system. The dynamic system is put into state space form as a combination of coupled first order, linearized differential conditions that take from,

Δx = AΔx+ BΔu

y = CΔx+DΔu

where, Δ shows a small deviation, A is the state matrix of size n$\times$ n, B is the control matrix of size n$\times$r, C is the output matrix of size mn, and D is forward matrix of size m$\times$ r. The values of the matrix D denote the proportion of input, which is directly shown in the output. The eigenvalues λ of the state matrix A can be find by solving det[A-λI] = 0. If $\lambda_i = \sigma_i \pm$ jω_i shows the i^{th} eigenvalue of the state matrix A, and real part gives the damping, and the imaginary part gives the frequency of oscillation. The relative damping ratio is :

$$\zeta_i = -\sigma_i / \sqrt{(\sigma_i^2 + \omega_i^2)}$$

A damping ratio between 5% to 10% is acceptable for most power systems; however, the 10% value is recommended for secure system operation.

3.2 POD design

The main design objective is to accomplish a predefined damping satisfactory level of the electromechanical oscillations to enhance the system performance.and general control diagram of the power system controlled by the POD is in Fig. 3.1 and 3.2.

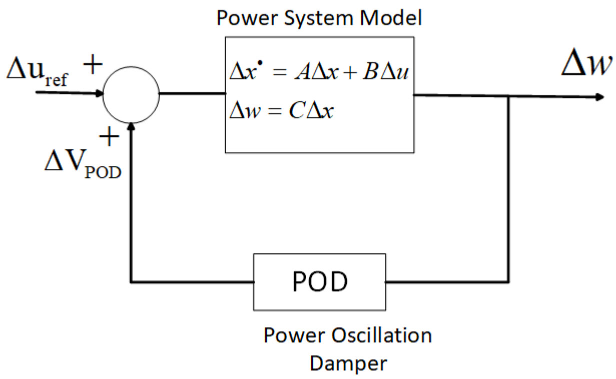


Figure 3.1: General feedback control system

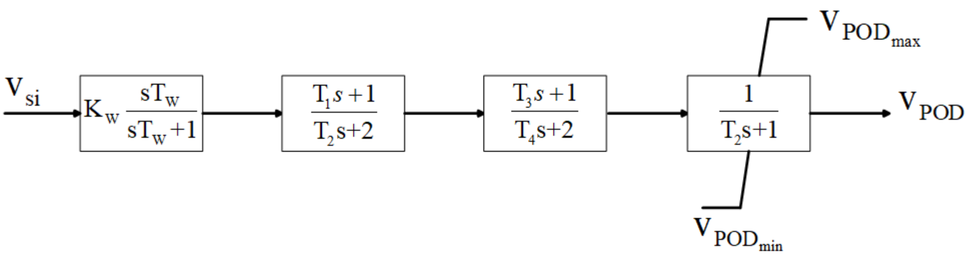


Figure 3.2: Scheme of the POD controller

In Fig. 3.2, the configuration of the POD controller is similar to the classical power system stabilizer (PSS). The controller contains of a stabilizer gain, a washout filter, and phase compensator blocks. The gain Kw determines the amount of damping presented by the POD and the phase compensator blocks shows the appropriate phase lead-lag compensation of the input signal. Fig. 3.1 general feedback control system Fig. 3.2: Scheme of the POD controller The main design steps of the POD design using the frequency response method is:

1. Eigenvalue analysis: In the critical modes of the uncompensated system (without the POD) are known based on eigenvalues.

2. State-space form: In this step, all output and input matrices are determined.

3. Nyquist analysis: This step, the value of washout filter time constant is taken between 1 and 20 Sec then the Nuquist plot of the uncompensated loop with the washout filter is created. The required phase compensation Φ is then shown from the created. Nyquist plot. mainly to obtain a good phase margin based on the critical frequency ω_n

4. Compensator blocks tuning: Based on the value of θ that is determined in the last step, the parameters of the phase compensator blocks are determined in this step using

$$\alpha = \{1 - \sin e(\theta/m_c)\} / \{1 + \sin(\theta/m_c)\}$$

$$T2 = \frac{1}{\omega n \sqrt{\alpha}}$$

$$T1 = \alpha T2$$

Where m_c is the number of the lead-lag blocks and ω_n is the frequency of the critical mode to be damped. The value ofm_c is usually one or two; Fig. 6 shows a POD with two lead-lag blocks (i.e. $m_c = 2$) In this layout, T3 and T4 are equal to T1 and T2.

5. Damping ratio adjustment: In this step, the root locus plot of the compensated system is used to determine the value of Kw that gives an adequate damping ratio (i.e. $\varsigma \geq 10\%$)

3.3 SVC and POD Modeling

The time constant regulator is used to represent the SVC (Figure 3.3). This model is usually used in stability analysis of power systems. As shown, the regulator has an anti-windup limiter. Therefore, reactance b_{SVC} is locked if one of its limits is reached and the first derivative is set to zero. In this model, a the dynamics of the SVC takes the form, The model is completed by the algebraic equation expressing the reactive power injected at the SVC node (Q_{SVC}).

$$Q_{SVC} = b_{SVC} V^2$$

The structure of the POD controller (Figure 3.2) is like the structure of the classical power system stabilizer (PSS). The controller comprises of a stabilizer gain, a washout filter, and phase compensator blocks. The washout signal confirms that the POD yield is zero in steady-state. The output signal v_{POD} is subjected to an anti-windup limiter and its dynamics are reliant on a low time constant (Tr = 0.01 s). The gain Kw decides the measure of damping presented by the POD and the phase compensator block give the suitable phase lead-lag compensation of the input Signal (vsi). The input signal is chosen in view of the adequacy of different observable and controllable inputs signals for power oscillation damping. The input signal may incorporate, however not constrained to, line current flow, line active power flow, line reactive power flow, and bus voltage. in this design, T3 and T4 are generally taken equivalent to T1 and T2 individually.

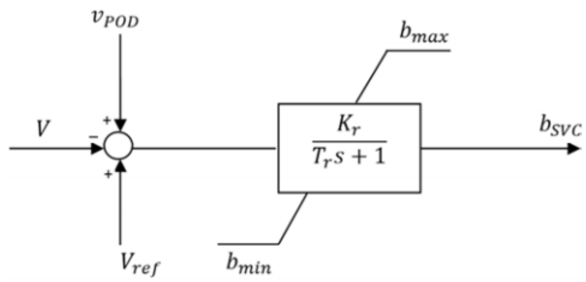


Figure 3.3: Simplified time-constant regulator model of SVCs

3.4 STATCOM and POD Modeling

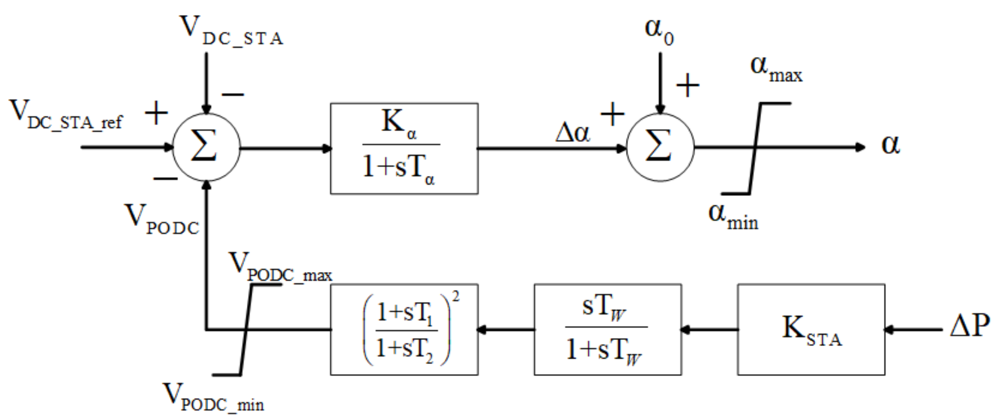


Figure 3.4: Control block diagrams of the proposed STATCOM including the designed PODC

Fig. 3.4 [22] shows the control block diagrams of the employed STATCOM including the proposed PODC.The eigenvalues of the studied two-area power system containing the DSIG-based WF. the eigenvalues are relate to the rotor-angle modes of local oscillation Area 1 (G1 against G2) and Area 2 (G3 against G4), respectively, while the eigenvalues refer to the mode of interarea oscillations between Area 1 and Area 2. The damping of this interarea oscillation mode can be improved by adding the designed PODC to the control loop of the proposed STATCOM. the output signal is $Y = \Delta P_{7-8}$, while $U = V_{PODC}$ is the input signal. The transfer function H(s) of the proposed PODC for the proposed STATCOM in s domain shown in Fig. 3.4 is given by

$$H(s) = \frac{U(s)}{Y(s)} = \frac{V_{PODC}(s)}{\Delta P_{7-8}(s)}$$

$$= K_{STA}\left(\frac{sTw}{1+sTw}\right)\left(\frac{1+sT_1}{1+sT_2}\right)^2$$

where T_W is the time constant of the wash-out term, K_S T_A is the gain, and T_1 and T_2 are the time constants of the lead-lag compensator of the designed PODC. The parameters of the lead-lag compensator can be determined by using phase-compensation method.

$$\alpha = \{1 - \sin(\theta/\ kern{-}m_c)\}/\{1 + \sin(\theta/m_c)\}$$

$$T_2 = \frac{1}{\omega_n\sqrt{\alpha}}$$

$$T_1 = \alpha T_2$$

where θ is the phase angle of the transfer function θ of the PODC, k is the angular frequency (rad/s) of the mode to be damped, and ms is the stage number for the lead-lag compensator. The designed results for the PODC using the proposed phase-compensation method are given as follows: $\omega_k = 6.183$ rad/ s, $m_s = 2$, $K_{STA} = 0.5$, $T_W = 10.0s$, $T_1 = 0.6824$ s, and $T_2 = 0.0303$ s.

Chapter 4

Simulation and Results

4.1 Two-Area Model With Wind Farm

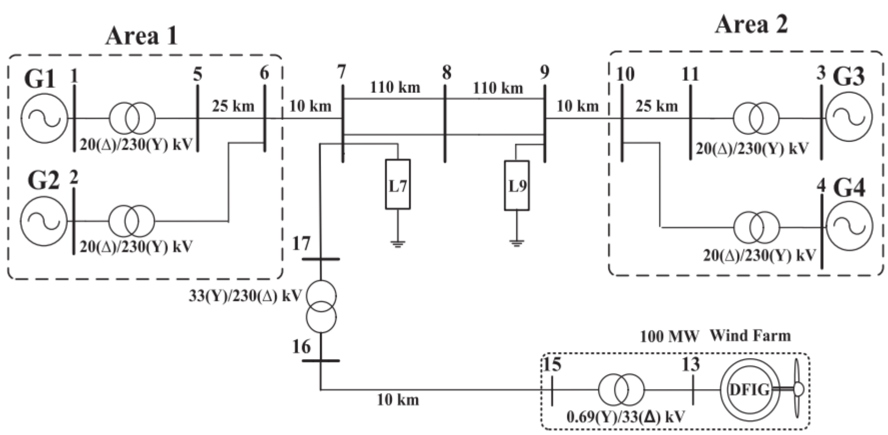


Figure 4.1: Two-area test system with DFIG connected to Area 1

The two-area model of kundur's 11 bus system has been used for the analysis of system stability. The system consists of two similar areas connected by weak tie line. Each area consists of two coupled units each having rating of 900 MVA at 20 KV. Each step-up transformer has an impedance of 0+j0.15 per unit on 900 MVA, 230 KV base. In the system the generator 3 is swing generator and G1,G2 has 700 MW and G4 has 719MW The load connected in area 1 is $P_L = 967MW, Q_l = 100MVAr$, $Q_L = 200MVAr$ and in area 2 is $P_L = 1767MW, Q_l = 100MVAr$, $Q_L = 350MVAr$

The DFIG of 100 MW is connected to area 1 with the transmission line of 10 km.

4.2 PSAT Simulaion of Two Area Model With Wind

This system has been studied and analyzed with the aid of the power system analysis toolbox (PSAT) version 2.1.9, the simulink and the control system toolbox of MATLAB 2014A

4.2.1 Case 1: When SVC and STATCOM are connected in system

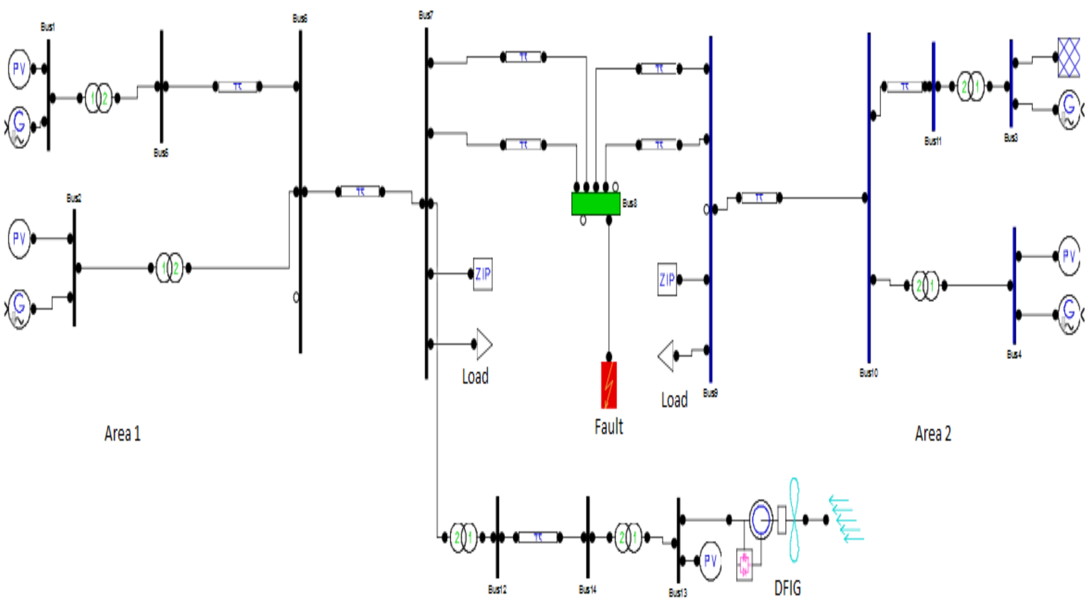


Figure 4.2: Two-area test system with DFIG connected to Area 1

In this simulation the fault has been created at time 5 seconds for the time interval 20 ms at bus number 8. The generator's behaviour is checked and the plots of real, reactive power and delta of synchronous generator is analyzed. For the compensation, FACTs devices SVC and STATCOM are connected on bus number 8.

Result of Active Power

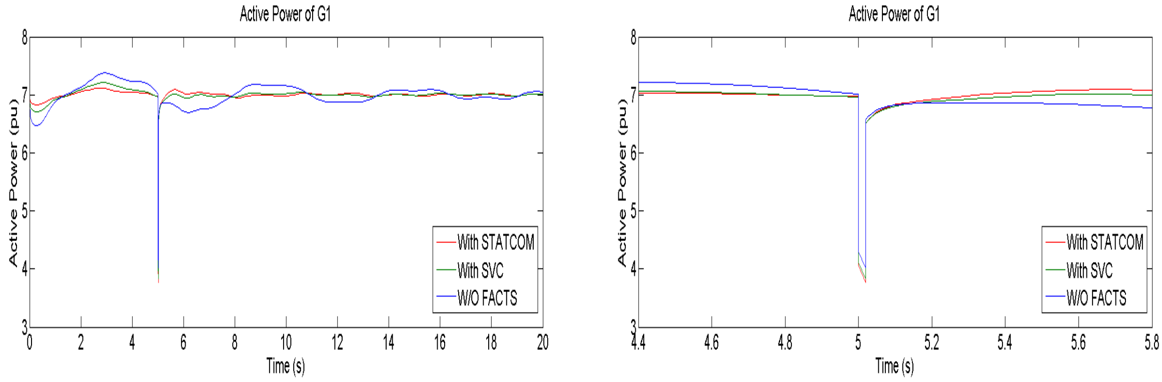


Figure 4.3: Active power of Generator 1

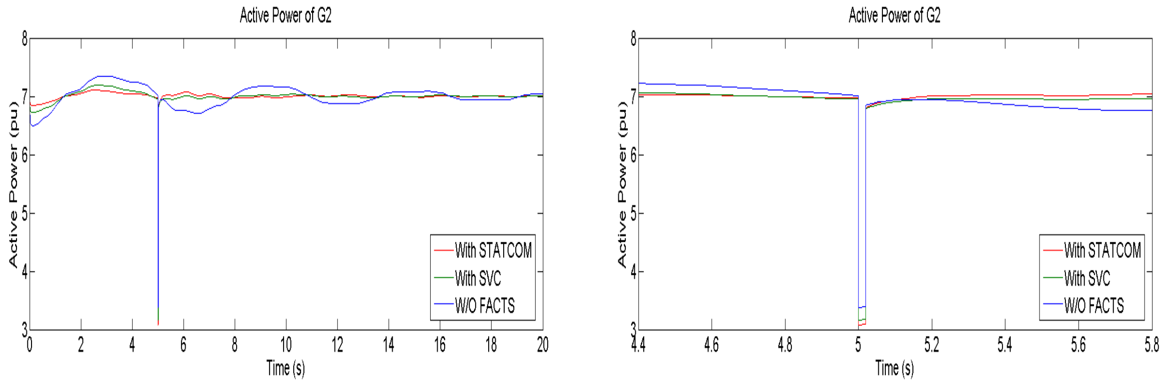


Figure 4.4: Active power of Generator 2

Figure 4.3 and 4.4 shows the variation of active power of generator 1 and 2 respectively under different conditions. It can be observed that with the FACTS devices the result is more stable and the STATCOM gives better results than the SVC.

Result of Reactive Power

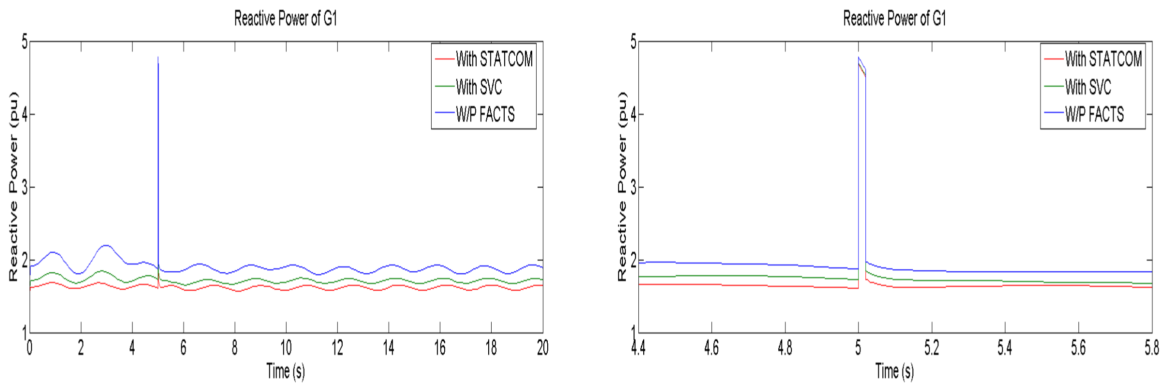


Figure 4.5: Reactive power of Generator 1

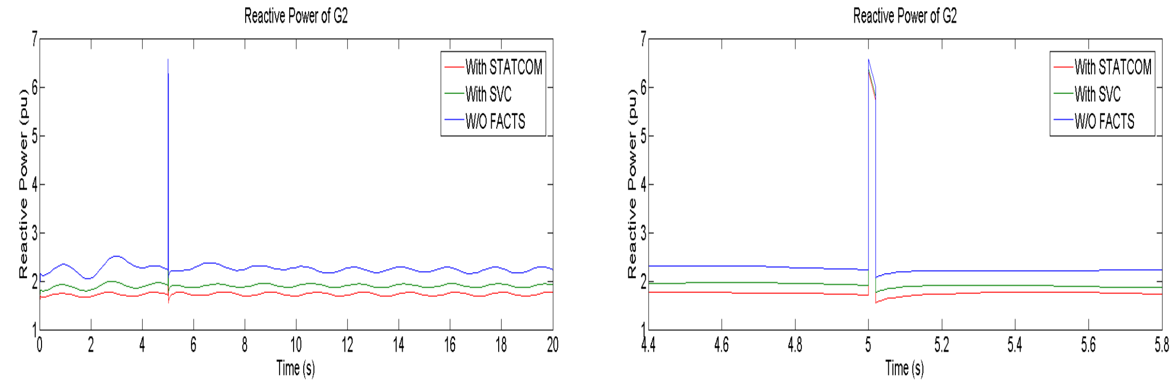


Figure 4.6: Reactive power of Generator 2

Figure 4.5 and 4.6 shows the graph of reactive power of generator 1 and generator 2 under different conditions. As at the time of fault DFIG doesn't provide the required reactive power support so FACTS device is considered. As observed from graph STATCOM gives better results and also gives better damping of oscillation than SVC.

Result of Voltages

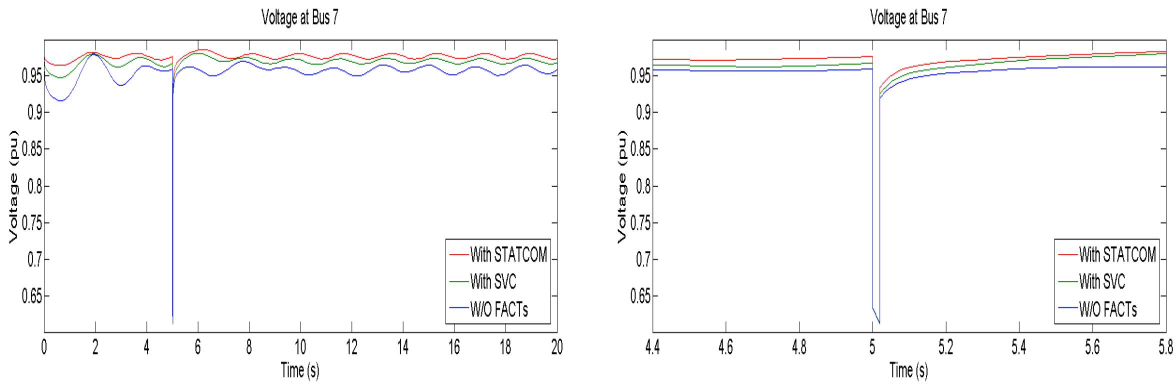


Figure 4.7: Voltage at Bus 7

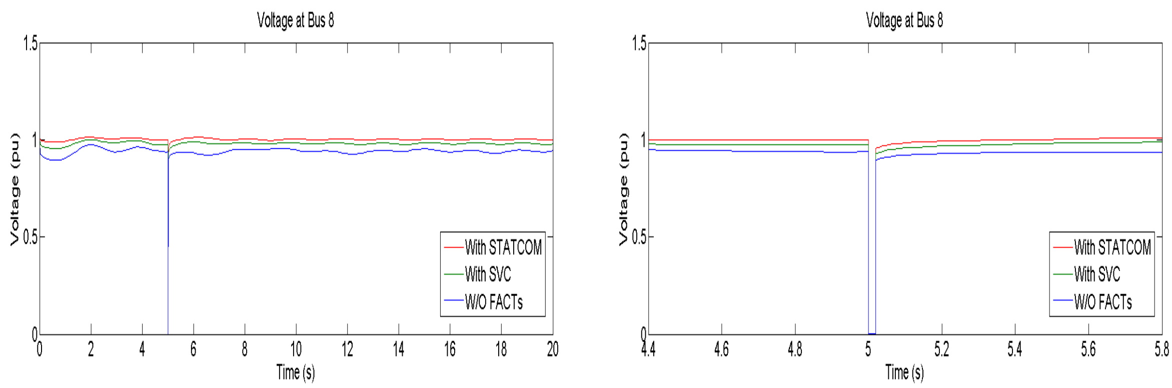


Figure 4.8: Voltage at Bus 8

Figure 4.7 and 4.8 shows the graph of voltage at bus 7 and 8 respectively under different condition. Fault was created at bus 8 while DFIG is connected at bus 7. During fault condition there is voltage drop, 0.95 to 0.65 at bus 7. The voltage drop reduces when FACTS device is connected. STATCOM gives better result and reduction in oscillations.

Rotor Speed

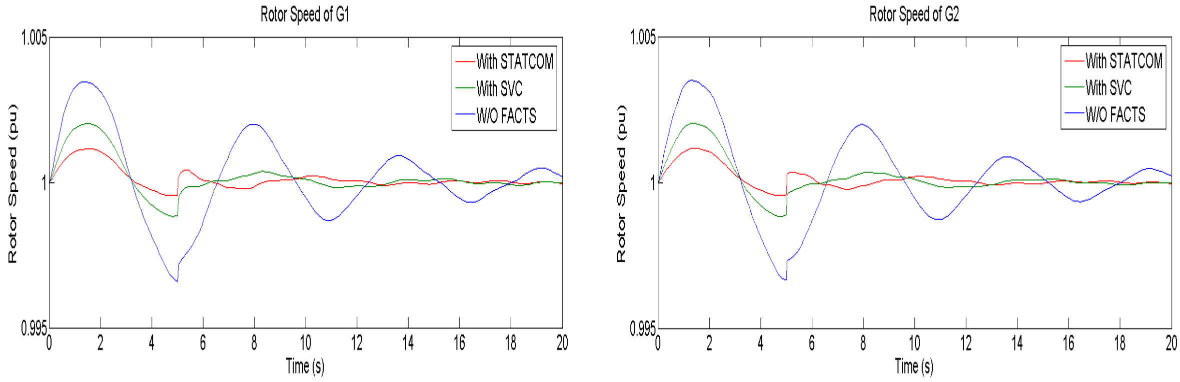


Figure 4.9: Rotor speed of Generator 1 and 2

Figure 4.9 and 4.10 shows the graph of rotor speed of generator 1 and generator 2. There is oscillation in normal condition when FACTS device is not connected. After connecting FACTS device there is reduction in oscillation. When STATCOM is connected in the system, during fault time, change in rotor speed is negligible as compared with system including SVC.

Rotor-angle difference

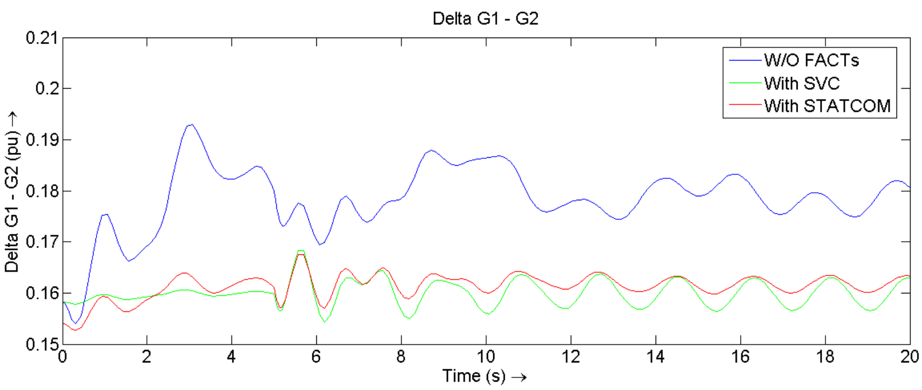


Figure 4.10: Rotor-angle difference G1 and G2

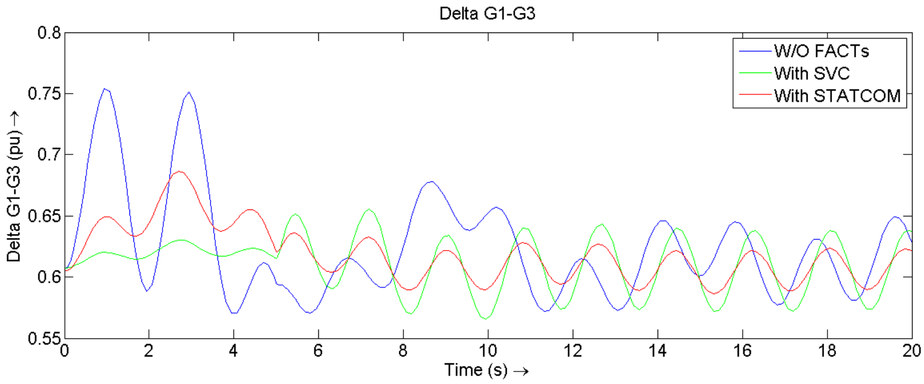


Figure 4.11: Rotor-angle difference G1 and G3

Figure 4.11 and 4.12 shows graph of rotor angle difference between Generator 1 and 2, Generator 1 and 3 respectively. Figure 4.11 depicts inter oscillation in generator 1 and 2, which reduces significantly by using FACTS device. STATCOM gives us minimum oscillation when connected to the system. Figure 4.12 depicts Inter-area oscillation in generator 1 and 3, which reduces significantly by using FACTS device. STATCOM gives us minimum oscillation when connected to the system.

It can be observed, that when disturbance occurs in the system the electromechanical osccilations are produced in the system, so to damp out the osccilations, FACTS device are used. STATCOM has given better results as compared to SVC. Oscillations can be damped significantly by using FACTS device with POD controller. In the next case, STATCOM device with POD controller is used for the same system.

4.2.2 Case 2: When STATCOM with PODC connected in system

In this case for the further damping of oscillation the POD controller is used in STATCOM, the STATCOM is connected at which the fault has been created.
The POD gain (Kw) is selected based on the root-locus. For a gain of 0.5, the 6.65% damping ratio becomes 18%. Therefore, this gain value results in acceptable damping ratio.

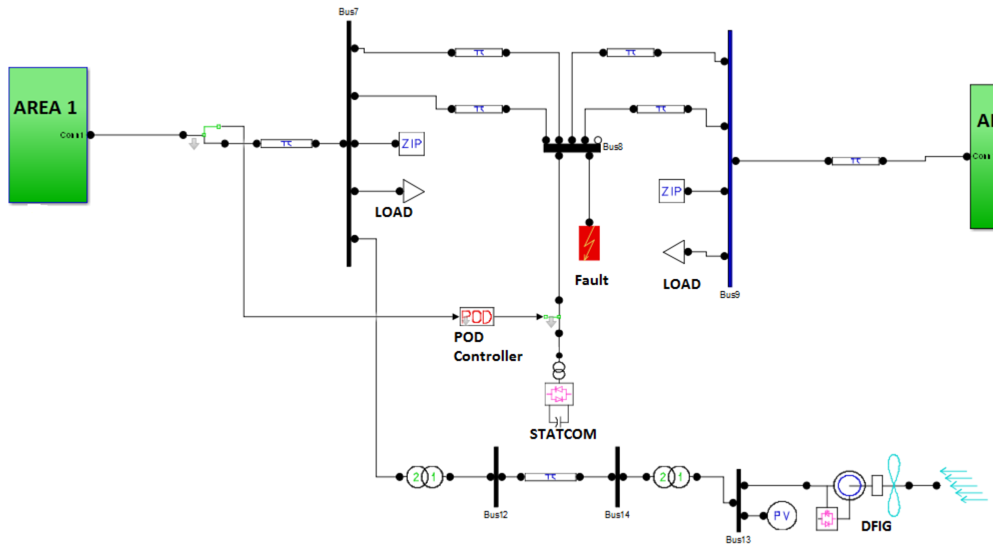


Figure 4.12: Two-area test system with DFIG connected to Area 1

Result of Active Power

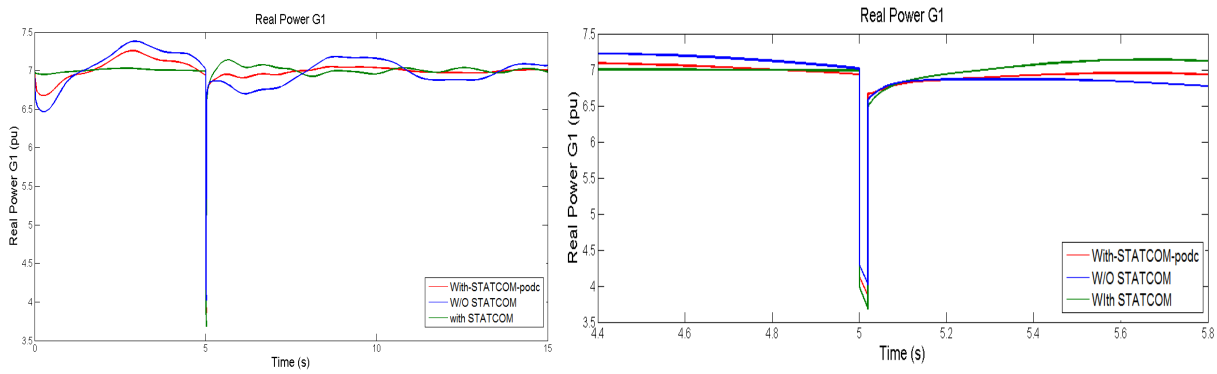


Figure 4.13: Active power of Generator 1

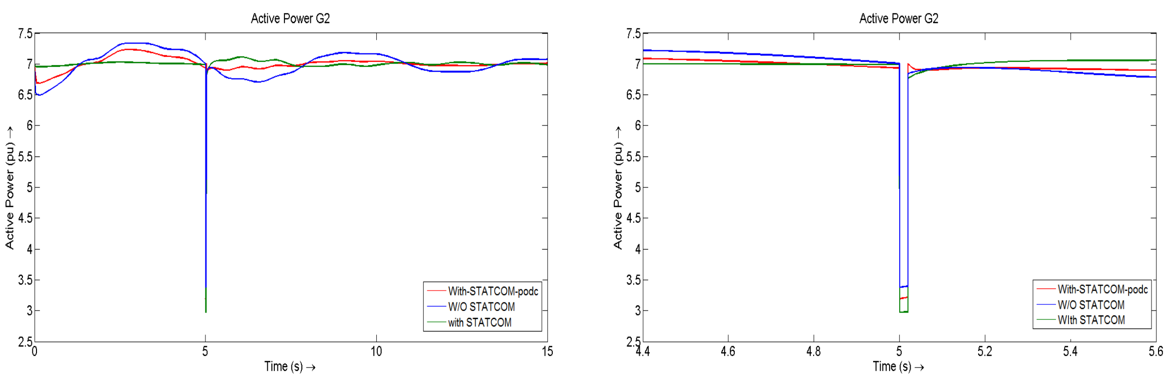


Figure 4.14: Active power of Generator 2

Figure 4.13 and 4.14 shows the graph of active power of generator 1 and 2 respectively. At the fault time the power drops, but there is change in waveform when the STATCOM and STATCOM with PODC connected in system. With the STATCOM with PODC devices result is more stable. Comparison between STATCOM and with PODC, the STATCOM with PODC is gives better results ie more damped waveform.

Result of Reactive Power

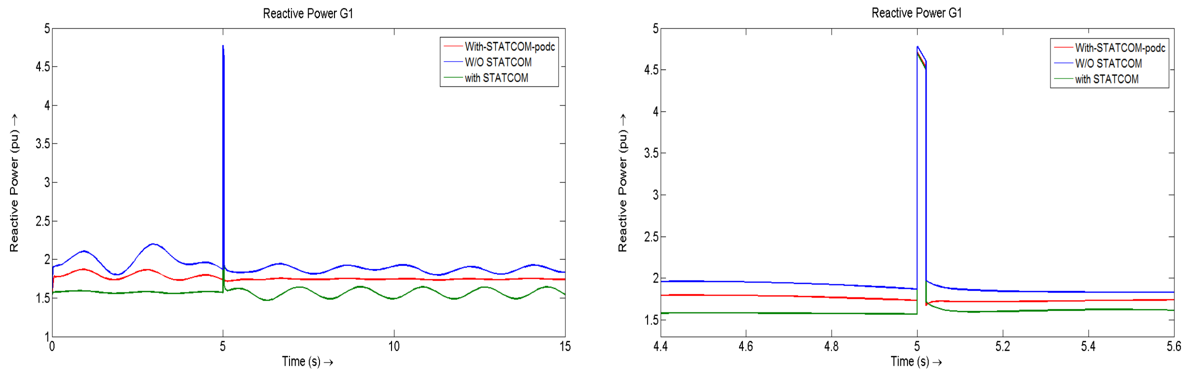


Figure 4.15: Reactive power of Generator 1

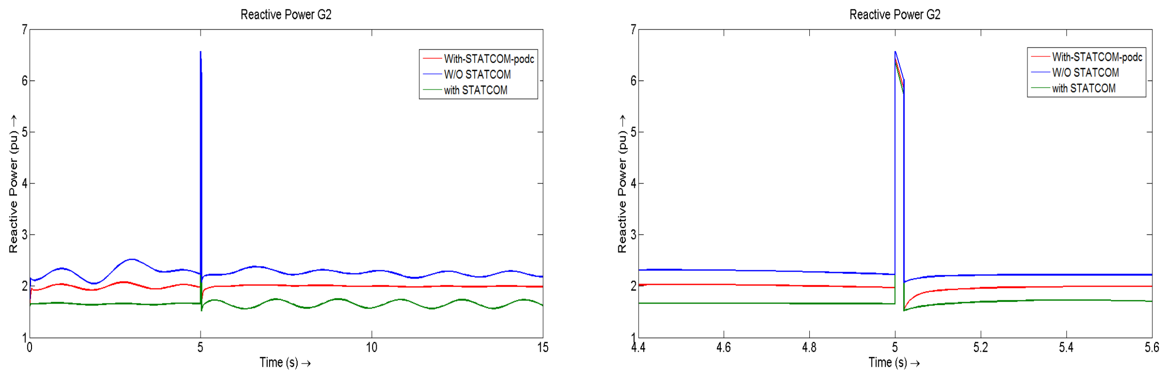


Figure 4.16: Reactive power of Generator 2

Figure 4.15 and 4.16 shows the graph of reactive power of generator 1 and generator 2. At fault time DFIG doesn't give the reactive power support required, Hence FACTs device is required. As shown in the graph, two conditions are used, STATCOM and STATCOM with PODC. STATCOM with PODC gives better results and also gives better damping of oscillation than without POD controller.

Result of Voltages

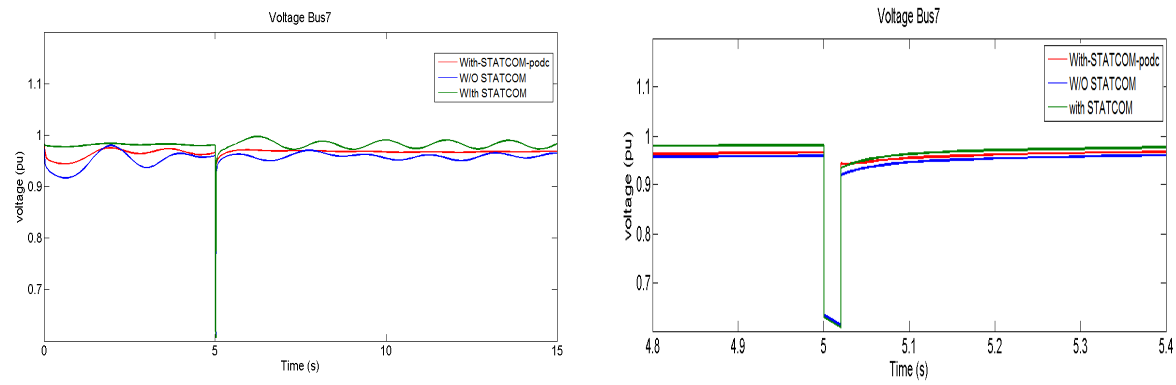


Figure 4.17: Voltage at Bus 7

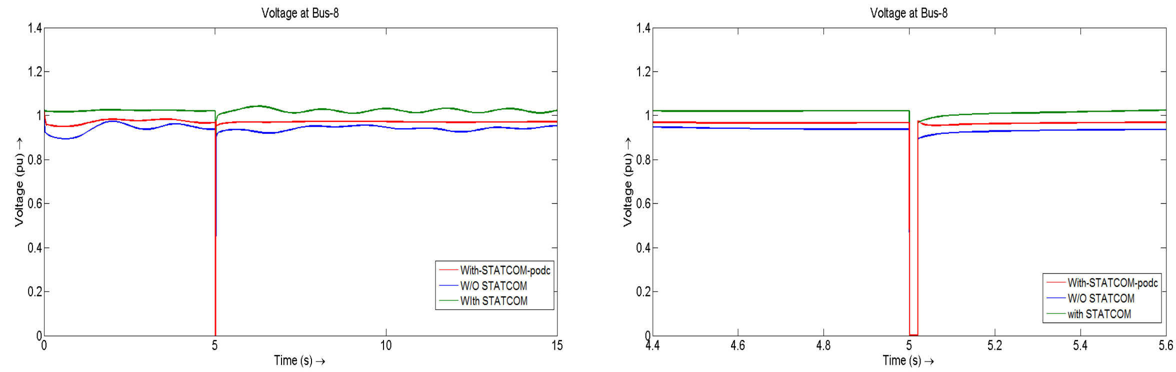


Figure 4.18: Voltage at Bus 8

Figure 4.17 and 4.18 shows the graph of voltage at bus 7 and 8 respectively. Fault was created at bus 8 while DFIG is connected at bus 7. During fault condition there is voltage drop, 0.95 to 0.65 at bus 7. The voltage drop reduces when STATCOM device is connected. And STATCOM with PODC gives better result and reduction in oscillations.

Rotor Speed

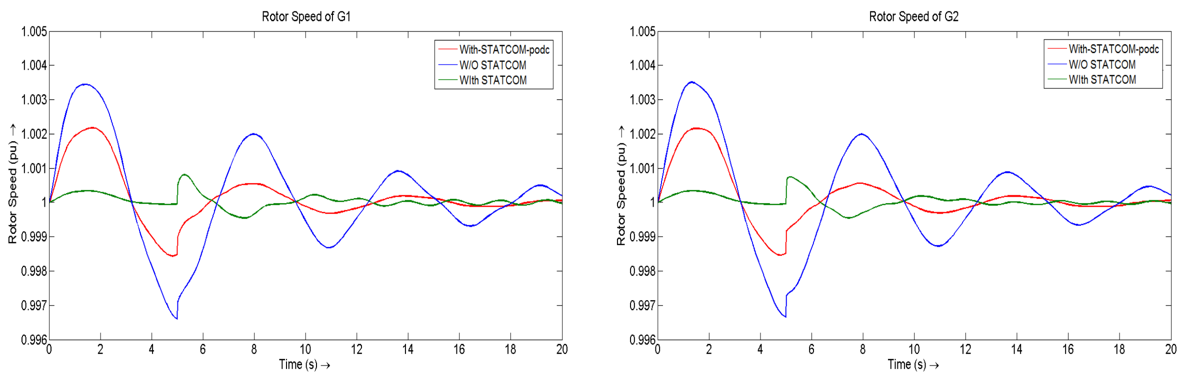
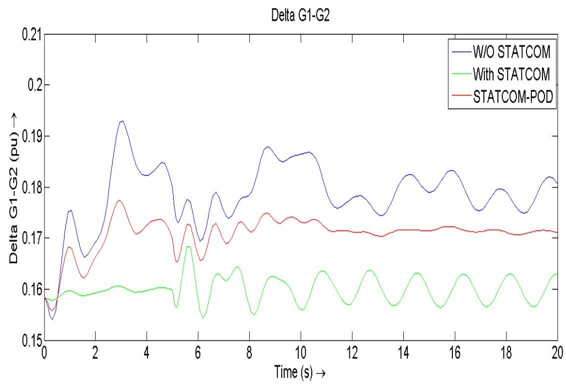


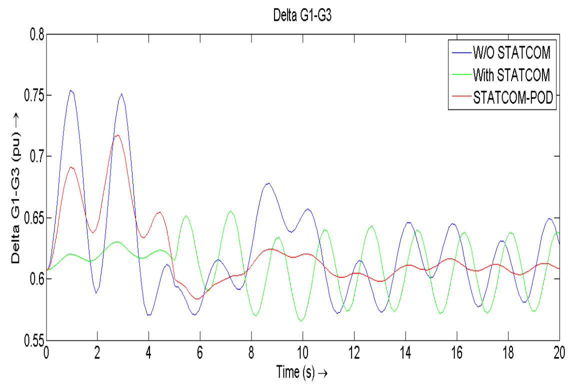
Figure 4.19: Rotor Speed of Generator 1 and 2

Figure 4.19 shows the graph of rotor speed of generator 1 and generator 2. There is an oscillation in normal condition when STATCOM device is not connected. After connecting FACTs device there is reduction in oscillation. When STATCOM with PODC is connected in the system, during fault time,change in rotor speed is negligible as compared to without PODC connected in STATCOM.

Rotor-angle difference



(a) Rotor-angle difference G1 and G2



(b) Rotor-angle difference G1 and G3

Figure 4.20a and 4.20b shows graph of rotor angle difference between Generator 1 and 2, Generator 1 and 3 respectively. Figure 4.20a depicts inter oscillation in generator 1 and 2, which reduces significantly by using STATCOM with PODC device. STATCOM with PODC gives us minimum oscillation when connected to the system. Figure 4.20b depicts inter-area oscillation in generator 1 and 3, which reduces significantly by using POD controller. STATCOM with POD gives us minimum oscillation when connected to the system.

The simulation is performed using the MATLAB control system toolbox. The responses of the system with and without PODC is compared as shown in above wave form. It is depicted from above wave form that the PODC improves the dynamic performance of the system through increasing the system damping, and decreasing the settling time.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

The stability improvement of an integrated wind farm fed to a two-area power system using a STATCOM. The STATCOM is proposed to connect to the bus 8 and the integrated wind farm is connected to Area 1 of the two-area power system. To supply the adequate reactive power to the system, a lead-lag type of PODC for the STATCOM has been designed by using the phase-compensation method to improve the inter-area oscillation mode of the studied two-area power system. Comparative dynamic and transient simulations of the studied system subjected to wind farms and a three-phase short-circuit fault at the bus have been systematically performed to demonstrate the effectiveness of the proposed STATCOM joined with the designed PODC on suppressing the inter-area oscillations of the studied system, respectively. It can be concluded from the simulation results that the proposed STATCOM joined with the designed PODC is capable of improving the damping characteristics of the studied two-area power system connected with the wind farms.

5.2 Future Scope

To damp the oscillations of Two area model with DFIG connected wind farm by using STATCOM with POD. This control strategy can be further implemented on larger test systems. Also variable wind speed can be considered. A hybrid of two different wind generators can be used.

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