MODELING AND RESONANCE ISSUES OF WIND FARM INTEGRATION WITH RELATED FACTS APPLICATIONS

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by

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ABSTRACT

This thesis deals with electromechanical oscillations, torsional oscillations and resonance issues in power systems fed by conventional steam-turbine generators and emerging wind turbine generators. Solutions to several of these problems are proposed using Flexible AC Transmission Systems (FACTS) Controllers. Inter-area oscillations are investigated in the IEEE 39 bus system and are damped by a novel Static VAR Compensator (SVC) control signal utilizing a weighted sum of remote generator speeds derived from bus voltage angles. The weights are calculated from participation factor analysis using commercial software Dynamic Security Assessment (DSA) Power Tools and are validated by EMTDC/PSCAD simulations. Subsynchronous resonance (SSR) in steam-turbine generators has been traditionally damped with SVC using either local signals or signals derived from a combination of local signals. This thesis proposes a novel SVC controller based on remote generator speed for alleviating SSR. This controller is shown from EMTDC/PSCAD simulations to be much more effective than the previously reported controllers for the IEEE First SSR Benchmark system. The efficacy is demonstrated for all the four critical series compensation levels.

With the worldwide growth of renewable energy, large wind farms are likely to be connected to series compensated networks for evacuation of bulk power. This may lead to the potential of SSR in the wind turbine generators. For the first time, a detailed electromagnetic transient study using EMTDC/PSCAD has been conducted in this thesis to demonstrate that subsynchronous resonance can be a cause of concern in series compensated wind farms at realistic levels of power flow and series compensation levels. Novel controllers for two FACTS devices - a Static VAR Compensator (SVC) and a Thyristor Controlled Series Capacitor (TCSC) - are proposed to mitigate SSR under all realistic compensation levels in a modified IEEE First Benchmark system. It is further shown that the performance of the TCSC is superior to SVC for damping SSR. These two FACTS devices are primarily employed for achieving other objectives, such as, power transfer improvement and are simultaneously utilized for damping SSR.
This thesis also examines for the first time the potential for overvoltages due to ferroresonance and self-excitation while connecting large wind farms to EHV lines. A detailed analysis of the factors influencing self-excitation and ferroresonance has been performed. The impacts of different generator models on the overvoltage issues are examined. Different measures of alleviating these overvoltages are proposed which include line differential protection and wind turbine generator excitation system control. This study has been conducted using EMTDC/PSCAD for an upcoming large wind farm in Ontario.

In an effort to validate a doubly fed induction generator (DFIG) model an additional study has been done to validate the DFIG model available in PSS/E from an extensive field validation study of Hydro One Network Inc.

Keywords: Power system stability, Transient stability, Inter-area oscillations, Remote Signals, Wide Area Measurement (WAM), Subsynchronous Resonance (SSR), Flexible AC Transmission Systems (FACTS), Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), Wind Farm, Wind Energy Conversion Systems (WECS), Wind Power Systems (WPS), Wind Turbine Generator (WTG), Self-excited induction generator (SEIG), Doubly Fed Induction Generator (DFIG), Ferroresonance, Self-excitation.
CO-AUTHORSHIP

Journal articles written from this thesis work are listed below. The individual contributions of all members are listed below.

CHAPTER 2

Article Title: Damping of Inter-Area Oscillation in Power Systems by Static Var Compensator (SVC) Using PMU Acquired Remote Bus Voltage Angles


This work is extensively supervised by Dr. R. K. Varma. All simulations pertaining to this paper in EMTDC/PSCAD and DSA Power Tools are conducted jointly by Soubhik Auddy and Dr. R. P. Gupta. The manuscript is written and all the plots and figures are primarily drawn by Soubhik Auddy and corrected by Dr. R. K. Varma. Reviewers’ comments are addressed by Soubhik Auddy and various formatting requirements needed to make the paper ready to print in the journal are also taken care of by Soubhik Auddy.

CHAPTER 3

Article Title: Mitigation of Subsynchronous Resonance by SVC using PMU-Acquired Remote Generator Speed

Status: A part of this work is published in Proc. of IEEE Power India Conference, New Delhi, India, April, 10–12, 2006. The entire contribution is to be submitted in IEEE Transactions in Power Delivery with a few more additional results.
This work is rigorously supervised by Dr. R. K. Varma. All the simulations in EMTDC/PSCAD and MATLAB are performed by Soubhik Auddy. The manuscript is written by Soubhik Auddy and corrected by Dr. R. K. Varma.

CHAPTER 4

Article Title: Mitigation of Subsynchronous Resonance in a Series Compensated Wind Farm using FACTS Controllers

Status: Accepted for publication in IEEE Transactions in Power Delivery, 2007

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CHAPTER 5

Article Title: Overvoltages at the Point of Interconnection of a Large Wind Farm and Extra High Voltage Double Circuit Transmission Lines

Status: The central issue of this work and a few key results are published in Proc. of CIGRÉ Canada Conference, Calgary, Alberta, August 26th-28th, 2007. Several major results with extensive simulations are to be submitted in IEEE Transactions in Power Systems.

This work is chiefly supervised by Dr. R. K. Varma and supported Dr. Michael Dang of Hydro One Network Inc. All the simulations in EMTDC/PSCAD and MATLAB are performed by Soubhik Auddy. The manuscript is written by Soubhik Auddy and corrected by Dr. R. K. Varma.
APPENDIX A

Article Title: Field Validation of a Doubly Fed Induction Generator (DFIG) Model and System Performance Improvement


This work is supervised by Dr. R. K. Varma and supported by Dr. Michael Dang of Hydro One Network Inc. All the simulations in EMTDC/PSCAD and MATLAB are performed by Soubhik Auddy. The manuscript is written by Soubhik Auddy and corrected by Dr. R. K. Varma and Dr. Michael Dang.
Dedicated to my

Parents
ACKNOWLEDGEMENTS

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Soubhik Auddy
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<tr>
<td>PSDC</td>
<td>Power Swing Damping Controller</td>
</tr>
<tr>
<td>WAM</td>
<td>Wide Area Measurement</td>
</tr>
<tr>
<td>PMU</td>
<td>Phasor Measurement Unit</td>
</tr>
<tr>
<td>SSR</td>
<td>Subsynchronous Resonance</td>
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<td>IG</td>
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<td>Wind Energy Conversion System</td>
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<td>WPS</td>
<td>Wind Power System</td>
</tr>
<tr>
<td>SEIG</td>
<td>Self-excited Induction Generator</td>
</tr>
<tr>
<td><strong>DFIG</strong></td>
<td>Doubly Fed Induction Generator</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td><strong>PSS/E</strong></td>
<td>Power System Simulator for Engineering</td>
</tr>
<tr>
<td><strong>EMTDC</strong></td>
<td>Electromagnetic Transients including DC</td>
</tr>
<tr>
<td><strong>PSCAD</strong></td>
<td>Power System CAD or Computer Aided Design</td>
</tr>
<tr>
<td><strong>EMTP</strong></td>
<td>Electromagnetic Transient Program</td>
</tr>
<tr>
<td><strong>FFT</strong></td>
<td>Fast Fourier Transform</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

The electric power system is highly nonlinear and time varying in nature. The operating conditions as well as the system configurations of a power system are changing at every instant. As a result the problems associated with such a system are diverse. Some of the problems in a power system employing multiple machines are inter-area oscillations, various network resonances such as subsynchronous resonance, ferroresonance, issues related to integration of wind farms, modeling and validation of emerging distributed generators, etc. This thesis deals with some of these power system problems and proposes respective solutions for them. A major portion of the proposed remedies use the application of a class of emerging high power electronic devices called Flexible AC Transmission System (FACTS) Controllers. In the following sections, these issues are independently addressed. Subsequently, the general FACTS devices are described along with their application in resolving the problems concerned. After that the motivation behind this work and the objectives of the thesis are presented in a concise manner. Finally a chapter-wise summary is provided for easy reference.

1.1 Inter-area Oscillations

A balance between the power supply and load demand is the basic requirement of a power grid. As the supply becomes limited and existing transmission networks become increasingly stressed the reserve margins tend to become lower. The consequent decreasing system stability is a serious concern for power engineers.

Electro-mechanical oscillations between interconnected synchronous generators are the phenomena inherent to power systems. The damping of these oscillations is of
vital concern, and is a prerequisite of stable system operation. These oscillations can be associated with a single generator, or a very closely connected group of units of a generating plant. Some unstable oscillations are also observed when large systems are connected through relatively weak tie lines. These electro-mechanical oscillations are of low frequency in nature and can be of various characteristics. Oscillations associated with a single generator or single plant are called local modes or plant modes. Similarly, oscillations between the rotors of a few generators close to each other are called inter-machine or inter-plant modes. On the other hand, oscillations involving groups of generators, or generating plants, on one side of the tie line oscillating against the groups of generators on the other side of the tie line are called inter-area modes or inter-area oscillations [1-6].

The typical frequency range of local modes or inter-machine modes is 0.7 to 2 Hz. On the other hand inter-area oscillations usually have two distinct ranges. One is in very low frequency range of 0.1-0.3 Hz essentially between two large areas each of which has a large number of generators. The other is in a slightly higher frequency range of 0.4-0.7 Hz involving sub-group of generators swinging against each other [6]. Out of these various types, inter-area modes are of main interest to this thesis and hence elaborated further.

To explain the phenomena of inter-area oscillations pictorially, a simple two-area system is considered in Fig 1.1. An “area” means a geographical boundary in which all the generators are tightly coupled and oscillate together. They can thus be modeled as a large equivalent machine. The system consists of four identical generators, two of which form one area. These two areas are connected through two weak tie lines, which are two transmission lines with high impedance. In this scenario, it is observed that if power is transferred from Area 1 to Area 2 or vice versa, generators of Area 1 may oscillate with respect to generators of Area 2. That means the rotors of \( G_1, G_2 \) may oscillate with respect to the rotors of \( G_3, G_4 \). These oscillations are reflected in the power transmitted through the tie line (since the power is a function of generator rotor angles) and are known as inter-area oscillations.
The question is what is the harm if generators of Area 1 oscillate against the generators of Area 2? The answer to this question comes from Fig 1.2. In this figure the same two-area system is depicted but this time there is a momentary fault F at the weak transmission line 2. After the removal of the fault the system becomes unstable if no measure is taken to damp those inter area oscillations which existed before. The instability will be in the sense that the oscillations in the power flow will grow in magnitude with respect to time and the generators will eventually fail to maintain synchronism with the grid.

The mathematical significance of inter area oscillations is the presence of a poorly damped system mode (eigen value of the system model linearized around a particular equilibrium point).

When a disturbance or a fault occurs in the system, this poorly damped mode gets excited and eventually becomes unstable (the corresponding eigenvalue moves to the right half of the s-plane). This is the reason of instability of the entire system.
1.2 Subsynchronous Resonance (SSR)

The Subsynchronous Resonance (SSR) phenomenon is usually associated with a synchronous machine connected to series compensated transmission network. The definition of SSR by IEEE SSR task force [7, 8] is: "Subsynchronous resonance is an electric power system condition where the electric network exchanges energy with the turbine-generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system".

The SSR phenomenon is known to manifest in two different forms [7-11]:

1. Self-excited or steady state SSR resulting from the following mechanisms:
   - Induction generator effects
   - Torsional interaction

2. Transient SSR

To understand these different aspects a simple radial system is considered. This system consists of a synchronous generator connected to an infinite bus through a series compensated transmission line as shown in Fig. 1.3.

![Fig. 1.3 Turbine generator feeding infinite bus through series compensated transmission line](image-url)
The series resonant frequency $f_e$ of the electrical network is given by:

$$f_e = f_0 \sqrt{\frac{X_c}{X_e}} = f_0 \sqrt{\frac{X_c}{X_e + X_s}} = \frac{f_0}{\sqrt{\frac{X_e + X_s}{kX_e}}} = \frac{f_0}{\sqrt{\frac{1 + \frac{X_s}{kX_e}}{kX_e}}}$$

(1.1)

Where

- $X_s$ = Reactance of the generator and transformer (pu)
- $X_e$ = Line reactance (pu)
- $X_c$ = Reactance of the series capacitor (pu)
- $X_e + X_s$ = Total reactance of the system
- $k = \text{Degree of series compensation} = \frac{X_c}{X_e}$
- $f_0 = \text{Nominal system frequency in Hz}$
- $f_e < f_0$ since $k < 1$

### 1.2.1 Steady State SSR

Electrical subsynchronous currents of frequency $f_e$ flowing in the armature induce subsynchronous torques and currents in the rotor circuit having frequencies $f_r$ given as:

$$f_r = f_0 - f_e$$

(1.2)

These rotor currents result in subsynchronous armature voltage components which may enhance subsynchronous armature currents to produce self excitation or steady state SSR. Self-excitation can be divided into two categories, one involving electrical system dynamics alone and the other involving both the electrical system and mechanical system (turbine-generator) dynamics.

#### 1.2.1.1 Induction Generator Effect

The induction generator effect relates only to the electrical system dynamics. This
results from the apparent negative resistance characteristic of generators at frequencies below the system synchronous frequency. At the system resonant frequency $f_e$, if this apparent negative resistance exceeds the sum of the armature and network resistances, the subsynchronous armature currents may be negatively damped.

### 1.2.1.2 Torsional Interaction

This form of self-excitation involves both the electrical and mechanical system dynamics. Torsional interaction problems may occur when the electrical resonant frequency $f_e$ is near the complement of a torsional resonant frequency $f_t$ of the turbine generator shaft system. In this context, the word complement implies the difference between synchronous frequency and the torsional natural frequency. Under these conditions, a small voltage induced in the generator armature by rotor oscillations can result in large subsynchronous current. When the net circuit resistance is positive, this current will produce a rotor torque which is phased to sustain or enhance the rotor oscillations. If the component of subsynchronous torque in phase with the rotor velocity deviation equals or exceeds the inherent damping torque of the rotating system, the coupled electromechanical system will experience growing oscillations.

It is emphasized that the induction generator effect and torsional interaction are not mutually exclusive but will co-exist. It is only due to ease in analysis they are treated separately.

### 1.2.2 Transient SSR

Transient SSR generally refers to transient torques on segments of the T-G shaft resulting from subsynchronous oscillating currents in the network caused by faults or switching operations. This usually occurs when the complement of the electrical network resonant frequency gets closely aligned with one of the torsional natural frequencies. Although, these transient torques decay with time their magnitudes are large and have the potential to cause serious damage to the T-G unit.
In fact, even if torques such as those produced by the steady state subsynchronous currents may be limited in magnitude and result in stresses within the elastic limit, failure of a shaft can be caused due to cyclic fatigue stress which is cumulative.

The phenomena of subsynchronous oscillations (SSO) are not restricted to series compensated system alone [7]. Subsynchronous oscillations have been reported to result on adverse interaction between the turbine torsional system and HVDC control, dc converter loads and power system stabilizers. Even the SSR can be created with shunt capacitor compensated system if it is attempted to operate a long distance transmission system at a power angle in excess of 180°.

1.2.3 Mitigation of SSR

SSR has been studied in depth and a number of counter measures to damp SSR have been devised by the utilities [9, 11]. The solution to SSR problems is classified in following categories:

- Filtering and damping
- Relaying and protective devices
- System switching and generator tripping
- Generator and system modifications

Injection of properly phased sinusoidal signal from rotor motion in the excitation regulator to damp out the modes to which turbine generator shaft unit is vulnerable, NGH-SSR damping scheme, extraction of the subsynchronous components from the transmission line currents and cancellation of the original subsynchronous currents which would otherwise cause SSR by this extracted current are some of the widely used SSR counter measures by electric utility. FACTS devices have also been successfully used to damp SSR which will be separately discussed in a subsequent section.
1.3 Ferroresonance and Self-excitation

The research involving ferroresonance in transformers dates back to as early as 1907 [12, 13]. In simple terms, ferroresonance is a series resonance involving a capacitor and a nonlinear inductor as shown in Fig.1.4.

Nonlinear inductor exhibits a nonlinear voltage versus current characteristic and hence has a variable reactance. Ferroresonance typically involves the saturable magnetizing inductance, which is a good example of nonlinear inductor, of a transformer and a capacitive distribution cable or transmission line connected to the transformer. When an unloaded or a lightly loaded transformer is energized, the inrush currents have instantaneous values that are much larger compared to the transformer rated current.

\[
\begin{align*}
\text{Fig. 1.4 Typical ferroresonance circuit with its characteristic frequency}
\end{align*}
\]

The worst case is encountered when the transformer is energized at the instant of the ac voltage reaching at its zero point on the voltage wave. As the voltage increases, the flux rises during the first half-cycle to a high value, creating high saturation of the transformer core. This results in the flow of excessively high values of exciting current. This high current persists for a few cycles and then gradually reduces to the normal low value of excitation current. If the transformer is fed from a series capacitor in the circuit, the high current may continue to flow. The series capacitor acts as an additional voltage source. A temporary or a permanent resonant condition might occur. Ferroresonance is different from the resonance in linear RLC circuit. In
linear systems, resonance results in high sinusoidal voltages and currents of the resonant frequency. Ferroresonance can also result in high voltages and currents, but the waveforms are usually irregular in shape. In fact, any operating mode which results in a significantly distorted transformer voltage and current waveform is typically referred to as ferroresonance. Higher order odd harmonics are the characteristic of the waveforms, whose shapes might be conceptually explained in terms of the effective natural frequency $f_M$ as $L_{LM}$ goes in and out of saturation. It is to be noted that although the ferroresonant frequency is attempted to be characterized with $f_M$ there is no definite resonant frequency, more than one response is possible for the same set of parameters, and gradual drifts or transients may cause the response to jump from one steady state response to another.

The following situations lead to ferroresonance [14, 15]:

1. Manual switching of an unloaded, cable-fed, three-phase transformer where only one phase is closed. Ferroresonance may be observed when the first phase is closed upon energization or before the last phase is opened on de-energization.
2. Switching of lightly loaded or unloaded transformers. Power transformers energized in only one or two phases.
3. Lightly loaded power transformers energized by a series compensated line.
4. Very long underground cable circuits.
5. Low-loss transformers
7. Voltage transformers energized through grading capacitors of open circuit breakers.
8. Voltage transformers connected to an isolated or resonant neutral system (distribution networks).

Self-excitation phenomenon in induction motors has been well-known since the 1930s [16]. When an induction machine is disconnected from the supply, and driven
by a mechanical source, terminal voltage builds up if its lagging VAR demand is supplied externally, and sufficient residual magnetism is present in the rotor core. This is known as self-excitation phenomenon. Shunt compensation capacitors are the most common VAR supplies for induction motors, which may result in self-excitation. The use of an induction machine as an autonomous generator has been extensively investigated by several researchers, especially for wind power generation [17]-[22]. Recommended practices for power-factor improvement of induction motors supplied from the utility grid are given in various standards and handbooks in detail [23], [24]. Since the motor reactive power does not change too much from no-load to full load, fixed shunt capacitors can be installed in different configurations for power-factor improvement. Among these, the use of capacitors directly connected to motor terminals is the cheapest and the simplest solution to this problem. Maximum capacitor rating should not be in excess of 100% and 90% of no-load reactive power consumption of the motor as recommended in [23] and [24], respectively. A capacitance higher than the recommended values leads to overvoltages at the motor terminals owing to self-excitation, when the motor is disconnected from the utility grid. Even though the capacitor ratings are chosen according to recommended practice, they may lead to self-excitation of the motor in some cases.

1.4 Integration of Wind Power Systems

1.4.1 Global Status of Wind Energy

Utilization of renewable energy as a means of environment friendly electric power generation is the current trend. Out of various renewable sources of energy such as solar, tidal, biogas etc, wind power systems is one of the fastest growing technologies of producing electricity. Global Wind Energy Council (GWEC) [25] announced 2006 to be another year of record increase in wind generation integration all over the globe. Wind energy developments in more than 70 countries around the world show that the year 2006 experienced the installation of additional 15,197 MW, taking the total installed wind energy capacity to 74,223 MW, from the previous 59,091 MW in 2005. The growth in total installed capacity of the wind power all over the world from 1995 to 2006 is shown in Fig. 1.5.
The countries with the highest total installed capacity are Germany (20,621 MW), Spain (11,615 MW), the USA (11,603 MW), India (6,270 MW) and Denmark (3,136). Thirteen countries around the world can now be counted among those with over 1000 MW of wind capacity, with France and Canada reaching this threshold in 2006 [25].

In terms of new installed capacity in 2006, the US continued to lead with 2,454 MW, followed by Germany (2,233 MW), India (1,840 MW), Spain (1,587 MW), China (1,347 MW) and France (810 MW) [25].

Despite the continuing growth in Europe, the general trend shows that the sector is gradually becoming less reliant on a few key markets, and other regions are starting to catch up with Europe. For example, Asia has experienced the strongest increase in installed capacity outside of Europe, with an addition of 3,679 MW, taking the continent over 10,600 MW. In 2006, the continent grew by 53% and accounted for 24% of new installations. The strongest market here remains India with over 1,840 MW of new installed capacity, which takes its total figure up to 6,270 MW. China
more than doubled its total installed capacity by installing 1,347 MW of wind energy in 2006, a 70% increase from last year’s figure. This brings China up to 2,604 MW of capacity, making it the sixth largest market world wide.

1.4.2 Wind Energy in Canada

The installed capacity in Canada till December, 2006 is 1451 MW [26]. As of now, total installed capacity of the wind farms in Canadian provinces has reached 1587 MW out of a proposed target of 2767 MW. Wind power penetration is expected to grow to around 7500 MW by 2012, representing 3.5% of Canada’s total generation mix.

The average annual growth rate in wind power penetration is 38% from year 2000 to 2005. This growth rate is accelerating and has reached 54% in 2005. In 2006, the installed capacity of wind power exceeded 600 MW. The total installed capacity of the country from 2000 to 2006 is shown in Fig. 1.6.

![Fig. 1.6 Total installed capacity of wind power in Canada](Source: CANWEA) [25]
In Ontario, between 2009 and December 2011, there would be an expected additional connection of 1,175 MW projects. Currently Hydro One Network Inc (HONI) of Ontario has three large wind farms in service. They are 39.6 MW EPCOR Kingsbridge Wind Farm near Goderich substation consisting of 22 VESTAS V80 1.8 MW wound rotor induction type wind turbine generators (WRIG), 99 MW AIM Erie Shore Wind Farm at Port Burwell Substation comprising 66 GE 1.5 MW doubly-fed induction type wind turbine generators (DFIG) and 67 MW Canadian Hydro Melanchton Wind Farm having 45 GE 1.5 MW doubly-fed induction type wind turbine generators (DFIG).

1.4.3 Wind Turbine Generator (WTG) Configurations

A wind farm usually comprises a group of identical wind turbine generators from a particular vendor. These wind turbine generators can be equipped with different types of three phase generator. Today, the demand for grid compatible electric current can be met by connecting frequency converters, even if the generator supplies alternating current (AC) of variable frequency or direct current (DC). Several generic types of generators may be used in wind turbines [27]:

- Asynchronous (induction) generator:
  - Squirrel cage induction generator (SCIG);
  - Wound rotor induction generator (WRIG):
    - OptiSlip induction generator (OSIG)
    - Doubly fed induction generator (DFIG)

- Synchronous generator:
  - Wound rotor synchronous generator (WRSG)
  - Permanent magnet synchronous generator (PMSG)

- Other generator types of potential interest:
  - High voltage generator (HVG);
  - Switch reluctance generator (SRG);
  - Transverse flux generator (TFG)
Out of these various configurations three widely used wind turbine generator configurations are described below. They are squirrel cage or self-excited induction generator (SEIG/SCIG), doubly fed induction generator (DFIG) and direct drive synchronous generator [28].

1.4.3.1 Squirrel Cage or Self-Excited Induction Generator (SEIG/SCIG)

The first configuration is a grid coupled squirrel cage induction generator as shown in Fig. 1.7. This type of WTG consists of a rotor coupled to a squirrel cage induction generator through a gearbox. The gearbox is needed, because the optimal rotor and generator speed ranges are different. The generator is directly coupled to the grid. Therefore, rotor speed variations are very small as the only speed variations which can occur are due to the changes in the rotor slip. The order of magnitude of these speed changes is usually small. The speed variations of these types of generators being very small, the turbine is normally considered to operate at constant speed. A squirrel cage induction generator consumes reactive power. Therefore in case of large wind turbines connected to weak grids, capacitors are normally added at the generator terminal to provide additional reactive support which in turn improves the power factor of the system.
The power extracted from the wind needs to be limited when wind flow crosses a particular speed limit. This wind speed is referred to cut-out speed. This is important as the high wind speed would otherwise overload the machine or the pullout torque could be exceeded leading to rotor speed instability. This is achieved by using the stall effect. This requires the rotor geometry to be designed in such a way that its aerodynamic properties make the rotor efficiency decrease in high wind speeds limiting the power extracted from the wind, preventing the generator from being damaged and the rotor speed from becoming unstable. It is to be noted that during normal operation of a stall regulated wind turbine no controllers are active.

1.4.3.2 Doubly Fed Induction Generator (DFIG)

The second configuration is a wind turbine with doubly fed (wound rotor) induction generator in which a back-to-back voltage source converter feeds the rotor winding. A gearbox is also necessary in this type of WTGs to couple the rotor to the generator, because of the difference in the rotor and generator speed ranges.

The stator winding of the doubly fed induction generator is coupled to the grid; the rotor winding is coupled to a back-to-back voltage source converter. The other side of the converter that feeds the rotor winding is coupled to the grid. The converter decouples the electrical grid frequency and the mechanical rotor frequency, thus enabling variable speed operation of the wind turbine. The sum of the mechanical rotor frequency, multiplied by the number of pole pairs, and the electrical rotor frequency equals the grid frequency applied to the stator. The system is depicted in Fig. 1.8.
Fig. 1.8 Doubly fed (wound rotor) induction generator with back-to-back voltage source converter feeding the rotor winding

Normally, the converter has current control loops. The ability to control the rotor current substantially contributes to the controllability of the wind turbine, because when the stator resistance is neglected, the electromechanical torque and stator reactive power are dependent on the quadrature and direct component of the rotor current respectively. The grid side of the converter is normally operated at unity power factor, thus not taking part in the reactive power exchange between the turbine and the grid. In this mode of operation, rotor current control enables full active and reactive power control. Active power is controlled in the following manner. With a frequency of about 20 Hz, an electrical power set point is generated, on the basis of the actual rotor speed and using the rotor speed versus power control characteristic. From this, a torque set point is calculated, again taking into account the actual rotor speed. Using this torque set point and a number of other parameters, the required rotor current is calculated.

As there is a difference between the mechanical rotor frequency and the stator frequency, a three phase voltage is induced in the rotor winding. Through the converter, a three phase current with the same frequency and the calculated amplitude is fed into the rotor winding. The generator and converter are prevented from being overloaded in high wind speeds by controlling the back-to-back voltage source converter in such a way that the nominal power of generator and converter is not exceeded. However, when the wind speed increases, the mechanical power extracted
from the wind increases as well, if no countermeasures are taken. This increases the rotor speed because the mechanical power becomes higher than electrical power. To limit the rotor speed, the blades are pitched, thus reducing the mechanical power extracted from the wind and restoring the balance between mechanical power and electrical power. In this way, the rotor speed is prevented from becoming too high.

### 1.4.3.3 Direct Drive Synchronous Generator

The third important contemporary wind turbine topology is the direct drive synchronous generator. In this configuration, the rotor is directly coupled to the generator and no gearbox is needed. The system is depicted in Fig. 1.9.

![Fig. 1.9 Direct drive synchronous generator grid coupled through a back-to-back voltage source converter or a diode rectifier and voltage source converter](image)

The synchronous generator is a ring generator with a large number of poles. In view of the low mechanical frequency, it is necessary to use a ring generator to achieve an acceptable generator weight for the desired power rating. The stator winding of the direct drive synchronous generator is coupled to a voltage source converter or a diode rectifier. When a back-to-back voltage source converter is used, the generator torque is controlled by changing the stator currents through controlling the generator side converter voltage. When a diode rectifier is used, the generator torque is controlled indirectly by controlling the DC link voltage using the voltage source converter at the grid side. As the voltage source converter is self-commutated, reactive power can be generated as well as consumed by the grid side of the converter.
by injecting a leading or lagging current. Thus, the current on the grid side of the converter is controlled in such a way that the generator real power is transferred to the grid and the terminal voltage nearly equals a reference value. In short this configuration enables full active and reactive power control. In high wind speeds the generator power is again limited to protect both the generator and the converter, resulting in an unbalance between mechanical power extracted from the wind and generated electrical power. This leads to an increase in rotor speed, which needs to be limited. This is again done by pitching the blades.

1.4.4 Grid Integration Issues of Wind Farms

With the abundance of priceless wind flow in nature, an obvious question which can be raised is why more and more wind farms are not allowed to be integrated with the grid. The answer to the question is not straightforward. Unlike conventional synchronous generators wind turbine generators are not so well understood and analyzed. The integration of a wind farm with grid may have a number of impacts and issues which need to be carefully analyzed before a wind farm is allowed to be connected to the grid. Some of the important issues of wind farm integration are briefly described below.

1.4.4.1 Modeling of Wind Turbine Generators

One of the main differences between wind farms and conventional power plants is that wind farms usually employ a number of identical wind turbine generators of induction type [29]. More over, to capture the optimum power output from the wind flow these fixed speed induction generators are equipped with power electronic converters connected to both the rotor and with the grid to make them variable speed. In addition to that, other types of machines such as permanent magnet synchronous machines are also emerging with full scale stator side converters having the rated capacity of the generator itself. Accurate models of these new classes of generators in different simulation domains are still the subject of research and are not readily available in literature.
Although wind turbine generator models based on wind turbine power curve, subtransient and transient models of wind turbine generators of various configurations are discussed and reported in literature [28, 30, 31, 32], neither the validation of these models with field tests is reported nor the systematic procedure of implementing these models in electro-magnetic transient domain or in transient stability domain is publicly available. As a result the challenge of properly modeling these wind turbine generators and validation of these models with field tests still exists. Extensive research is needed to implement and validate these models in EMTDC/PSCAD or in PSS/E and to make these models available for the ready use in system studies.

1.4.4.2 Reactive Power Requirement of Wind Farm

Induction generators do not have the capability to produce reactive power without being connected to the grid. Even though the wind turbine generators are equipped with power converters to control the active and reactive power produced by them they need to remain connected to the grid to achieve this controllability. Whether there is a need to have additional fast reactive power support when these generators are subject to contingencies [31], if these generators can operate in islanded mode without having a dedicated energy source such as battery storage to keep their excitation system alive and how fast the machines can ride through the fault, are subjects of research. It has been reported that dynamic reactive support by means of shunt Flexible AC Transmission System (FACTS) devices namely Static VAR Compensators (SVC) or Static Synchronous Compensator (STATCOM) is required for a self excited induction generator to make them ride through the fault at the generator terminal. The power electronic converters at the grid side of Doubly Fed Induction Generators (DFIG) can provide reactive support during contingencies and hence do not require any FACTS devices [31]. However, even with DFIGs the question remains how far these machines can survive in the face of multiple contingencies? The current trend and IEEE standards recommend the disconnection of any distribution generator from the grid with the onset of contingencies. However, this practice has to be changed and remedial measures have to be taken to keep them operational in order to maintain electric power supply from renewable sources to the grid.
1.4.4.3 Series Compensated Wind Farm

With the growing wind power penetration, bulk power needs to be transmitted through the transmission corridors. It is well known that series compensated transmission line is an effective means of transmitting large amounts as of power over long distances. However, series compensation is known to have a detrimental effect on steam turbine driven synchronous generator which is subsynchronous resonance as mentioned in section 1.2. SSR comprises the induction generator effect, and hence when actual wind turbine driven induction generators are connected to series compensated transmission lines for evacuation of bulk power, there is a strong likelihood of SSR [32-36]. Hence the potential issue of subsynchronous resonance must be thoroughly analyzed before the interconnection of large wind farms with series compensated transmission lines.

1.4.4.4 Overvoltages Encountered by Wind Farms

Wind farms are usually integrated with a grid in two ways. One is high tension interconnection where a high voltage transmission line typically operating at 118 kV, 230 kV or in rare cases 500 kV voltage rating is tapped at a particular location through a step down transformer of voltage levels 34.5 kV or 27.6 kV and the wind turbine generators are normally connected at the low tension side of the transformer.

On the other hand, wind farms can also be connected to the grid through 44 kV or 13.8 kV distribution feeders. In this connection a distributed feeder which normally supplies the load also accommodates the wind farm.

Problem of overvoltage due to ferroresonance and self-excitation could occur in the High Voltage (HV) connection especially when the line which is tapped for the interconnection of the wind farm gets opened at its both ends. In this case, first of all the shunt line charging capacitor may now appears in series with the step down transformer and the voltage at the charging capacitance will immediately be impressed across the transformer driving it deep into saturation. If the transmission line to which the wind farm is interconnected is of double circuit configuration,
disconnection of the tapped line may lead to the strong interaction of the coupling capacitance between the two lines with the step down transformer and can cause ferroresonance. The overvoltages due to ferroresonance may then damage the wind turbine generators. To suppress this problem the ferroresonance path is normally disrupted and the wind farm is disconnected from the transformer along with the transmission line. This could further lead to self-excitation of the shunt compensated induction type wind turbine generators supplying power to the grid. The magnitude of the overvoltage also depends on the load at the generator terminal as the loads form an energy dissipation path of the isolated generators.

In the wind farm connection to the distribution feeders, the line charging capacitance is low and hence it is not likely to interact with the main step down transformer. However, the shunt compensator at the induction generator terminal may still be a candidate to self-excite the machine if the ratings of these capacitors are not properly chosen.

1.5 Flexible AC Transmission System (FACTS)

With the growing requirement of transmitting bulk power to expanding load centers over restricted right of ways, the need for optimum utilization of existing transmission facilities is being increasingly recognized. The power transfer capability of long transmission line is limited from both steady state and transient stability considerations. An inadequate level of available system damping may further aggravate the problem.

As stated in section 1.1, transfer of bulk power over long and weak tie lines from one area to another leads to under-damped, low frequency oscillations. Power transfer is restricted due to the existence of these inter-area oscillations. The inherent ability of Flexible AC Transmission System (FACTS) devices to provide rapid, continuously controllable reactive compensation in response to changing system conditions, has been shown to result in addition to many other advantages, an enhancement of these stability limits and increased system damping. However, a pure voltage or reactive power control is often not adequate for the damping of power swings in the system. A
significant contribution of system damping is achieved when auxiliary feedback is introduced in the FACTS control system. This leads to further improvement in power carrying capability of the network.

Flexible AC Transmission System (FACTS) is defined by IEEE as [37]: "Alternating current transmission systems incorporating power electronic-based and other static Controllers to enhance controllability and increase power transfer capability." FACTS devices incorporate switches and passive elements such as inductors and capacitors. The power electronic switches are Insulated Gate Bipolar Junction Transistors (IGBTs), Gate Turn Off Thyristors (GTOs) etc.

The main idea of introducing power electronic switches is to achieve the following objectives:

- Very fast switching of capacitors and inductors.
- Continuous control of reactive power.

FACTS devices are broadly classified into the following categories:

- Shunt connected devices such as: Static Var Compensator (SVC), Static Compensator (STATCOM) etc.
- Series connected devices such as Thyristor Controlled Series Capacitors (TCSC), Static Synchronous Series Compensators (SSSC)
- Composite series and shunt devices such as Unified Power Flow Controller (UPFC) etc.

Another classification of FACTS devices could be based on the power electronic implementation which is as follows:

- Thyristor based FACTS devices such as SVC, TCSC, Thyristor Controlled Phase Angle Regulator (TCPAR) etc.
- Voltage source converter based FACTS devices namely STATCOM, SSSC, UPFC, Interline Power Flow Controller (IPFC) etc.
SVCs and TCSCs are the two widely used devices in power systems worldwide. Hence main emphasis is given to these two devices in this thesis. In the following paragraph, operating principles of these two devices are described.

1.5.1 Basic Elements of SVC

The entire structure of an SVC with its full control and power circuits are shown in Fig 1.10 [38]. This is a TSC (Thyristor Switched Capacitor)-TCR (Thyristor Controlled Reactor) type SVC. It has three parts:

- Measurement components
- Control components
- Power Components

![Fig. 1.10 Basic elements of SVC and its control system](image)

The SVC is supposed to maintain the voltage at a specified voltage reference $V_{ref}$ at its HV bus. The measurement components measure the bus voltage and other control signals. It also filters these signals for the use in control system inputs. The error between the actual voltage and measured voltage is fed to the voltage regulator. The voltage regulator generates the required firing angle of the thyristor switches to be fired so as to provide the necessary reactive compensation.
The steady state and dynamic characteristics of an SVC describe the variation of SVC bus voltage with SVC current or reactive power. Two alternative representations of these characteristics are shown. Fig. 1.11(a) illustrates the terminal voltage - SVC current characteristic while Fig. 1.11(b) depicts the terminal voltage - SVC reactive power relationship. The dynamic V-I characteristics of the SVC comprise:

- A voltage reference $V_{\text{ref}}$ at the terminals of the SVC during floating condition i.e. when the SVC is neither absorbing nor generating any reactive power. The reference voltage can be varied between the maximum and minimum limits $V_{\text{ref max}}$ and $V_{\text{ref min}}$ either by the SVC control system (in case of thyristor controlled compensators) or by the taps of the coupling transformer (in the case of saturated reactor compensator).

- A linear operating range over which SVC terminal voltage varies linearly with SVC current or reactive power as the latter is varied over its entire capacitive to inductive range.

- A slope or droop of the $V$-$I$ characteristic defined as the ratio of voltage magnitude change to current magnitude change over the linear controlled range of the compensator and several other operating limits such as overload limit, over current limit etc to prevent the costly power electronic devices.

Although SVC is a Controller for voltage regulation, that is, for maintaining constant voltage at a bus, a finite slope is incorporated in the dynamic characteristic of an SVC. The slope reduces the reactive power rating of the SVC substantially for achieving nearly the same objective. It also prevents the SVC from reaching its reactive power limits too frequently. Due to this slope, sharing of reactive power is facilitated among multiple compensators operating in parallel. These are a few advantages of slope despite a slight deregulation of the bus voltage.

It is to be noted that this configuration itself does not have any capability to provide damping. This can be achieved with a separate controller named auxiliary or power swing damping controller, which modulates the bus voltage and thereby
introduces system damping. This auxiliary control is based on additional signals such as line current, bus frequency, remote generator speed etc. These auxiliary signals provide a measure of the rotor oscillations which need to be damped. The controller structure including auxiliary controller is shown in Fig. 1.12.

Fig. 1.11: (a) V-I characteristics of an SVC; (b) Q-V characteristics of an SVC

Fig. 1.12 Control structure of the SVC
1.5.2 Basic Elements of TCSC

The basic operation of the TCSC is depicted in Fig. 1.13. The entire module is connected in series with the transmission line. The model consists of a fixed capacitor in parallel with a thyristor-controlled reactor. By controlling the firing angle of the thyristors, one can get a variable inductive reactance in parallel with a fixed capacitance. As a result the entire module can offer a variable capacitive compensation to the transmission line to both control and enhance power transfer.

![Fig. 1.13 Basic elements of a TCSC and its control system](image)

The RMS capacitor voltage $V_C$, RMS capacitor current $I_C$ and RMS thyristor current $I_T$ are plotted in Fig. 1.14 (a) as a function of reactor per unit conduction. In the capacitive mode $I_C > I_T$ while in the inductive mode $I_C < I_T$. The resulting circulating current in capacitive mode causes the capacitor current, capacitor voltage and consequently the apparent capacitive reactance to increase with thyristor conduction. The corresponding variation of TCSC net reactance with per unit reactor conduction is also superimposed for comparison in Fig. 1.14 (b). The permissible range of firing angle will therefore be determined based on the voltage and current rating of the fixed capacitor. At the resonant point the TCSC exhibits very large impedance and results in a significant voltage drop. This resonant region is avoided by installing limits on the firing angle.
TCSC can be operated in a number of control modes. In this thesis only closed loop current control mode of TCSC is utilized. It is pointed out that TCSC also requires an auxiliary controller to damp power swings. However, as this series device itself is immune to subsynchronous oscillations, no additional control is considered. In Fig 1.15 a current control scheme of a TCSC is shown. Again the idea is the same as that of SVC. Instead of voltage, now the line current is measured and compared to the reference current $I_{\text{ref}}$. The error between the actual current and the measured current is fed to the PI controller, which issues the required firing angle for the TCSC. The firing pulse generator sequentially implements that angle order in the real power circuit. Additional signals such as power flow through the compensated line; bus voltage, line current etc. can also be used as the auxiliary signals for the design of damping controller for a TCSC.
1.5.3 Applications of FACTS Devices

Various types of FACTS devices are available with their individual versatility of applications. SVC and TCSC are the two major thyristor based FACTS devices which are considered in this thesis to alleviate inter-area oscillations and subsynchronous resonance. It is to be pointed out that voltage source converter (VSC) based FACTS devices such as STATCOM, SSSC, UPFC etc., can also be equally effective in these applications. However, their design and control for these purposes are beyond the scope of this thesis and hence are not discussed further.

1.5.3.1 Damping of Inter-area Oscillations

SVC and TCSC both have been successfully used to damp inter-area oscillations in power system. A vast body of literature [40-66] is available which reports the application of different linear control techniques such as pole placement, gain margin and phase margin, $H_\infty$ control, linear matrix inequality (LMI) etc to design the auxiliary controller for these FACTS devices. On the other hand, intelligent control methods based on neural network, fuzzy logic, genetic algorithm etc are also applied for the design of power swing damping controller (PSDC).

Successful design of auxiliary controllers or power swing damping controllers (PSDC) also depends substantially on the proper choice of auxiliary signal. The
auxiliary signal is the main input to the PSDC which actually modulates the bus voltage in case of shunt FACTS devices such as SVC or the line power in case of series FACTS devices such as TCSC and thereby damps the power swing. The chosen signal must contain the oscillating mode which is to be damped. In mathematical terms, the undamped mode must be controllable by the chosen auxiliary signal and also must be observable in the same signal [45].

Local signals which are readily available at the terminals of the FACTS devices have been successfully used in past to damp inter-area oscillations [43-55]. However, with the growing complexity and vastness of today's power system it is quite possible that an undamped mode has participation from rotor speeds or rotor angles of a number of generators remotely placed from the location of the installed FACTS devices. In addition, several undamped modes are likely to contribute to a power swing. In this scenario, a single controller may not be sufficient to damp all the modes. Therefore, an obvious choice is to go for multiple FACTS Controllers. Another requirement for the stable operation of a large interconnected power system network is to have an overall picture of all the generator rotor angle modes, which reflect the information of power system oscillations. After capturing this information, a coordinated control strategy may need to be implemented to stabilize the entire power system subjected to a list of credible contingencies. The control strategy should ensure a proper coordination of multiple FACTS Controllers with respect to all the sensitive system modes. To achieve such a broad picture of a system, the Wide Area Measurement (WAM) technology [68-80] is utilized. The idea is depicted in the following picture:
WAM structure works as follows:

- Phasor Measurement Units (PMUs) sample the voltage and current signals from different buses and transmission lines in a large power system.
- Sampled signals with their sampling instant are sent to Geostationary Positioned Satellite (GPS) via Communications Channels and Links.
- GPS system sends the samples to the Control Centre. In Control Centre, the current and voltage phasors are computed. The phasor information is sent to auxiliary controller of the FACTS devices installed in actual power system for damping control.

Wide Area Measurement based remote signals are demonstrated to damp inter-area oscillations of a very large power system having several undamped low frequency modes [67]. In several cases, dedicated optical fibers are utilized for transmitting the control signal from remote generators to the FACTS devices []. It is also shown that the performance of such a decentralized controller which uses remote or global signals of a power system is better than local signal based centralized controller. Several advanced control techniques have been applied to design remote signal based damping controller.

One drawback of acquiring remote signals is the inherent signal transmission delay. The typical range of such delay is 10-40 milliseconds. Transmission delays could be detrimental and could make the system eventually unstable if they are not properly taken into account while designing the damping controller. Proper representation of the time delays and the design of damping controllers which will be unaffected by the effects of these delays are also reported [81, 82]. However, the compensation of such time delays is often found to be difficult to achieve and is still under research.

1.5.3.2 Damping of Subsynchronous Resonance

Static VAR Compensator (SVC) is shown to successfully damp all the four SSR modes which are critically excited with specific levels of series compensation in IEEE
Benchmark Model. The SVC is originally installed at the generator terminal for the voltage control purpose. Addition of a suitably designed auxiliary controller damps the torsional and self-excitation modes of this system [83].

Thyristor controlled reactor used in a modulated inductance stabilizer (MIS) is also proved to provide positive damping to SSR modes when a zero phase shift is produced in its control [84].

A comparative study of damping SSR by an SVC using various auxiliary signals such as computed internal frequency (CIF) [86, 87], computed rotor frequency (CRF), bus frequency and line reactive current has been reported in past. The CIF signal gives the best damping performance for all the SSR modes for all levels of series compensation (5%-99%).

Similar to SVC, a vast body of literature is also available showing the effectiveness of the series FACTS devices in damping SSR. Series devices have inherent capability to damp SSR [88-91]. More specifically, series FACTS devices are immune to SSR because at the subsynchronous frequencies these devices offer very high impedance. As mentioned in section 1.3, thyristor controlled series compensators (TCSC) are widely used series devices. It is reported in [88] that a TCSC with an open loop firing angle control when employed in a transmission system supplied with conventional steam turbine-driven synchronous generators, offers more resistance at increased levels of series compensation at subsynchronous frequencies while at fundamental frequency the same TCSC offers capacitive reactance enhancing the power flow through the transmission line. This shows that TCSC has an inherent capability of damping SSR while increasing the power transfer capability of a transmission line.

1.6 Motivation of the Thesis

Proposition of some innovative techniques to solve some of the diverse power system problems described in previous sections is the main motivation behind the thesis. The thesis starts with a very general idea of damping inter-area oscillations with static var compensators (SVC) employing remote signals as the input to the
auxiliary controller. With today's complex, interconnected and multi-machine power system, the remote signal is shown to provide better damping than the local signals which may not necessarily exhibit the most undamped mode of oscillations. The performance of various remote and local signals and their varied combination has been thoroughly investigated to find out the best auxiliary signal.

Subsynchronous resonance of series compensated transmission network is another intricate problem where multiple modes of subsynchronous frequencies become unstable. The instability is much more complicated than the low frequency inter-area oscillation because of the fact that at a particular level of series compensation all four subsynchronous modes need to be damped. Another challenge is to ensure that a single controller configuration with same parameter values should be able to damp all the unstable SSR modes. To achieve both of these objectives the possibility of utilizing remote signal as the input to subsynchronous damping controller of a FACTS device has been explored for the first time.

With the increased penetration of wind power a natural question is that can SSR occur in a series compensated wind farm? To answer the question a new area of research is opened up by investigating the possibility of the existence of subsynchronous resonance in such a wind farm and its potential solutions.

Another aspect of research is to examine the issues related to interconnecting large wind farms directly to an Extra High Voltage (EHV) double circuit transmission line. This thesis studies the overvoltage issues arising from interconnecting a large wind to such a network.

It is found from the study of overvoltages across the wind farm that the characteristics of overvoltages may depend on the modeling of WTGs. Especially, the modeling of the DFIG in this study is crucial as it is equipped with a voltage-source converter based excitation system being a potential factor of severe overvoltages. To obtain the accurate model of a WTG the simulation model needs to be validated with the field test results. Although the overvoltage study is performed in electromagnetic transient domain, as the first step towards achieving a field validated model, a widely used transient stability software package having a readily available DFIG model is
used in this thesis. Wind turbine generator models manufactured by different vendors and having various configurations may be readily available in software packages. However, neither the detailed implementation procedure of these models is disclosed nor there is any literature reporting the validation of these existing models with the field test results. In this thesis an attempt is made for the first time to validate a doubly fed wind turbine generator model with the field test results.

1.7 Objective and Scope of the Thesis

The objectives and the scope of the thesis are as follows:

1. Damping of inter-area oscillations in multi-machine power system with static VAR compensator using the derivative of the remote generator bus voltage angle as the auxiliary signal to the SVC power swing damping controller and to study the effect of remote signal transmission delay with its compensation.

2. Damping subsynchronous resonance (SSR) with a static VAR compensator using remote generator speed as the auxiliary signal to its subsynchronous damping controller.

3. To study the potential of the SSR occurrence in a series compensated wind farm and to damp this SSR using different FACTS devices namely SVC and TCSC.

4. To thoroughly investigate the overvoltage problem at the terminal of a large wind farm to be interconnected with the EHV double circuit transmission corridor and to propose various economical means to suppress the overvoltages caused by ferroresonance, self-excitation etc.

5. To validate GE 1.5 MW doubly fed wind turbine generator models of PSS/E with the field test results and to propose some system performance improvements by tuning the parameters of the models. To further recommend some guidelines to conduct more successful tests and also to obtain more accurate test results of a wind farm.
1.8 Outline of the Thesis

A chapter-wise summary of the work done in this thesis is given below:

In chapter 2, it is shown that irrespective of the complexity and the number of machines of a given power system, the derivative of generator bus voltage angle closely follows the low frequency inter-area oscillations observed in generator rotor speed. In other words, the derivative of generator bus voltage angle mimics generator rotor speed signal. An SVC utilizing the weighted combination of the derivative of the participating generator bus voltage angle as the input to its auxiliary controller is used to damp the low frequency inter-area oscillations in IEEE 39 bus New England Test System which is subjected to a number of contingencies and varied operating conditions. A transmission delay of reasonable duration is purposely simulated to show that it can make the system eventually unstable. A suitable lead lag compensator is designed to compensate the delay. The robustness of such a compensator is extensively tested by varying the duration of the time delay. It is observed that the compensator is equally effective within a wide range of time delay.

Chapter 3 demonstrates for the first time the effectiveness of the remote generator speed in damping SSR through SVC. It is proved that the same subsynchronous damping controller of a mid-point located SVC in the IEEE 1st Benchmark system can effectively damp all the SSR modes for three critical levels of series compensation. A slight variation of the same controller is able to damp the SSR modes corresponding to the fourth and the highest compensation level.

Chapter 4 establishes the existence of SSR in a series compensated wind farm. It is first of all shown that induction generator effect and torsional interaction both co-exist in a wind farm consisting of a group of self-excited induction generators and supplying power through a series compensated transmission line. The frequencies of subsynchronous oscillations are also identified. It is found that the subsynchronous oscillations due to the induction generator effect and torsional interaction can be detrimental even at very realistic levels of series compensation. The subsynchronous oscillations due to these two effects are damped by a simple voltage regulator of a
static VAR compensator originally employed at the generator terminal for the fast voltage or reactive power support of the wind farm. Addition of an auxiliary controller to the SVC, using generator rotor speed deviation as the input signal is found to have better performance in damping the oscillations due to torsional interactions. A performance comparison is carried out to prove that thyristor controlled series compensator (TCSC) is more effective compared to SVC in damping SSR even if the SVC is equipped with subsynchronous damping controller (SSRDC).

Chapter 5 is concerned with the overvoltage problem encountered by a large wind farm connected to EHV lines. The upcoming Kingsbridge II wind farm will be connected to a 500 kV long double circuit transmission line of Hydro One Networks Inc. through a step down transformer. This transmission corridor is a major interconnection transferring bulk power from Bruce nuclear power station to Longwood. The problem of potential overvoltage, which may be encountered by this wind farm if the breakers at both ends of the transmission line to which it is connected get opened, is rigorously addressed. Extensive nonlinear time domain simulations have been carried out to study the overvoltages faced by the wind turbine generators. It is found that the voltage at the point of interconnection reaches detrimental magnitude within two to three cycles if proper protection measures do not disconnect the wind farm from the high voltage transmission line. The overvoltages may occur due to several reasons such as ferroresonance involving the capacitive coupling of the double circuit transmission line and the magnetizing inductance of the station transformer, self-excitation of the wind farm employing induction generators, LC oscillations between the line charging capacitance and transformer leakage inductance, etc. In addition to damaging the costly wind turbine generators this severe overvoltage may drive the transformer into saturation and thereby reducing its life of operation. Self-excited induction generators (SEIG) and doubly fed induction generators (DFIG) are considered to study this phenomenon. Several mitigating measures have been proposed to arrest this overvoltage.

Finally, Chapter 6 concludes the thesis along with some directions of future research.

Appendix A deals with the extensive validation of an existing model of a variable
speed doubly fed induction generator with the field test results in the Hydro One network. AIM Erie Shore wind generating station interconnected to the 118.1 kV Cranberry Junction transformer station (TS) of Hydro One Network Inc. (HONI) has a group of GE 1.5 MW wind turbine generators. These wind turbine generators are of doubly fed induction generator configuration which is already implemented in PSS/E Wind software. Out of a series of tests conducted at the same generating station, a few of them are simulated in PSS/E to validate the existing models. Simulation results are found to be in good agreement with the field test results confirming the accuracy of the GE 1.5 MW wind turbine generator models of PSS/E Wind. In addition, a systematic tuning of various controller parameters of the power electronic converter is carried out to obtain improved system performance. It is shown that with the slight variation of the controller gain the settling time of the voltage and the reactive power could be substantially reduced. The extent of mismatch between the simulation and experimental results is also reported and the reasons for the mismatch are pointed out. Finally, a number of recommendations are made to conduct more meaningful testing of WTGs.

1.9 References


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CHAPTER 2

Damping of Inter-Area Oscillation in Power Systems by Static Var Compensator (SVC) Using PMU Acquired Remote Bus Voltage Angles

2.1 Introduction

Electromechanical oscillations (0.1 to 2.0 Hz) are phenomena inherent to power systems [1]. There are mainly two types of electromechanical oscillations involved in power systems: one associated with a single generator or a single plant called local mode oscillation (0.8 to 2.0 Hz) and the other related to a group of generators or group of plants called inter-area oscillation (0.1 to 0.8 Hz) [1]. Conventionally, Power System Stabilizers (PSS) are used to damp electro-mechanical oscillations [2], [3]. However, PSS is more effective in damping local mode oscillations as compared to inter-area mode oscillations [4].

Flexible AC Transmission System (FACTS) Controllers are effective means of damping low frequency inter-area oscillations following a disturbance in power systems [5], [6]. Static Var Compensators (SVC) are a class of FACTS Controllers that are widely used in power systems for voltage control as well as for damping enhancement using auxiliary control signals [7]. An additional controller called power swing damping controller (PSDC) is separately designed to increase the damping of the system. Traditionally, local signals such as, bus frequency, line active power and line current magnitude, are utilized to increase the modal damping of the power system, for ease of
availability and high reliability. However, local signals usually do not have information about the entire modal dynamics of the power system. This provided the motivation to adopt remote/global signals. Since transmission of remote signals posed problems in the past, remote signals have been synthesized using local measurements [8]-[11] to improve the damping of inter-area modes in power systems.

The aggregate machine angles of the coherent areas are synthesized using local voltages and current measurements, and assuming equivalent impedances [6], [8] between aggregate generator bus and the bus where FACTS Controller is connected. It is to be noted that the estimated value of the equivalent impedance should be close enough to the actual one in order to get satisfactory response of power swing damping control. Thevenin’s voltage at the SVC bus has been used as a control input signal to the PSDC loop of the SVC installed on the 500 kV transmission line between Arizona and California [9]. The Thevenin’s voltage is synthesized using local measurements and the estimated value of the Thevenin’s equivalent impedance seen from the SVC bus. In another scheme for system damping, the SVC is made to use the phase angle signal (bus voltage angle of the generator relative to the SVC bus) as a feedback signal. This signal is synthesized using local measurement of voltage and power at the SVC location [10]. An auxiliary signal designated Computed Internal Frequency (CIF) is reported in [11] which synthesizes internal voltage frequency of the remote generator from electrical measurements at the SVC bus. In general, the mechanisms to synthesize remote signals using local measurements on the SVC location are dependent on the exact knowledge of intervening impedance between the SVC bus and the generator bus. If the actual generator and SVC are connected on the same line, the computation becomes complex due to the presence of intermediate loads. Despite being more effective than local signals, the synthesized signals, at best, give only an indirect estimation of the oscillations of generator rotor.

In the last few years, due to rapid advancements in wide area measurement (WAM) technology [12], [13] remote signals such as remote line currents, remote line power, remote bus frequency, etc. have been actively considered as control input signals for
auxiliary damping controllers of FACTS devices [14] - [17]. In general, the choice of control signals plays a key role in the effective damping of inter-area oscillations in power systems [18]. The chosen control input signal should have high modal content of particular mode of interest. Also, there is a need to address the issue of delay introduced while transmitting the signals from remote site to the location of FACTS Controller.

In view of the above, the motivation for the damping concept proposed in this chapter is as follows. Inter-area oscillations are essentially caused by the oscillations of the generators. Hence the ideal control signals for damping inter-area oscillations would be the rotor angles of the key generators that participate in inter-area oscillations. It is noted that the voltage angle of a generator bus closely follows the rotor angle of the generator itself. Therefore, intuitively, it seems that the bus voltage angle most closely represents the rotor angle signal as compared to any other signal. While it may not be possible to transmit these generator rotor angles to remotely located FACTS Controllers, it may be easier to transmit the generator bus voltage angles utilizing the Wide Area Measurement (WAM) technology through Phasor Measurement Units (PMUs) [13].

In this chapter, the proposed concept of SVC damping control based on a weighted sum of the derivatives of voltage angles of relevant remote generator buses is compared with SVC control based on the conventional local line current signal for damping inter-area oscillations in a 39-bus multi machine system. Eigenvalue study is carried out using SSAT/DSA software [19] to analyze the modal behavior of the system and also to design the SVC auxiliary control. An electromagnetic transient simulation study is then conducted using PSCAD/EMTDC software [20] to validate the results of eigenvalue study. An effective control strategy to compensate the delay in the transmission of remote bus voltage phasors is also presented. The designed compensator is shown to be robust enough to handle signal transmission delays over a wide range.

The organization of the chapter is as follows. Section 2.2 shows the mathematical relationship between the generator load angle and bus voltage angle. The system modeling for eigenvalue analysis is briefed in section 2.3. Section 2.4 describes the
auxiliary controller design for the SVC. The major portion of this chapter is covered in section 2.5. It starts with the description of the studied system along with its operating conditions. The system studies for those operating conditions both in time domain and in frequency domain are reported. Next, the effectiveness of the proposed signal is demonstrated with a range of varied operating conditions. The impacts of signal transmission delay and the delay compensation technique are also elaborated in this section. The robustness of the delay compensator is depicted by time domain simulations in section 2.6. Various issues of this study have been summarized in section 2.7. Finally, section 2.8 concludes the chapter.

2.2 Relationship between Generator Load Angle and Bus Voltage Angle

The relationship between generator load (rotor) angle and generator bus voltage angle, as described below, applies for any generator in a power system. However, the concept is illustrated by a phasor diagram of a generator supplying power at lagging power factor in a Single Machine Infinite Bus (SMIB) system shown in Fig. 2.1. The phasor diagram is shown in Fig. 2.2.

![Fig. 2.1 Single Machine Infinite Bus (SMIB) system](image-url)
where,
- \( V_i \) = generator terminal voltage
- \( I_i \) = generator current
- \( E \) = internal voltage
- \( R_a \) = winding resistance
- \( X_q \) = generator d-axis reactance
- \( \delta \) = generator load angle
- \( \varphi \) = generator power factor angle
- \( \theta \) = generator bus voltage angle
- d-axis = generator d-axis
- q-axis = generator q-axis
- D-axis = system D-axis
- Q-axis = system Q-axis

Fig 2.2 Phasor diagram

The generator bus voltage angle \( \theta \) is related to the generator load angle \( \delta \) as

\[
\theta = \delta + \cot^{-1} \left( \frac{|I_i| X_q \cos \varphi - |I_i| R_a \sin \varphi}{|V_i| + |I_i| R_a \cos \varphi + |I_i| X_q \sin \varphi} \right) \tag{2.1}
\]

Eq. (2.1) reveals that the generator bus voltage angle \( \theta \) varies linearly with the generator load angle \( \delta \). It also implies that the derivative signal \( d\theta/dt \) follows \( d\delta/dt \) (the speed \( \omega \)) of the generator. Hence, \( \delta \) and \( \omega \) will be observable in \( \theta \) and its derivative \( (d\theta/dt) \), respectively. The generator bus voltage angle \( \theta \) can be easily calculated by phasor measurement unit and transmitted to the location of damping controller almost in the real time using the wide area measurement (WAM) techniques. This relationship between \( d\theta/dt \) and \( \omega \) is validated through time domain simulation using PSCAD/EMTDC software in 39-bus New England system later in this chapter.
2.3 System Modeling for Eigenvalue Analysis

Eigenanalysis is conducted using SSAT/DSA software [19]. In these linear system analyses, the synchronous generators are represented by their detailed flux linkage model with one damper winding on d-axis and two damper windings on q-axis [2]. Exciters are modeled according to IEEE Type-1 model [2]. The SVC is modeled as a thyristor switched capacitor (TSC) connected in parallel with thyristor controlled reactor (TCR). SVC voltage regulator is modeled as a PI (proportional integral) controller with SVC slope reactance.

The linearized model of the ac network is expressed as:

\[ \Delta I = [Y] \Delta V \]  \hspace{1cm} (2.2)

Here \( \Delta I \) denotes the vector of incremental bus current injections obtained as the output of the dynamic device models. \( \Delta V \) denotes the vector of incremental bus voltages. \([Y]\) is the bus admittance matrix for the system.

The overall model of the SVC compensated system is given as:

\[ \frac{d}{dt} (AX) = [A_{sys}] AX \]  \hspace{1cm} (2.3)

Here, \([A_{sys}]\) is the overall system state matrix which is computed by SSAT [19].

2.3.1 Eigenvalues of the State Matrix and Participation Factors

The eigenvalues of the state matrix \(A_{sys}\) and the corresponding eigenvectors are defined by the following equations:

\[ A_{sys} \varphi = \lambda \varphi \]
\[ \psi A_{sys} = \lambda \psi \]  \hspace{1cm} (2.4)

In this equation:
\( \lambda \) is an eigenvalue of the state matrix \( A_{sys} \);
\( \varphi \) is the right eigenvector associated with \( \lambda \);
\( \psi \) is the left eigenvector associated with \( \lambda \).

The modal matrices comprising the left and right eigenvectors are given below:

\[
\Phi = [\varphi_1 \varphi_2 \ldots \varphi_n] \\
\Psi = [\psi_1 \psi_2 \ldots \psi_n]^T
\]  
(2.5)

A mode is related to the individual state variables by:

\[
Z_j(t) = \psi_{j1}x_1(t) + \psi_{j2}x_2(t) + \ldots + \psi_{jn}x_n(t)
\]  
(2.6)

Here \( x_i \) is the state variable and \( \psi_{ji} \) is the \( i^{th} \) element in the left eigenvector \( \psi_j \).

One problem in using directly the left eigenvector to quantitatively determine the contribution of a state variable to a mode is that the elements of the left eigenvector are dependent on units and scaling. The solution is to weight the left eigenvector by the right eigenvector to obtain a quantity independent of unit and scaling which is expressed by the following equation:

\[
P_{ji} = \psi_{ji} \varphi_{ji}
\]  
(2.7)

\( p_{ji} \) is the participation factor. Participation factors measure the participation of state variables in modes. For instance, the larger the value of \( p_{ji} \) the more the state variable \( x_i \) participates in the \( j^{th} \) mode.

The eigenvalues of system state matrix reveal the modal behavior of the system. Modal damping, if less than 2% [2, 4], needs to be improved for power system stability. In this chapter, SVC auxiliary control with PMU-acquired bus voltage angle as a feedback signal is proposed, designed and utilized to improve the damping of inter-area oscillations.
2.4 SVC Auxiliary Controller Design

SVC is mainly used to regulate the system bus voltage during disturbances in the system. In addition, an auxiliary control loop is designed and added suitably to enhance the modal damping of the system. The controller parameters are chosen using systematic hit and trial method.

A typical structure of SVC auxiliary control loop used in this study is given in Fig. 2.3.

![Fig. 2.3 Structure of SVC auxiliary control](image)

The measured signal is converted into its p. u. value and then processed through a 2\textsuperscript{nd} order low-pass filter to pass only the electromechanical signals (0.1 to 2.0 Hz), as shown in Fig. 2.3. Subsequently, the filtered signal is transmitted to the lead/lag block through a washout circuit $10s/(1+10s)$. The purpose of washout circuit is to prevent the auxiliary controller from responding to steady state power flow variations. The output of the lead/lag block is then fed to SVC voltage regulator loop. A 3.0 % slope in SVC control characteristic is considered in the present study.

2.5 System Studies

2.5.1 System Description

The New England power system consists of 39-bus and 10-generators as shown in Fig. 2.4 [22]. An SVC connected at bus 16 [24] is considered in the study to demonstrate the efficacy of the proposed auxiliary signal in large, multi-machine power systems. The
rating of SVC is 300 MVAR capacitive and 200 MVAR inductive, as determined from power flow studies [4].

Fig. 2.4 The New England system with SVC at bus 16

2.5.2 Operating Conditions

This study is carried out at a highly stressed system operating point in order to demonstrate the effectiveness of SVC auxiliary control with the proposed feedback signal which is the weighted sum of derivatives of the PMU-acquired remote generator bus voltage angles. Both the generations and loads are increased by 150% to that given in [22] in order to achieve a highly stressed operating state with negative system damping. In this initial steady state, the SVC bus power is 890 MW with 354 MVAR reactive power, both passing through bus 16 to buses 15 and 17. This initial steady state is chosen identical to that in [24] in order to compare the performance results of different SVC damping controllers.
2.5.3 Validation of the Relationship between Rotor Angle and Generator Bus Angle

This relationship is demonstrated through time domain simulation using PSCAD/EMTDC software in the 39-bus New England system. The plots of speed of generator 1 and derivative of bus voltage angle of generator 1, both with respect to generator 5, are shown in Fig. 2.5 and Fig 2.6 (a-c) without and with SVC auxiliary control using the proposed feedback signal. The plots of the signals in Fig 2.6 (a), (b) and (c) correspond to disturbances 1, 2 and 3, respectively. These disturbances, that are considered to be critical, are defined as in [24]:

- Disturbance 1: A 3-phase short circuit occurs at bus 17 and cleared in 0.1 s without line tripping.
- Disturbance 2: A 3-phase short circuit occurs at bus 3 and cleared in 0.14 s by tripping lines 3-18.
- Disturbance 3: A sudden 75 % reduction of the load at bus 16 and restored in 1.0 s.

![Fig. 2.5 Comparison of actual speed signal $\omega_{15}$ and the derivative of generator bus voltage angle $d\theta_{15}/dt$ without SVC auxiliary control for disturbance 1](image)
It is observed from Fig. 2.5 and Fig. 2.6 (a), (b) and (c) that derivative of generator bus voltage angle \( \frac{d\theta}{dt} \) consistently follows the speed \( \omega \) of the generator for 150 % loading both without and with SVC auxiliary control for all three disturbances in the system. This validates the analytical relation between \( \delta \) and \( \theta \) given by Eq. (2.1).

### 2.5.4 Case Studies

To examine the effect of the SVC auxiliary control with the proposed feedback signal, no other damping controllers such as PSS are included in the system. Various cases have been studied on the 39-bus New England System as follows:

1) Without SVC auxiliary control.
2) With local line current signal.
3) With remote generator speed signal, and.

4) With proposed feedback signal (weighted sum of derivative of bus voltage angles of remote generators) for SVC auxiliary control.

The SVC auxiliary control has been designed using a systematic hit and trial procedure, as mentioned in the earlier section, to provide best possible damping and minimum post-fault settling time in each case. The performance of the different SVC auxiliary controllers is compared for all the three disturbances as described above. In practice, the remote signal is transmitted to the SVC location through a communication system, which causes a signal transmission delay. The study is extended to observe the effect of delayed feedback signal on the performance of the SVC auxiliary control. A simple lead compensator is proposed and designed in order to compensate the time delay introduced by the remote transmission of the feedback signal. The eigenvalue analysis and time domain simulation studies have been carried out using SSAT/DSA and PSCAD/EMTDC software, respectively.

2.5.5 Eigenvalue Analysis

The complete lists of eigenvalues of the study system without SVC and with SVC auxiliary control are calculated using SSAT/DSA software [19] and are shown in table 2.1 and 2.2 respectively. In this study, the generators are modeled as round rotor synchronous machines with their 6th order dynamics. The models of the generators are called ‘GENROU’ in SSAT. On the other hand, the exciters associated with each of the generators are modeled as IEEE Type 1 Exciter. The exciter dynamics are modeled by 4th order differential equations. The models of Type 1 exciters are called ‘IEEET1’. The SVC is represented with its 4th order dynamics representing its main voltage regulator and the auxiliary controllers. The purpose of these tables 2.1 and 2.2 is to depict the dominant modes and the maximum participating states corresponding to each of the modes of the 10 machine 39 bus system with and without static VAR compensator respectively.
The complete eigenvalue analysis is summarized in table 2.3 which shows mainly two electromechanical modes – 1) an unstable mode of frequency 0.1685 Hz and (2) a stable mode of frequency 0.4072 Hz in the 39 bus system without considering SVC auxiliary control at an operating point corresponding to 150% of the base loading condition. These modes are referred as mode-1 and mode-2 in the subsequent parts of the chapter. Eigenvalue analysis also demonstrates that generators 1 and 5 mainly contribute to mode-1 and generators 9 and 5, to mode-2.

<table>
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<tr>
<th>Serial No.</th>
<th>Real part of the Eigen Values</th>
<th>Imaginary Part of the Eigen Values</th>
<th>Frequencies of the Modes (Hz)</th>
<th>Damping Ratio (%)</th>
<th>Maximum Participating States</th>
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Table 2.1: Complete eigenvalues of the study system without SVC
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<th>Maximum Participating States</th>
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<tr>
<td>27</td>
<td>-49.2973</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>35 : G₆ : Kₐ/Tₐ</td>
</tr>
<tr>
<td>28</td>
<td>-47.7653</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>30 : G₁ : ψ₁d</td>
</tr>
<tr>
<td>29</td>
<td>-48.0822</td>
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<td>0</td>
<td>100</td>
<td>34 : G₅ : Kₐ/Tₐ</td>
</tr>
<tr>
<td>30</td>
<td>-42.4952</td>
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<td>0</td>
<td>100</td>
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</tr>
<tr>
<td>31</td>
<td>-42.7212</td>
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<td>0</td>
<td>100</td>
<td>34 : G₅ : ψ₁d</td>
</tr>
<tr>
<td>32</td>
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<td>0</td>
<td>100</td>
<td>36 : G₇ : Kₐ/Tₐ</td>
</tr>
<tr>
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<td>100</td>
<td>33 : G₄ : ψ₁d</td>
</tr>
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<td>0</td>
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<td>36 : G₇ : ψ₁d</td>
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<tr>
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<td>-38.2032</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>32 : G₃ : ψ₁d</td>
</tr>
</tbody>
</table>

Table 2.2: Complete eigenvalues of the study system with SVC auxiliary control with optimal weights
Table 2.2 (Continued)

To verify the modes found from eigenvalue study, time domain simulations have been carried out at 150% loading condition. In these simulations depicted in Fig. 2.7, a three phase fault at bus 17 (disturbance 1) is considered to excite electromechanical modes in the system. Mainly two modes are observed – (i) 0.16 Hz and (ii) 0.4 Hz. The mode corresponding to 0.4 Hz decays out in a few seconds after the disturbance while the mode corresponding to 0.16 Hz continues to grow in the absence of SVC auxiliary control.
The plot of SVC bus power in Fig. 2.7 shows the unstable behavior of the system at 150% loading. The speeds of all the generators, after the mode corresponding to 0.4 Hz has decayed out, are shown in Fig. 2.8. The following observations are made:

- System is unstable at 150% loading condition.
- Generators 2 to 10 are swinging against generator 1.
- Frequency of oscillation is 0.16 Hz.
- Magnitude of oscillation in the speed of Generator 5 is the maximum as compared to that of other generators.

The above observations confirm the presence of one electromechanical mode of frequency 0.16 Hz with negative damping obtained from eigenvalue study. The major contribution of Generators 1 and 5 to this mode is also established. Since the mode corresponding to 0.4 Hz decays out even without SVC auxiliary control, the positive damping of this mode, as obtained from the eigenvalue study, is also confirmed.
This indicates the need for SVC auxiliary control to improve modal damping. SVC auxiliary controllers are designed using both local and remote signals. Line current magnitude, which is considered to be one of the most effective damping signals [4], is utilized as one of the local feedback signals. The other local signal considered is the SVC line active power flow signal, which is the sum of the powers flowing outwards from SVC bus in the lines 16-17 & 16-15. The combination of generator speed signals $\omega_{15}$ and $\omega_{95}$ has been taken as one of the remote feedback signals while designing the auxiliary controllers. It is important to choose the appropriate weights for the remote speed signals $\omega_{15}$ and $\omega_{95}$. A modal damping analysis is carried out for different weights of remote signal $\omega_{15}$ in the combination of ($\omega_{15}$ and $\omega_{95}$) signal and depicted in Fig. 2.9. The following observations are made:
- Damping of mode-2 is better than that of mode-1 for any combination of remote speed signals.
- Weights of 0.75 and 0.25 for speed signal $\omega_{15}$ and $\omega_{95}$, respectively, impart maximum damping to mode-1.

Therefore, the combination of weights (0.75 $\omega_{15}$ and 0.25 $\omega_{95}$) is considered for further studies.

After choosing the SVC auxiliary controller parameters, modal analysis is again carried out to check the effect of SVC auxiliary control on the same operating condition corresponding to 150% loading. It is observed from Table 2.3 that the damping of mode-1 improves from -1.84 to 3.61 both with actual speed signals of the remote generators and the derivative of bus voltage angles of the same remote generators. Also, the damping of mode-1 with the remote signal is superior to that provided by either of the two local signals (line power flow or line current magnitude). The performance of line current magnitude is however, better than that of line power flow. It is to be noted that the controller gain for different signals is appropriately chosen to ensure the fastest settling time. These observations confirm the proposed concept of derivative of PMU-acquired remote generator bus voltage angle as a better and feasible feedback signal for SVC auxiliary control.
2.5.6 Time Domain Simulations

A detailed time domain simulation is carried out on the 39-bus New England system using PSCAD/EMTDC software to validate the results obtained from eigenvalue analysis by SSAT/DSA software. The system behaviour with SVC auxiliary control using the proposed remote feedback signal \( d\theta/dt \) is compared with actual generator speed signal \( \omega \) and local line current magnitude signal for different disturbances described in the earlier section. The “proposed \( d\theta/dt \) signal” refers to the \( (0.75d\theta_1/dt + 0.25d\theta_9/dt) \) signal, whereas the remote generator speed signal \( \omega \) corresponds to \( (0.75 \omega_1 + 0.25 \omega_9) \) signal.

The rotor angles of generators 9 and 1 with respect to that of generator 5, SVC bus power, SVC bus voltage magnitude and the reactive power drawn by the SVC are shown in Fig. 2.10 (a), (b), (c), and (d), respectively for the critical disturbance 1. Following observations are made:

- An SVC auxiliary control using remote signals \( \omega \) and proposed \( d\theta/dt \) is more effective as compared to the local current signal.
- The performance of SVC auxiliary control with proposed derivative of bus voltage signal \( (0.75 d\theta_1/dt + 0.25 d\theta_9/dt) \) almost matches with the actual generator speed signal \( (0.75 \omega_1 + 0.25 \omega_9) \).

The study is repeated for other critical disturbances 2 and 3 and simulation results are shown in Fig. 2.11 and 2.12. It is observed from Fig 2.10 and 2.12 that the responses with \( \omega \) and \( d\theta/dt \) signals are very close, in fact, overlapping each other.
Fig. 2.10 System performance for disturbance 1
Fig. 2.11 System performance for disturbance 2
Fig. 2.12 System performance for disturbance 3 at 150 % loading

- (a): Gen. angle GI-5 (degree)
- (b): Gen. angle GI-6 (degree)
- (c): SVC bus power (p.u.)
- (d): Vsec (p. u.)
- (e): Qsec (MVA)

Legend:
- Grey dashed line: without auxiliary control
- Black dashed line: with gen. speed (o) signal
- Black solid line: with proposed dB/dt signal
2.5.7 Performance with Varying Loading Conditions

In this chapter, the system is loaded to a highly stressed state, i.e. at 150% higher loading than that considered in [23]. It is noted that the SVC auxiliary controller using the proposed feedback signal, designed and tuned at 150% loading, performs effectively at 100% loading condition with a settling time of 4.8 sec. as compared to 7.0 sec. that was reported for another SVC damping controller presented in [23]. This indicates the efficacy of the SVC auxiliary control at different operating points.

The SVC rating is kept constant in both the operating conditions to avoid imparting unrealistic control effort by it. This is also proved from the SVC reactive output $Q_{\text{svc}}$ shown in the Fig. 2.10-2.12. It is evident from these figures that in none of the operating conditions SVC reaches its reactive compensation limits.

2.5.8 Effect of Transmission Delay and Delay Compensation

The actual time delay in signal transmission is represented by $e^{-sT_d}$ [23], which is generally modeled by Pade’s first order approximation as:

$$
e^{-sT_d} = \frac{1-\left(sT_d/2\right)}{1+\left(sT_d/2\right)}$$

(2.8)

In this study, however, no approximation is made for the delay. The time delay in transmission of signal from the location of remote generator to the SVC site is modeled exactly as $e^{-sT_d}$ both in the eigenvalue study (using SSAT/DSA software) and time domain study (employing EMTDC/PSCAD software).

Although, typical time delay of 40-60 millisecond is reported in actual field for fiber optics or microwave transmission, an extremely large delay of $T_d = 0.75$ sec. is deliberately considered to examine its effect. It is found that this delay in the transmission of the proposed signal introduces modal instability (as depicted in table 2.3).
This instability is also validated through the time domain simulation in Figs. 2.13 to 2.15 for the three critical different disturbances. The phase lag introduced in the proposed feedback signal is 48 degrees for the electromechanical mode of frequency 0.1783 Hz.

A suitable lead compensator is designed [2] to neutralize the effect of the time delay introduced by remote signal transmission. The structure of the lead circuit is given below:

\[
K \left( \frac{1 + sT_1}{1 + sT_2} \right)^2
\]  

(2.9)

Here, \( K = 0.28 \), \( T_1 = 0.64 \) sec., and \( T_2 = 0.1 \) sec.

It is observed from eigenvalue studies reported in table 2.3 that the damping of the critical inter-area mode improves from -0.39% to 3.61% after introducing a suitable lead compensator. This is also validated by time domain simulations in Figs. 2.13 to 2.15 for all the three disturbances.
Fig. 2.13 Performance considering transmission delay and with delay compensator for disturbance 1 at 150% loading

Fig. 2.14 Performance considering transmission delay and with delay compensator for disturbance 2 at 150% loading
2.6 Robustness of the Delay Compensator

To test the robustness of the designed compensator, signal transmission delays of different ranges are considered. The maximum signal transmission delay is intentionally chosen to be 0.8s to demonstrate the robustness of the compensator. It is found that the controller is still effective even if this unusually large delay is involved in signal transmission. Fig. 2.16 depicts stable SVC bus power, speed deviation between G9 and G1 and SVC reactive power even though the signal transmission involves the unusually large transmission delay mentioned above.

In the second test a typical signal transmission delay of 40ms is considered. In this case also the performance of the delay compensator is satisfactory. Fig. 2.17 plots the same signals as mentioned above in case of a realistic 40 ms delay. In this case also the system is stable and the oscillations are damped rapidly.
Fig. 2.16 (a) SVC bus power, (b) speed deviation between G9 and G1 and (c) reactive support of SVC for 0.8s signal transmission delay.
Fig. 2.17 (a) SVC bus power, (b) speed between G9 and G1 and (c) reactive support of SVC for 40 millisecond signal transmission delay.
2.7 Discussions

Since inter-area oscillations essentially originate from the generators, it is expected that a damping signal derived from generator rotor angles should be most effective. Generator bus voltage angles closely follow the generator rotor angles. Hence, a new damping signal based on the derivative of bus voltage angle of the generators that participate in the highly damped or un-damped inter-area mode is proposed. It is shown that the derivative of generator bus voltage angle signal is almost as effective as the generator speed signal. If more than one generator participates in the inter-area mode concerned, a weighted sum of the derivative of bus voltage angles of those generators has to be chosen. The weights assigned to each generator will depend on its contribution to the inter-area mode as determined from eigenvalue analysis and transient stability simulation studies.

The proposed remote signal which is derived from signals resembling rotor oscillations of actual generators participating in the inter-area mode is shown to be better than the conventionally preferred local signal – magnitude of the line current. The effectiveness of the proposed SVC auxiliary controller is demonstrated for a very stringent system operating condition. This corresponds to a 150% loading of the system at which the system is inherently unstable without SVC damping control. In an actual SVC installation, the remote signal can be used as the primary signal for SVC damping control, while the local signal can serve as a suitable backup.

2.8 Conclusions

In this chapter, a new concept of static VAR compensator control for damping inter-area oscillations based on remote signals is presented. The proposed damping signal comprises a weighted sum of the derivative of bus voltage angles of remote generators that participate in the inter-area mode oscillations. It is shown for a highly stressed 39-bus New England system that an SVC damping control based on above signal, which closely resembles the rotor angles of critical generators, and which can be acquired through phasor measurement units, is far superior to an SVC control based on the
conventionally used local signals. A second order lead compensator can suitably mitigate the adverse effect of the transmission delays over a wide range, thus maintaining the effectiveness of these remote signals.

2.9 References


CHAPTER 3

Mitigation of Subsynchronous Resonance by SVC using PMU-Acquired Remote Generator Speed

3.1 Introduction

Series compensation in an AC transmission line is an effective means to enhance power transfer capacity and improve transient stability. However, one of the important problems in power systems employing series capacitors in AC transmission lines is the interaction between mechanical system comprising various stages of steam turbines, generator rotor and the series compensated electrical network. If any natural frequency of oscillation of the combined torsional system matches with the complement of the resonant frequency of the line inductance and series capacitance, growing oscillations of subsynchronous frequencies result in the power system. This phenomenon is called subsynchronous resonance.

SSR with its various preventive measures have been well discussed in a vast body of literature [1, 2]. Subsynchronous oscillations due to the interactions of series capacitors with turbine-generator mechanical shaft system lead to the failure of the entire shaft system, causing electrical instability in a frequency range lower than the normal system frequency.

Successful application of Flexible AC Transmission System (FACTS) Controllers has been reported in past to mitigate subsynchronous resonance [3]. One of the widely referred examples of such applications is [4] where Hammad et. al. used thyristor
controlled VAR compensator for damping subsynchronous oscillations. They used a thyristor controlled VAR compensator connected in shunt at the synchronous generator bus to damp subsynchronous oscillations besides controlling the system voltage. Generator speed signal was used as the only stabilizing signal in designing the SVC auxiliary controller. A practical installation of SVC for SSR mitigation is reported in [5].

Recently, with the advent of Wide Area Measurement (WAM) technology, it is possible to measure the states of a large interconnected power system with synchronized phasor measurement units (PMU) [6]. The measurements of states are done at widely separated geographical locations encompassing the interconnected power system. The measurements are time synchronized by global positioning system (GPS) technology at each geographical location. Dedicated fiber-optic communication lines are used to transmit these measured states to the control centre. These measurements when collected at a central location provide a coherent picture of a power system network. This information of the entire power system network is used to design Power System Stabilizers (PSS) and FACTS Controllers to damp inter-area oscillations [6, 7].

An analysis was performed for an SVC located at the midpoint of a long distance series compensated line in respect of its effectiveness in damping the generator torsional oscillation modes in [8], [9]. The signals examined were computed internal frequency (CIF) [10], computed rotor frequency (CRF), bus frequency and line reactive current. It was reported that a combination of CIF and line current signals with appropriately chosen auxiliary controller parameters could concurrently damp the low frequency zeroth mode and the subsynchronous torsional modes for all levels of series compensation (5%-99%) including the different critical compensation levels. The composite CIF line current auxiliary signal was successful in achieving the same objective for different values of generator power output and transmission line length [11]. However, in this chapter, a new concept of using remote generator speed signal to mitigate SSR is proposed. It has been reported in [12] that through a dedicated fiber-optic link the generator speed can be transmitted to the location of the FACTS Controller to damp inter-area oscillations in a large interconnected system. In this work, the remote generator speed signal is utilized by an SVC located at the mid-point of a transmission line to damp subsynchronous
oscillations. The SVC is primarily installed to enhance power transfer capacity but with the proposed controller it can additionally damp all subsynchronous oscillation modes. It is found that with the remote generator speed a simple subsynchronous damping controller (SSDC) can damp all the SSR modes with all critical levels of compensation.

The organization of the chapter is as follows: section 3.2 describes the configuration and modeling of the study system. The overview of the controller design for the SVC is given in section 3.3. Section 3.4 discusses monotonically increasing oscillations of the unstable system along with the SSR modes; the auxiliary controller performance has also been reported in this section. A short description of the effect of signal transmission delay is presented in section 3.5. Finally, section 3.6 concludes the chapter.

3.2 System Configuration and Modeling

3.2.1 Configuration

The system considered in this work is the IEEE First Benchmark Model for SSR studies originally reported in [11]. The operating conditions, mechanical system modeling and the contingency applied are exactly the same as in [11] and given in Appendix B. In the study system, the SVC is installed in the middle of the transmission line. The system configuration with the SVC at the midpoint is shown in Fig 3.1. The rating of the SVC is: $Q_L = 300$ MVAR and $Q_C = 340$ MVAR. This is determined from the loadflow studies.

3.2.2 Modeling

Modeling of the study system shown in Fig. 3.1 has been performed using different commercial grade software. The steady state modeling of the system for loadflow studies has been performed with PSAT of DSA Power Tools [13]. The steady state power flow results have been used to initialize all the dynamic devices in the nonlinear time domain simulations performed with EMTDC/PSCAD [14].
3.3 Controller Design of SVC

SVC is mainly used to regulate the system bus voltage during disturbances in the system. In addition, an auxiliary subsynchronous damping controller (SSDC) is designed and added suitably to enhance the torsional mode damping of the system. The general linearized configuration of an SVC with its voltage regulator and auxiliary controller is shown in Fig. 3.2.

In this study the voltage regulator is a simple PI controller. The proportional gain $K_p$ and integral gain $K_i$ are varied systematically by hit-and-trial method. The best $K_i$ results in a minimal settling time with acceptable overshoots in generator terminal voltage in response to a step change in the reference voltage $V_{ref}$. The auxiliary controller $H(s)$ can
take many different structures depending on which control design technique is employed [15]. The structure of the auxiliary subsynchronous damping controller (SSDC) is shown in Fig. 3.3 where $\Delta$Sig is the incremental value of auxiliary feedback signal. The different signals generally considered as the input signals to the auxiliary controller are line real power flow, line current magnitude, bus frequency, bus voltage magnitude etc [3]. In this chapter, the generator speed deviation ($\Delta$\omega) is used as an auxiliary signal to damp the unstable modes. This choice is due to the fact that the generator speed contains all the torsional modes of oscillations and also because the SSR phenomenon primarily impacts the generator rotor speed. It is apparent from Fig. 3.1 that the generator speed is not readily available at the SVC location. It is assumed according to [12] that through a dedicated fiber optic link remote generator speed can be transmitted to the location of SVC.

The SSDC comprises a proportional and derivative controller (PD) together with a washout circuit. The purpose of washout circuit is to prevent the auxiliary controller from responding to steady state power flow variations. The gain and the parameters of SSDC are determined from systematic hit and trial using the nonlinear time domain simulation using PSCAD software to result in fastest settling time. The designed PD controller is sufficient to damp all the four SSR modes with the generator remote speed. The output of the SSDC is then fed to SVC voltage regulator as shown in Fig. 3.3.

![Fig. 3.3 Structure of SVC Subsynchronous Damping Controller (SSDC)](image-url)
3.4 Performance of the System with SVC-SSDC using Remote Generator Speed

The performance of the system is first studied without any static var compensator in the system. The objective is to test the existence of the four critical modes reported in [11] in the torque signals between various turbine stages as well as in the generator speed signal. It is found by FFT analysis with MATLAB that all the four modes exist in the generator speed and the torque signals of various turbine stages.

In this work, the performance of the system with and without SVC is tested for all four critical compensation levels reported in [11]. The results for all four critical compensation levels are reported. They are: (1) $X_c = 0.47$ p.u., (2) $X_c = 0.38$ p.u. (3) $X_c = 0.285$ p.u. (4) $X_c = 0.185$ p.u.

### 3.4.1 Critical Series Compensation $X_C = 0.47$ p.u.

Fig. 3.4 depicts the FFT plot for this series compensation. It shows a maximum destabilization for 15.71 Hz mode. The positive influence of SVC-SSDC is studied through the following signals:

1. Mechanical torque between shaft segments connecting LPA and LPB turbines.
2. Mechanical torque between shaft segments connecting generator and exciter.
3. Generator rotor speed.
4. Generator terminal voltage.
5. SVC reactive power.

The same signals are examined for all the four critical levels of compensation. It is found that the same controller structure is sufficient to damp all the SSR modes. A PD Controller with remote generator speed successfully damps all the SSR modes. Figs. 3.5, 3.7, 3.9, and 3.11 depict the generator rotor speed, LPA-LPB torque, generator to exciter torque and generator terminal voltage, respectively, without SVC, whereas Figs. 3.6, 3.8,
3.10, and 3.12 illustrate the same signals with the SVC-SSDC. The responses of the system with and without SVC auxiliary control are shown adjacently to have a better comparison of the performance of the remote generator speed signal. Without SVC, monotonically increasing oscillations are seen in all signals, whereas the SVC-SSDC successfully damps all the subsynchronous oscillations. Fig. 3.13 shows the SVC reactive power during the damping process.

![FFT Magnitude of Generator Speed](image)

Fig. 3.4 FFT of generator rotor speed for $X_C = 0.47$ p.u.

![Generator Rotor Speed](image)

Fig. 3.5 Generator rotor speed without SVC for $X_C = 0.47$ p.u.
Fig. 3.6 Generator rotor speed with SVC-SSDC for $X_C = 0.47$ p.u.

Fig. 3.7 LPA-LPB torque without SVC for $X_C = 0.47$ p.u.

Fig. 3.8 LPA-LPB torque with SVC-SSDC for $X_C = 0.47$ p.u.
Fig. 3.9 Gen-Exc torque without SVC for $X_C = 0.47$ p.u.

Fig. 3.10 Gen-Exc torque with SVC-SSDC for $X_C = 0.47$ p.u.

Fig. 3.11 Machine terminal voltage without SVC for $X_C = 0.47$ p.u.
3.4.2 Critical Series Compensation $X_C = 0.38$ p.u.

At this critical level of compensation Figs. 3.14, 3.16, 3.18, and 3.20 depict the generator rotor speed, LPA-LPB torque, generator to exciter torque and generator terminal voltage, respectively, without SVC, whereas Figs. 3.15, 3.17, 3.19, and 3.21 illustrate the same signals with the SVC-SSDC. Without SVC, growing oscillations are seen in all signals, whereas the SVC-SSDC successfully damps all the subsynchronous oscillations. Fig. 3.22 shows the SVC reactive power.
Fig. 3.14 Generator rotor speed without SVC for $X_c = 0.38$ p.u.

Fig. 3.15 Generator rotor speed with SVC-SSDC for $X_c = 0.38$ p.u.

Fig. 3.16 LPA-LPB torque without SVC for $X_c = 0.38$ p.u.
Fig. 3.17 LPA-LPB torque with SVC-SSDC for $X_c = 0.38$ p.u.

Fig. 3.18 Gen-Exc torque without SVC for $X_c = 0.38$ p.u.

Fig. 3.19 Gen-Exc torque with SVC-SSDC for $X_c = 0.38$ p.u.
Fig. 3.20 Machine terminal voltage without SVC for $X_c = 0.38$ p.u.

Fig. 3.21 Machine terminal voltage with SVC-SSDC for $X_c = 0.38$ p.u.

Fig. 3.22 SVC reactive power for $X_c = 0.38$ p.u.
3.4.3 Critical Series Compensation $X_C = 0.285$ p.u.

Similar to the previous section, at this level of compensation Figs. 3.23, 3.25, 3.27, and 3.28 depict the generator rotor speed, LPA-LPB torque, generator to exciter torque and generator terminal voltage, respectively, without SVC, whereas Figs. 3.24, 3.26, 3.28, and 3.30 illustrate the same signals with the SVC-SSDC. Here also the SVC-SSDC successfully stabilizes all the SSR modes. Fig. 3.31 depicts the SVC reactive power.
Fig. 3.25 LPA-LPB torque without SVC for $X_C = 0.285$ p.u.

Fig. 3.26 LPA-LPB torque with SVC-SSDC for $X_C = 0.285$ p.u.

Fig. 3.27 Gen-Exc torque without SVC for $X_C = 0.285$ p.u.
Fig. 3.28 Gen-Exc torque with SVC-SSDC for $X_C = 0.285$ p.u.

Fig. 3.29 Machine terminal voltage without SVC for $X_C = 0.285$ p.u.

Fig. 3.30 Machine terminal voltage with SVC-SSDC for $X_C = 0.285$ p.u.
3.4.4 Critical Series Compensation $X_C = 0.185$ p.u.

Finally, at the minimum level of critical compensation Figs. 3.32, 3.34, 3.36, and 3.38 depict the generator rotor speed, LPA-LPB torque, generator to exciter torque and generator terminal voltage, respectively, without SVC, whereas Figs. 3.33, 3.35, 3.37, and 3.39 illustrate the same signals with the SVC-SSDC. Similar observations can be made as reported in the previous subsections. SVC-SSDC is performing successfully: all SSR modes get damped. Fig. 3.40 shows the SVC reactive power.
Fig. 3.33 Generator rotor speed with SVC for $X_c = 0.185$ p.u.

Fig. 3.34 LPA-LPB torque without SVC for $X_c = 0.185$ p.u.

Fig. 3.35 LPA-LPB torque with SVC for $X_c = 0.185$ p.u.
Fig. 3.36 Gen-Exc torque without SVC for $X_c = 0.185$ p.u.

Fig. 3.37 Gen-Exc torque with SVC for $X_c = 0.185$ p.u.

Fig. 3.38 Machine terminal voltage without SVC for $X_c = 0.185$ p.u.
3.5 Effect of Signal Transmission Delay

An important aspect with remote signal acquisition is the transmission delay. This is the delay in the transmission of the acquired signal from the remote site to the location where it is to be used. The typical range of this delay is 40-50 milliseconds. The delayed arrival of the remote signal to the FACTS Controller location may cause system instability. As a result, suitable controllers have been recently designed to compensate the effect of delay in damping inter-area oscillation modes typically in the frequency range 0.1-0.8 Hz [6].
The effect of transmission delay in remote signals is examined for the damping of SSR modes (typically in the range of 10-40 Hz) by the SVC SSDC. It is found that a 40 milliseconds delay may cause the system to become unstable. The delay is modeled with a transportation lag block \( \text{e}^{-sT} \). Suitable compensator is being designed to offset the effect of this delay.

### 3.6 Conclusions

In this chapter, the performance of the remote generator speed to damp SSR has been studied. It is found that a subsynchronous damping controller (SSDC) of SVC that is based on remote generator speed, can successfully damp all SSR modes for all critical compensation levels. The SSDC has a simple structure of a proportional derivative controller. The same SSDC can damp all subsynchronous oscillations modes for three critical compensation levels. A minor change in the SSDC gain can stabilize all the oscillation modes for the fourth critical compensation level, too. Thus the midpoint SVC can achieve both the objectives of power transfer enhancement and SSR mitigation, simultaneously. The signal transmission delay is found to make the system unstable. An appropriate scheme of delay compensation is being developed.

### 3.7 References


CHAPTER 4

Mitigation of Subsynchronous Resonance in a Series Compensated Wind Farm using FACTS Controllers

4.1 Introduction

Environmental pollution and shortage of conventional fossil fuel are the two major concerns which have led to the global emergence of wind energy as an effective means of power production. Wind generating capacities have increased from negligible levels in early nineties to over 74 GW today [1-2]. This shift to wind energy will inevitably lead to large wind turbine generators (WTG) being integrated into electric power grids. It will be further necessary to transmit the generated power through transmission networks that can sustain large power flows. It is well known that series compensation is an effective means of increasing power transfer capability of an existing transmission network. However, series compensation is shown to cause a highly detrimental phenomenon called Subsynchronous Resonance in electrical networks [3-4].

Flexible AC Transmission System (FACTS) can provide an effective solution to alleviate SSR [5-9] and Thyristor Based FACTS Controllers have been employed in field for this purpose [10-11]. Wind turbines are subject to mechanical modes of vibrations related to turbine blades, shaft, gear train, tower, etc [12-13]. In the case of wind turbine generators operating radially on the end of a series compensated transmission line there is the potential for induction machine self-excitation SSR [14-15].
The main motivation behind this work is to utilize thyristor based FACTS devices for mitigation of SSR. The FACTS devices may be already installed for achieving other objectives and SSR damping function can be additionally included, or the FACTS devices can be exclusively connected for mitigating SSR. For instance, an SVC may be already located at the wind farm for dynamic reactive power support or for other power quality improvement purposes. Similarly, a TCSC may already be inserted in the transmission network to increase the power transfer capability, and the large capacity wind farm may now need to evacuate power through this series compensated network.

In this work, both an SVC at the wind farm terminal and a TCSC in series with the line are applied to damp subsynchronous oscillations. The SVC performance is examined with both voltage controller and auxiliary SSR Damping Controller (SSRDC). The TCSC is equipped with a current controller. The performance of SVC and TCSC in damping SSR is investigated over a wide range of operating conditions.

The organization of the chapter is as follows. The two mechanisms of SSR - induction generator (IG) effects and torsional interaction (TI) effects are briefly described in section 4.2. Section 4.3 outlines the study system configuration; section 4.4 proves the potential occurrence of SSR both due to IG and TI effects in a series compensated wind farm. Section 4.5 covers the control system design of the SVC and TCSC. The performance of the SVC in mitigating SSR is shown in section 4.6. The comparative performance of SVC and TCSC in obviating SSR is presented in section 4.7. Finally section 4.8 concludes the chapter.

4.2 Subsynchronous Resonance

Subsynchronous resonance occurs in a power system network when the mechanical system of the generator exchanges energy with the electrical network [3-4]. Series compensation in the line results in excitation of subsynchronous currents at electrical frequency $f_e$ given by:
Where \( x_c \) = reactance of the series capacitor; \( x_\Sigma \) = reactance of the line including that of the generator and transformer; and \( f_0 \) = the nominal frequency of the power system.

These currents result in rotor torques and currents at the complementary frequency \( f_r \) as

\[
f_r = f_0 - f_e\tag{4.2}
\]

These rotor currents result in subsynchronous armature voltage components which may enhance subsynchronous armature currents to produce SSR. There are two aspects of the SSR:

(a) Self excitation involving both Induction generator effect and Torsional Interaction  
(b) Transient torque (also called as transient SSR)

### 4.2.1 Induction Generator Effect

Self-excitation of the electrical system alone is caused by induction generator effect. This can be explained in case of a wind farm comprising self excited induction generators (SEIG) from the generic equivalent circuit of SEIG drawn in Fig. 4.1. As the rotating MMF produced by the subsynchronous frequency armature currents is moving at a speed \( N_s \) which is slower than the speed of the rotor \( N_r \), the resistance of the rotor (at the subsynchronous frequency viewed from the armature terminals) is negative, as the slip “s” of the induction generator is negative. This is clear from the equivalent circuit shown in Fig. 4.1.

\[
s = \frac{N_s - N_r}{N_s} \tag{4.3}
\]

When the magnitude of this resistance exceeds the sum of the armature and network resistances at a resonant frequency, there will be self-excitation, and the subsynchronous electrical current will tend to increase rapidly.
Fig. 4.1 Equivalent circuit diagram of a generic induction machine

\[ R_1 = \text{stator resistance}; \quad X_1 = \text{stator leakage reactance}; \quad R_2 = \text{rotor resistance referred to stator}; \quad X_2 = \text{rotor leakage reactance referred to stator}; \quad R_e = \text{core-loss resistance}; \quad X_m = \text{magnetizing reactance}. \]

4.2.2 Torsional Interactions

This form of self excitation involves both the electrical and mechanical dynamics. This may occur when the electrical resonant frequency \( f_e \) is near the complement of a torsional resonant frequency \( f_n \) of the turbine-generator (TG) shaft system [3-4]. The torques at rotor torsional frequencies may then get amplified and potentially lead to shaft failure.

4.2.3 Transient SSR

Transient SSR generally refers to transient torques on segments of the T-G shaft resulting from subsynchronous oscillating currents in the network caused by faults or switching operations. This usually occurs when the complement of the electrical network resonant frequency gets closely aligned with one of the torsional natural frequencies.
4.3 System Configuration

4.3.1 Choice of the System Parameters

Wind farms with tens or even hundreds of similar wind turbine generators (WTGs) have been erected, leading to large scale wind power projects [1]. The choice of the study systems in this chapter are based on the rating of wind farms functioning in Ontario province in Canada, as well as the wind farms operational worldwide. In Ontario, wind farms of 100 MW capacity are already in service for instance, the Kings Bridge North II wind farm and the Erie Shore wind farm at Port Burwell.

In USA, the King Mountain Wind Range in Upton County, West Texas consists of 214 wind turbines of 1.3 MW each leading to a capacity of 278.2 MW [21]. Moreover, several alternatives of integrating 500 MW to 1000 MW conventional induction wind generations are being investigated into the Dakotas transmission system, for export to the Twin Cities, Wisconsin, Iowa and Illinois [14]. In [20], a conventional synchronous generator is replaced with an equivalent wind turbine of 500 MVA rating. Based on these practical systems, the system studies in this chapter are conducted for a wind farm having a power output varying from 100 to 500 MW. Most studies are reported for a realistic wind power generation of 100 MW. Since a majority of existing Wind Turbine Generators (WTGs) are based on Self Excited Induction Generator (SEIG) [1], the studies in this chapter are conducted with SEIG based WTGs. In addition to that, as SEIG is an economic and widely used wind turbine generator with its inherent ruggedness, it is still being installed in actual field.

4.3.2 Actual Study System

The transmission network of the study system is derived essentially from the IEEE first benchmark model of SSR studies [16]. There are two separate systems which have been investigated. First of all, a set of coherent induction generators is connected to grid
through a fixed series compensated line which is depicted in Fig. 4.2. An appropriately large number of 1000 HP self excited double cage induction generators [18] are assumed to be connected together in the wind farm to provide a net power output which can vary from 100 MW to 500 MW. As induction generators do not have internal excitation system additional reactive support is needed to operate the induction generators with an improved power factor in the range of 0.98-0.99 [14] lead/lag. Two study systems are considered. In Study system 1 an SVC is connected at the induction generator terminal for dynamic reactive power support.

Fig. 4.2 Study system 1 - Wind turbine generator shunt compensated with SVC

In Study system 2 no SVC is considered. Instead, the series capacitor $X_C$ is replaced with a TCSC as shown in Fig. 4.3. The capacitive reactance of the TCSC is the same as variable line series compensation. The detailed data for both study systems are presented in the Appendix C.

Fig. 4.3 Study system 2 - Wind turbine generator with the transmission line compensated by a TCSC
4.4 SSR in Series Compensated Wind Farm

In this section both the induction generator self excitation and torsional interaction effects are studied in the Study system 1 depicted in Fig. 4.2. The system is first modified to remove the SVC so that the possibility of SSR can be examined in a non-FACTS equipped series compensated wind farm. A three phase to ground fault is implemented to study the potential of both self excitation and torsional interactions. The power flow studies are conducted using the DSA Power Tools software [17] and the electromagnetic time domain simulations are performed with the PSCAD/EMTDC software [18].

4.4.1 Induction Generator (IG) Self-Excitation Effect

The torsional system of wind turbine generator (WTG) is disabled in this investigation. Studies reported in this section show that there are two factors which influence the self-excitation phenomenon of an induction generator. These are:

- Power output of the WTG
- Levels of series compensation

These factors are addressed separately.

4.4.1.1 Variation in Wind Generator Power Output

The electromagnetic torque is obtained for WTG power outputs of 100MW, 200MW, 300MW and 500MW to examine the onset of induction generator self-excitation. The results are depicted in Fig.4.4. It is observed that for a power transfer “P” of 100 MW, the induction generator self excitation effect is not so prominent even with a series compensation level $p = 90\%$. Oscillations are visible in the electromagnetic torque but they decay with time. However, as the power transfer level is increased to 300 MW, oscillations of high magnitude appear in the electromagnetic torque. When the power transfer level reaches 500 MW, the oscillations start growing and eventually make the
system unstable. At this high power level, the induction generator is operated at a much higher speed over the synchronous speed. This increased power transfer makes the apparent negative rotor resistance exceed the sum of total armature and network resistance, thus giving rise to subsynchronous oscillations. The dominant electrical mode \( f_e \) in this case is 20.54 Hz.

For each power flow level, if the line resistance is decreased, these oscillations become larger and continue for a longer duration which is expected of induction generator self excitation oscillations. However, the line resistance reduction is not a realistic option and is hence not reported here.

Fig. 4.4 Electromagnetic torque for different WTG power outputs and same series compensation level
4.4.1.2 Variation in Levels of Series Compensation

Next, the series compensation level is varied for 500 MW generator power output. The electromagnetic torque is depicted for 50%, 60% and 80% line compensation in Fig. 4.5 while that for 90% compensation is already illustrated in Fig. 4.4. It is observed that with increasing series compensation levels the oscillations due to induction generator self excitation get enhanced making the system eventually unstable. The electrical frequency $f_e$ in the electromagnetic torque increases according to (1) and consequently, the rotor torque frequency $f_r$ decreases as in (2).
Fig. 4.5 Electromagnetic torque for different series compensation and same power flow level
4.4.2 Torsional Interactions (TI)

A very high level of series compensation is typically needed as indicated by (1) and (2) to generate a rotor torque at a frequency in the close vicinity of the resonant frequency of the wind turbine mechanical system (comprising rotor blades and gear train). There are in fact two typical resonant frequencies [12-13]:

- 1.1 Hz corresponding to the tower side ways oscillations
- 2.5 Hz relating to mechanical system

A two-mass torsional system model is added to the induction generator model in PSCAD [18]. Since both the frequencies are very close, only one torsional frequency is considered to represent the effect of both these natural frequencies. Hence, Mass 1 models the combined tower and wind turbine mechanical system and Mass 2 represents the inertia of the generator. In this case also varied levels of power flow as well as series compensations are considered to verify the existence of the torsional interactions.

4.4.2.1 Variation in Wind Generator Power Output

The WTG power output is varied with a very high level of series compensation of 90%. Fig 4.6 depicts both the electromagnetic torque $T_e$ and mechanical torque between mass 1 and mass 2, $T_{12}$, for varying levels of power flow of 50 MW, 70 MW and 100 MW. It is observed that even at 70 MW power flow the system becomes unstable with growing oscillations visible both in $T_e$ and $T_{12}$. 
Fig. 4.6 Mechanical torque between mass 1 and mass 2 ($T_{12}$) and electromagnetic torque $T_e$ for different power transfer levels at same series compensation.
Electromagnetic Torque (p.u.)
Mechanical torque between Mass 1 and Mass 2 (p.u.)

(b) $P$: 70 MW; $p = 90\%$

(c) $P$: 100 MW; $p = 90\%$

Fig. 4.6 (Contd.)
### 4.4.2.2 Variation in Levels of Series Compensation

The mechanical torque \( T_{12} \) between Mass 1 and Mass 2 and electromagnetic torque \( T_e \) of the WTG are depicted for varying levels of series compensations of 50\%, 65\% at 100 MW power flow in Fig. 4.7. The results for 90\% are already displayed in Fig. 4.6. It is observed that with increasing series compensation levels the oscillations due to torsional interaction also get enhanced making the system eventually unstable even at realistic levels of compensation of 65\% [3,4,5,19]. In each case, the electromagnetic torque signal displays both the torsional mode and subsynchronous electrical mode oscillations superimposed on it.

![Graph showing mechanical and electromagnetic torques](image)

**Fig. 4.7** Mechanical torque between mass 1 and 2 \( T_{12} \) and electromagnetic torque \( T_e \) for different series compensation and same power flow; \( f_r = 0.8 \) Hz
4.5 Controller Design of SVC and TCSC

4.5.1 Controller Design of SVC

In Study system 1, the SVC is mainly used to regulate the wind farm bus voltage during disturbances in the system. An auxiliary subsynchronous resonance damping controller (SSRDC) is designed and added suitably to enhance the torsional mode damping of the system. The general configuration of an SVC with its voltage regulator and auxiliary controller is shown in Fig. 4.8.
In this study the voltage regulator is a simple PI controller whose proportional gain is set to zero. The integral gain is selected by systematic hit-and-trial method using time domain simulation [18] to give the best $K_I$ which results in a fast rise time and minimal settling time with acceptable overshoot (10%) in generator terminal voltage in response to a step change in the reference voltage $V_{ref}$. The auxiliary controller $H(s)$ can take different structures depending on which control design technique is being employed [19]. The structure of the auxiliary subsynchronous damping controller (SSRDC) is shown in Fig. 4.9 where $\Delta SiG$ represents the incremental value of the auxiliary signal or the feedback signal. The different signals generally considered as input to the auxiliary controller are line real power flow, line current magnitude, bus frequency, bus voltage magnitude, etc [6]. In this chapter, the wind turbine generator speed deviation ($\Delta \omega$) has been used as an auxiliary signal to damp the unstable modes.

The SSRDC comprises a simple proportional controller through a washout circuit. The purpose of washout circuit is to prevent the auxiliary controller from responding to steady
state power flow variation. The proportional gain of SSRDC is determined from systematic hit and trial using the nonlinear time domain simulation using PSCAD software to result in fastest settling time. The output of the SSDC is then fed to SVC voltage regulator as shown in Fig. 4.9.

4.5.2 Controller Design of TCSC

The thyristor controlled series capacitor (TCSC) increases the power transfer capability of a transmission network in addition to several other functions [5-6]. It provides a rapid, continuous control of the transmission line series compensation level thus dynamically controlling the power flow in the line.

In Study system 2, the TCSC is assumed to be primarily employed in the network for controlling line reactance and thereby the power flow. The SSR damping function is added through constant current control for this study. It is reported [9] that a TCSC operating at fundamental frequency offers a pure capacitive reactance to increase the power transfer capability of the network. On the other hand the same TCSC offers resistive and inductive impedance at subsynchronous frequencies which assists in damping subsynchronous modes. The resistive impedance of the TCSC increases with the increased boost factor which is the ratio of the capacitive reactance offered by the TCSC and the total line reactance.

The general configuration of a TCSC is shown below:

![Fig. 4.10 General configuration of a TCSC](image)

For this configuration the equivalent TCSC reactance is computed as per the following equation:
\[
X_{TCSC} = X_C - \frac{X_C^2}{X_C - X_L} \frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{X_C - X_L} \frac{\cos^2 \beta}{k^2 - 1} \frac{k \tan k\beta - \tan \beta}{\pi}
\] (4.4)

Here \( \beta \) = angle of advance (before the forward voltage becomes zero) = \( \pi - \alpha \), \( \alpha \) is the firing angle of the thyristors. It is noted from (4) that a parallel resonance is created between \( X_C \) and \( X_L \) at the fundamental frequency, corresponding to the values of firing angle \( \alpha_{res} \), given by:

\[
\alpha_{res} = \pi - (2m - 1) \frac{\pi \omega}{2\omega_r}
\] (4.5)

The different resonances can be reduced to only one by proper choice of \( k = \omega_r/\omega = \sqrt{(X_C/X_L)} \) in the range \( 90^0 < \alpha < 180^0 \). As \( X_C \) is known, \( X_L \) can be calculated once a proper value of \( k \) is chosen to ensure a single resonant peak. Once the \( X_C \) and \( X_L \) values of the TCSC are computed, a closed loop current control scheme is employed for the proposed application. The functional block diagram of TCSC is depicted in Fig. 4.11.

![Fig. 4.11 TCSC Constant Current Controller](image)

Here \( I_{ref} \) is the pre-fault or pre-contingency current calculated from EMTDC/PSCAD line-current phasor. The main current controller is a PI Controller. The parameters of this controller are also adjusted systematically through electromagnetic transient simulation studies by hit-trial to get the minimum settling time or fastest damping.
4.6 Performance of SVC in the Mitigation of SSR

Having demonstrated above that the SSR phenomenon can potentially exist in the series compensated wind farms, the damping of subsynchronous oscillations (SSO) through SVC control is now considered in this section.

4.6.1 Damping of IG Effect

The performance of the SVC in alleviating IG effect is evaluated at the worst possible operating point of 500 MW power transfer and 90% series compensation level. Fig. 4.12 depicts signals below with and without SVC voltage regulator.

- Electromagnetic torque of the generator ($T_e$)
- Generator rotor speed ($\omega_r$)
- Generator terminal voltage ($V_t$)
- SVC reactive power ($Q_{SVC}$)

![Fig. 4.12 Performance of SVC in damping SSO due to IG effect: (a) Electromagnetic torque](image)
Fig. 4.12 (Contd.) (b) Generator rotor speed; (c) Generator terminal voltage; (d) SVC reactive power
4.6.2 Damping of TI Effect

Torsional interactions become prominent at a power transfer level of 100 MW. As a result the damping performance of SVC with respect to TI effect is shown at 100 MW power flow and 90% series compensation. The signals reported to demonstrate the damping performance of SVC are:

- Mechanical torque between Mass 1 and Mass 2 ($T_{12}$)
- Generator rotor speed ($\omega_r$)
- SVC reactive power ($Q_{svc}$)

The impact of the SVC voltage regulator and SSRDC is displayed in Fig. 4.13. It is observed that the SVC voltage regulator damps the SSO due to TI effect. Moreover, the damping is substantially enhanced by SSRDC of SVC.

![Fig. 4.13 Performance of SVC in damping SSO due to TI Effect (a) Mechanical torque between Mass 1 and Mass 2](image.png)
4.7 Performance of TCSC in Mitigation of SSR and Comparison with SVC

Intuitively, a series device can directly influence the line impedance of a network unlike a shunt device which always imparts a reactance in parallel with the network. As mentioned in section 4.5, increasing the TCSC series compensation offers more resistive and inductive impedance at subsynchronous frequencies. As TCSC is a series device, more resistance will directly add on to the line impedance improving the system.
damping. From these two factors TCSC is expected to be more effective in damping SSR both due to torsional interactions and induction generator effects. The following figures compare the performance of the TCSC and SVC in damping IG and TI effects. In case of torsional interactions TCSC closed-loop current control performs even better than the SSRDC of the SVC.

### 4.7.1 Damping of IG Effect

In this case, the damping performance of the TCSC is shown for the worst possible operating condition of 500 MW power flow and 90% series compensation. The signals utilized for examining the damping performance of TCSC are:

- Electromagnetic torque of the generator \(T_e\)
- Generator rotor speed \(\omega_r\)
- Generator terminal voltage \(V_t\)

These signals are depicted in Fig. 4.14 for the cases - without any FACTS device, with SVC voltage regulator (VR) and with TCSC current controller (CC). The performance of TCSC is clearly superior in damping SSO due to IG effect for the case of 90% series compensation.

![Fig. 4.14 Performance comparison of SVC and TCSC in damping SSO due to IG effect](image)

(a) Electromagnetic torque
4.7.2 Damping for TI Effect

Finally, the damping of TCSC in mitigating torsional interaction is investigated. The signals examined are:

- Mechanical torque between Mass 1 and Mass 2 \((T_{12})\)
- Generator rotor speed \((\omega_r)\)
- TCSC reactance \((X_{TCSC})\)
These signals are plotted in Fig 4.15 for the cases - without any FACTS device, with SVC-SSRDC and with TCSC-CC. Even though the SVC auxiliary controller for SSR (SSRDC) improves the damping of the mechanical torque between Mass 1 and Mass 2, the TCSC closed-loop control provides a much faster damping.

Fig. 4.15 Performance comparison of SVC and TCSC in damping TI (a) Mechanical torque between Mass 1 and Mass 2 (b) Generator rotor speed
4.8 Conclusions

With the rapid growth of wind power penetration into the power system grid, wind farms will likely be evacuating bulk power through series compensated networks. This will render the power system vulnerable to SSR. In this chapter two thyristor based FACTS devices, SVC and TCSC are applied to damp SSR in such a series compensated wind farm. The following conclusions are drawn from extensive electromagnetic transient simulation studies over widely varying levels of power flow and series compensation:

- SSR is a potential threat in series compensated wind farms even at realistic levels of series compensation and practical levels of power flow.
- SVC and TCSC are both effective in damping subsynchronous oscillations due to torsional interaction as well as induction generator effects, when the system is subjected to a severe fault.
- SVC-SSRDC provides an improved damping of the torsional interactions as compared to a pure SVC voltage regulator.
- TCSC current control is better than SVC in mitigating SSR even when the SVC is equipped with the SSRDC.
In this chapter, the possibility of SSR occurrence is studied with self-excited induction generators (SEIG) based wind farms. Studies are presently being conducted to investigate the SSR potential with WTGs based on doubly fed induction generators (DFIG) and AC-DC-AC converter based synchronous generators.

4.9 References


CHAPTER 5

Overvoltages at the Point of Interconnection of a Large Wind Farm and Extra High Voltage Double Circuit Transmission Lines

5.1 Introduction

Ferroresonance and self-excitation are two known causes of severe overvoltages, transformer saturation and harmonic pollution in power systems [1-4]. These two phenomena can occur in a variety of system configurations. Double circuit transmission line is one of the configurations where ferroresonance is reported to occur [2]. Application of extra high voltage (EHV) double circuit lines is an effective means of transmitting bulk power over long distances. However, when the two lines run on the same tower there exists a capacitive coupling between them. If one of the two lines gets disconnected due to any contingency, high amount of electric charge is trapped in this capacitive coupling which may interact with the magnetizing inductance of a transformer connected to the de-energized line. This is a classical ferroresonance scenario and can be the cause of severe overvoltages across transformer terminals [2]. With the increasing penetration of wind energy based distributed generation in power systems, large wind farms will likely be connected to the low tension side of such a transformer feeding the grid through these EHV double circuit lines. The wind turbine generators may then be subjected to overvoltages caused by ferroresonance.
In a severe contingency of this nature warranting the disconnection of the main transmission line, protection systems will ensure the shut down of the wind farm connected to it. In this scenario, as an operational wind farm supplying power through the same interconnection suddenly gets disconnected, self-excitation of the wind turbine connected induction generator may occur due to its interaction with the compensating capacitance connected either at its own terminal \([5-9]\) or with the power electronic converter associated with it. This self-excitation will aggravate the overvoltage and eventually lead to potential damage of costly wind turbine generators and other installed equipment.

Although the issue of overvoltages caused by distributed generators has been addressed in literature \([10-12]\), the case of large wind farms of capacity greater than 100 MW and especially its interconnection in the unique double circuit configuration, have not been considered. In this chapter, first the wind farm is represented as a group of self-excited double-cage induction generators with their detailed nonlinear electromagnetic transient models. Later, the wind turbine generators are modeled as a vector controlled doubly fed induction generator (DFIG) of appropriate rating. DFIG is also modeled in detail, representing all the power electronic converters with their nonlinear high frequency switching characteristics. A number of operating conditions are studied to investigate the severity of the problem. It is observed that the overvoltages at the point of interconnection and also at the generator terminal are generic and independent of generator configurations. Several remedial measures have been further proposed to arrest the overvoltage.

The organization of the chapter is as follows. In section 5.2 the study system is described with its operating conditions. Modeling of the system is briefly outlined in section 5.3. Section 5.4 proves the existence of ferroresonance in this unique configuration of double circuit transmission line. The overvoltages encountered by the wind farm with different modeling details are reported in section 5.5. In this section the need for the field validated model of a doubly fed induction generator is pointed out. Possible mitigating measures are proposed in section 5.6 with an emphasis on most
economical solution. In this section, first of all the protection of the transmission line is proposed and then it is shown that even after the protection isolates the wind farm from the grid, it is still subjected to self-excitation. Further, protection of the wind turbine generators from self-excitation is also reported in this section. Finally, section 5.7 concludes the chapter.

5.2 Study System

An example of a large wind farm connected to double circuit EHV lines is the upcoming Kingsbridge II wind farm with the 500 kV Bruce Longwood coupled double circuit line. The transmission system around the Kingsbridge II wind farm is shown in Fig. 5.1. This is a part of the electric grid of Hydro One Networks Inc. In this system, Bruce A and Bruce B are two major Nuclear Power Stations which are connected to Longwood by a 500 kV, 250 km double circuit transmission line. These two lines are called B562L and B563L and run on the same tower. Currently each of these lines carries a maximum power of 800 MW and 100 MVAR resulting in a total power transfer of 1600 MW to Longwood. B562L is tapped at a distance of 65 km from Bruce B for a future interconnection of Kingsbridge II Wind Generating Station of 160 MW capacity through a 175 MVA 500 kV/ 34.5 kV Y-Δ connected transformer. The wind farm will comprise 69 Siemens Mark 2.3 MW wind turbine generators.

Fig. 5.1 Study system
This system has a unique configuration of double circuit transmission line. Usually double circuit lines are connected to the same generating source. However, here the two lines B562L and B563L originate from two different generating stations Bruce A and Bruce B but run on the same tower for a distance of 250 km and eventually merge in the same TS called Longwood. Due to their proximity there exists a high coupling capacitance between these two lines.

5.3 System Modeling

The study system shown in Fig. 5.1 is modeled using the nonlinear, electromagnetic transient program EMTDC/PSCAD [13]. Power flow through the lines is specified by Hydro One. Unified magnetic equivalent circuit or UMEC approach of the EMTDC has been adopted to model the transformer with its detailed saturation characteristics supplied by the manufacturer. In UMEC modeling approach, the transformer saturation is modeled using a piecewise linear technique. Wind turbine generators are also modeled with high accuracy and detail. Self-excited induction generators are modeled as squirrel cage induction machines with double cage rotor. On the other hand the doubly fed induction generator is modeled as an appropriately rated wound rotor induction machine with grid side and rotor side voltage source converters which are vector controlled to achieve decoupled active and reactive power flows.

5.4 Ferroresonance

The part of the study system which is likely to cause ferroresonance is identified in Fig. 5.2. In this diagram the system comprises the double circuit transmission line and the interconnecting transformer which is open at its secondary side. Ferroresonance will occur the moment the breakers $B_1$ and $B_2$ get opened and $B_5$ fails to open. At this instant the saturable transformer magnetizing reactance appears in series with the coupling capacitance between the two lines, forming a ferroresonance path. This is a practical scenario where $B_1$ and $B_2$ can malfunction due to any contingency outside their
protection zone and get opened at the same time. This is typically called nuisance tripping of the breakers. As the breaker B5 will experience high voltage due to the opening of B1 and B2, B5 may get stuck and fail to isolate the transformer.

![Diagram of the system for Ferroresonance studies](image)

Fig. 5.2 Part of the system for Ferroresonance studies

Varying power flow levels of 150 MW, 500 MW and 800 MW through B562L are considered to study the magnitude of the overvoltage and the time it takes to reach a detrimental level. In each of the cases power flow through B563L is maintained at a constant level of 800 MW. Breakers B1 and B2 are tripped at t = 2s. Fig. 5.3 (a), (b) and (c) display the instantaneous voltages of phase A at the point of tapping for 150, 500, 800 MW power flow levels respectively. The voltage waveform shows that within 3 cycles, it reaches 3.0 pu peak which could be detrimental for the transformer. For low levels of power flow the voltage reaches higher value than that of a higher power flow level. The reason is at high power flow the inductive effect of the line reduces the pre-contingency voltage at the point of tapping. However, the voltage magnitude remains almost same for 100 MW and 500 MW power flows through B562L. For 800 MW power flow it reduces to 2.5 pu peak which is not widely different from that of 100 MW or 500 MW scenario. The frequency content of the voltage signal is shown in Fig. 5.4. There is a prominent third harmonic component due to transformer saturation.
Fig. 5.3 Instantaneous voltage at the point of tapping for varying power flow levels
Studies reported in this section confirm that the loading level of the transmission line (B562L) which is connected to the transformer has minor influences on the overvoltage magnitude due to ferroresonance. Power flow through the other line (B563L) has hardly any impact on the overvoltages caused by the ferroresonance.

Similarly, Fig. 5.5 (a), (b) and (c) respectively show the transformer primary current through phase A for the same power flow levels mentioned before. After the breakers get opened the current reaches 5 p.u. peak within 3 cycles which is unacceptably high. The current peak after the contingency is approximately same for all the three power flow levels considered in this study. The frequency spectrum of the current waveform shown in Fig. 5.6 confirms the presence of a strong third harmonic in addition to fifth and seventh harmonics of relatively less magnitude.
Fig. 5.5 Transformer primary current in phase A for varying power flow levels
5.5 Effect of Wind Farm Interconnections

Wind farm interconnections with a utility network can be classified into two broad categories. In the first category, the wind farm is connected to a high voltage transmission line through a station transformer owned by the utility. Typical transmission line voltage levels are 115 kV, 230 kV, 500 kV etc. On the other hand the wind farm may be directly connected to a low voltage distribution network through the pad-mounted transformers of the wind turbine generators. Distribution network can also be of different voltage levels such as 28 kV, 34.5 kV, 44 kV etc. Kingsbridge II wind farm falls in the first category. This will be interconnected at the 34.5 kV side of the transformer shown in Fig. 5.1. The effects of this upcoming wind farm and its interactions with the Bruce-Longwood transmission corridor of Hydro One are studied in this section.

5.5.1 Wind Farm Modeled as an Ideal Source

First of all the wind farm is simulated to be an ideal source which is added to the 34.5 kV side of the transformer. The power output of the wind farm is varied from 50% to 100% of its rated capacity. The power flows through B562L and B563L are kept constant to a level of 800 MW which is currently the maximum power transfer through Bruce-Longwood transmission corridor. For this power flow level, the effects of 50% and 100%
wind penetration on the overvoltage at the point of interconnection are examined. The
contingency is the same as described in section 5.4 (i.e. Breakers B₁ and B₂ are tripped at
t = 2s).

In this scenario B562L which is the main line transmitting power from Bruce A and
also from the Kingsbridge II wind farm, is suddenly disconnected. Operation of B₁ and
B₂ disconnects Bruce A but the wind farm near Kingsbridge will continue to feed B562L
which is already de-energized. However, as there is no energy dissipation path
overvoltage is experienced by the transformer and the wind generating station. After
B562L is disconnected, the remaining path comprising the wind farm and its
interconnecting transformer may be prone to the following:

- Ferroresonance between the mutual coupling of the two transmission lines and the
  magnetizing inductance of the transformer.
- Self-excitation of the wind turbine generators.
- LC oscillations between the line charging capacitance and the transformer leakage
  inductance.

The overvoltage could also be a combined effect of all the factors mentioned above.

Fig. 5.7 (a) and (b) show the instantaneous voltage at interconnection point for 80 MW
(50%) and 160 MW (100%) wind power penetrations whereas Fig. 5.8 (a) and (b) display
transformer primary current for the same wind power generation. Overvoltage magnitude
in this case reaches to 3.0 p.u. peak as observed in Fig. 5.7.
Fig. 5.7 Instantaneous voltage of phase A at the point of tapping for varying wind power penetration.

Fig. 5.8 Transformer primary current in phase A for varying wind power penetration.
Comparison of Fig. 5.3 and Fig. 5.7 shows that although the overvoltage peak after the addition of wind farm reaches 3.0 p.u. momentarily it does not increase any further unlike the ferroresonance scenario where the voltage waveform was of modulated nature with an increased peak of 5.0 pu. As a result, addition of the wind farm as an ideal source, which is essentially a sink, provides a dissipation path of the trapped energy in the coupling capacitance of the double circuit line previously causing ferroresonance. In this case as well, the variable output of the wind farm has insignificant effects on the overvoltages caused due to the tripping of B562L. The magnitude of voltage and current peaks remains almost same in Fig. 5.7 and 5.8, respectively.

5.5.2 Wind Farm Modeled as SEIG

In the next stage of studies, the wind farm is modeled as a group of 200, 1000 HP coherent self-excited induction generators. The wind farm generates 50% of its rated capacity which is 80 MW. The output of the wind farm is kept much less than its rated capacity, as all the wind turbine generators of a wind farm rarely operate at their full capacity at the same time. However, wind farm operating at its full capacity has also been studied. The overvoltage peak remains same for that case as explained in section 5.5.1.
The power flow through B562L, B563L and the contingency are same as in the previous sections.

Fig. 5.9 (a), 5.10 (a), 5.11 (a) respectively depict the instantaneous voltage of phase A at the point of interconnection, transformer primary current and the terminal voltage at the wind turbine generators. Fig. 5.9 (b), 5.10 (b) and 5.11 (b) show the Fast Fourier Transform (FFT) analysis of the corresponding signals. It is apparent from all the figures that the voltage and current peaks reach a dangerous level within 3 cycles after the tripping of the breakers. The frequency spectrum shows that both the voltage and currents contain prominent third and fifth harmonics which appear due to the saturation of the interconnecting transformer.

Fig. 5.9 (a) Instantaneous voltage of phase A at the point of tapping and (b) its frequency content
Fig. 5.10 (a) Transformer primary current in phase A (b) its frequency content

Fig. 5.11 (a) Instantaneous phase A voltage at wind turbine generator terminal
It is observed that wind turbine generators modeled as SEIG can absorb the energy in motoring mode only. In this case also the generators (SEIG) go into motoring mode as their active and reactive power outputs oscillate between positive and negative values. This is shown in Fig. 5.12 below. Similarly, the speed of the generator oscillates from subsynchronous to supersynchronous region as shown in Fig. 5.13. LC oscillations of fundamental frequency are also seen to exist along with the harmonic components which are clear from the FFT plots of voltage and current signals shown in Fig. 5.9 (b) and Fig. 5.10 (b).

Fig. 5.12 Active and reactive power of the wind farm
5.5.3 Wind Farm Modeled as DFIG

Same scenario as in previous sections is simulated when the wind turbine generators are modeled as doubly fed induction generators (DFIG). The power flow levels, contingency and the examined signals are identical to section 5.5.2.

Fig. 5.14 (a), 5.15 (a), 5.16 (a) respectively show the instantaneous phase A voltage at the point of connection, instantaneous transformer primary current through phase A and A phase terminal voltage of the wind turbine generators. Fig. 5.14 (b), 5.15 (b) and 5.16 (b) depict the frequency components of the corresponding signals. Similar to the case of SEIG, the DFIG is subjected to an overvoltage of 3.0 p.u. peak once B562L is de-energized. Here also, odd harmonic components are prominent in transformer primary current due to the saturation of the transformer.

Doubly fed machines also operate in motoring mode and are vulnerable to overvoltages of detrimental magnitudes when they are connected to a de-energized long transmission line. Power output from the generator depicted in Fig. 5.17 oscillates between positive and negative values which clearly show the machine is oscillating between generating and motoring mode. Similar is the situation of reactive power output of the machine in Fig. 5.18. Generator rotor speed in Fig. 5.19 stays subsynchronous.
Fig. 5.14 (a) Instantaneous voltage of phase A at the point of tapping and (b) its frequency content

Fig. 5.15 (a) Transformer primary current in phase A
Fig. 5.15 (Contd.) (b) its frequency content

Fig. 5.16 (a) Instantaneous phase A voltage at wind turbine generator terminal and (b) its frequency content
Fig. 5.17 Active power output of the wind farm

Fig. 5.18 Reactive power output of the wind farm

Fig. 5.19 Generator rotor speed
5.5.4 Limitations of the DFIG Model

The study of overvoltages at the terminal of the wind farm comprising an appropriately rated DFIG is carried out with the generic model available in EMTDC/PSCAD. The magnitude of the overvoltage peak and the time it takes to reach the peak value depend on the proper modeling of the doubly fed generator and the converter system associated with it. Hence a field validated DFIG model in EMTDC/PSCAD is necessary to further evaluate the overvoltages at its terminal. Prior to the validation of a DFIG model in electromagnetic transient domain, the validation of the same DFIG model in transient stability domain may be necessary. The Appendix A of this thesis reports such a validation study of a doubly fed induction generator model with field test results in transient stability domain. The GE 1.5 MW doubly fed wind turbine generator model available in PSS/E Wind Software and installed at AIM Erie Shore Wind Farm of HONI is attempted to validate with the field tests conducted at this wind farm.

5.6 Remedial Measures of the Overvoltages

Protection of the transmission line along with the wind farm from this detrimental overvoltage is challenging. The first step is to protect the transmission line which is subjected to overvoltage at the point of interconnection. Fig. 5.20 pictorially depicts the protection task.

With the simultaneous opening of B₁ and B₂, B₅ should disconnect the transformer along with the wind farm. This will break the ferroresonance path and also save the transmission line. However two concerns are raised by Hydro One with this protection scheme. First of all this study proves that if B₅ fails to operate severe overvoltage may damage the transmission line, transformer and the wind turbine generators. To overcome this situation another breaker B₅₅₆₅ is planned to be installed as the backup of B₅. The main challenge in this scheme is to ensure synchronized operation of B₁, B₂, and B₅ or B₅₅₆₅. At the first stage it was planned to divide B₅₆₅₂ into two separate zones of protection so that the entire line section will not be out of service at the same time. The wind farm will
always be connected to the grid through the transmission line section which is operational. The protection scheme is shown in Fig. 5.21.

In Fig. 5.21, the line B562L is split into two zones by installation of two additional breakers $B_{1A}$ and $B_{2A}$. These two breakers will ensure that for any contingency outside or inside their protection zones if $B_1$ gets opened $B_{1A}$ will simultaneously be opened. Similar is the case of $B_2$ and $B_{2A}$. As a result, the wind farm in this configuration will always be connected to grid either through path 1 or through path 2. Even though it seems to be an ideal situation this is a highly expensive scheme requiring two additional breakers.
A more practical 3-ended differential protection scheme is eventually proposed which is shown in Fig. 5.22.

The 3-ended differential scheme on B562L will have 'A' and 'B' line differential relays at Bruce A, Longwood and Kingsbridge II tap substation. Channel 'A' scheme is described with the understanding that the 'B' scheme is similar.

The 'A' protection will have a GE L90 at each of the three terminals listed above, linked by dedicated communication channels (Ch1 and Ch2). As an arbitrary assignment, Ch1 will daisy chain from Bruce A L90, to Kingsbridge II Tap L90 to Longwood L90, and back to Bruce A L90. Ch2 will daisy chain the other way - from Bruce A L90 to Longwood L90 to Kingsbridge II Tap L90, and back to Bruce A L90. With this configuration, each L90 is in direct communication with the other two L90s, so that any failure on any one leg of a channel is not a problem, as the L90s connected to the broken channel can still communicate via the third L90 on the non-problematic channel.

For the situation where Bruce A, and Longwood both open the B562L line simultaneously, the L90 logic can be made to evaluate the status of breakers and line disconnects at both Bruce A and Longwood. If all breaker-switch combinations point to an open line, the L90s at both Longwood and Bruce A can send trip to Kingsbridge II
Tap station. The typical transmission time would be 8 ms through synchronous optical network (SONET).

It is to be noted that the protection schemes mentioned above will ensure the complete protection of the transmission line. However, even if B_5 or B_{5A} operates the wind farm is still connected to the transformer and is subject to the overvoltages caused by self-excitation. This is shown in Fig. 5.23.

Studies are conducted to show that once the wind farm is disconnected from the transformer, even though the voltage at the point of interconnection and the transformer primary current become zero, wind turbine generators are indeed subjected to overvoltages due to self-excitation. The SEIG and DFIG configurations of wind turbine generators are considered to study the effects of self-excitation in wind farm.

![Diagram](image)

Fig. 5.23 Possible occurrence of self-excitation of the wind farm

### 5.6.1 Self-excitation in SEIG

In this section the wind farm is represented as in section 5.5.2. The self-excitation occurs due to the interaction of the induction generator with its shunt compensator. In this case B_1, B_2 and B_5 are opened simultaneously at t = 2s with the transformer and the wind farm connected.
Fig. 5.24 (a) Instantaneous voltage at the point of tapping
(b) Transformer primary current, (c) WTG terminal voltage
From Fig. 5.24 (a) and (b) it is clear that although the instantaneous voltage at the point of interconnection and transformer primary current become zero once \( B_5 \) gets opened, the voltages at the WTG terminal still exist and reach as high as 2.5 pu peak and shown in Fig. 5.24 (c). This overvoltage could be harmful for the wind turbine generators if proper protection is not there. The FFT analysis of the generator terminal voltage depicted in Fig. 5.24 (d) proves a few high frequency harmonic contents in the range of 100 to 200 Hz which may be caused by the self-excited, isolated generator. Further analysis is needed to theoretically justify the reasons for the emergence of these modes.

### 5.6.2 Self-excitation in DFIG

The wind farm is now modeled as in section 5.5.3. In this case the self-excitation occurs due to the interaction of the excitation system of DFIG comprising the power electronic converters and the induction generator. Only the voltage at the wind turbine generator terminal is shown in Fig. 5.25 (a). The instantaneous voltage at the point of interconnection and the transformer primary current will remain same and are already displayed in Fig. 5.24. It is clear from Fig. 5.25 that high terminal voltage of 4.0 pu peak will occur at the generator terminal which is a potential threat to the costly generators. The FFT analysis of the generator terminal voltage as shown in Fig. 5.25 (b) depicts a few predominant high frequency harmonics in between 125 Hz and 135 Hz. There are
some more high frequency contents around the frequency ranges of 300 and 410 Hz respectively with far less magnitude than the harmonic content between 125 Hz and 135 Hz. These high frequency contents may be due to the self-excited doubly fed induction generator whose rotor speed will naturally increase once it is isolated from the transmission line. The power electronic converters may also be responsible to produce some of these high frequency components. However, further analytical studies will be required to determine the origin of these modes.

Fig. 5.25 (a) The self-excitation effect of the DFIG and (b) its FFT analysis
5.6.3 Mitigation of Self-excitation

Transfer trip scheme is usually installed with the new interconnection of wind farms, especially for high voltage interconnection of this type. However, transfer trip scheme may be too slow in this situation. This is due to the fact that the transmittal time of the trip signal through communication channels is directly proportional to the length of the transmission line. However, the overvoltages may reach a dangerously high magnitude within 3 cycles (less than 50 ms time) which is much faster than the signal transmission time of transfer trip scheme. That is one of the reasons for the proposal of 3-ended differential protection. However, as it is shown in the previous sections 5.6.1 and 5.6.2 respectively that differential protection of the transmission line alone may not guarantee the full protection of the system due to the self-excitation effects of the generators.

In addition to that the excitation system of the generators has to be shut down with equal speed as that of the transmission line breakers. Disconnecting the excitation system solves the self-excitation problem and a few wind turbine generator manufacturers such as VESTAS do ensure that the shunt capacitor at the generator terminal gets disconnected when the machine is cut out from the system. Similar recommendations are also applicable to the DFIG where the switches of the power electronic converters have to be blocked once the machine is out from the point of connection. Then only full overvoltage protection could be ensured. The protection scheme to completely alleviate this overvoltage problem is shown in Fig. 5.26. In this figure B6 and B7 must be opened with the opening of B5 or B5A. The generator terminal voltages for the SEIGs and DFIGs after their excitation systems are turned off are shown in Fig. 5.27 and Fig. 5.28, respectively. It is clear that once the excitation system is turned off high voltage across the disconnected generator disappears. The machine terminal voltage decays to zero. As there is no shunt capacitor at the DFIG terminal the voltage across it decays much faster than that of the SEIG. However, it also depends on the machine time constants and parameters.
3-ended differential protection scheme which will ensure almost simultaneous operations of B, B₂ and B₅.

![Diagram of protection scheme](image)

Open Breaker Status
Closed Breaker Status
Backup of B₅
Ensures disruption of Ferroresonance path

B₆ and B₇ must be opened with the opening of B₅ or B₅A.

Fig. 5.26 Protection scheme to fully alleviate the overvoltage problem

![Graph of phase A instantaneous voltage](image)

Fig. 5.27 Mitigation of self-excitation of SEIG
5.7 Conclusions

In this chapter the overvoltage problem encountered by a large wind farm connected to a long, high voltage double circuit transmission line of unique configuration is thoroughly studied. Extensive nonlinear time domain simulations using EMTDC/PSCAD have been carried out to prove that the wind farm is subjected to severe overvoltage if the transmission line through which it is connected to the grid is suddenly disconnected. The possible causes of this overvoltage include ferroresonance between the capacitive coupling of the double circuit transmission line and the magnetizing inductance of the transformer, self-excitation of the singly excited and doubly fed induction generators and also LC oscillations of the line charging capacitance and the transformer leakage inductance or the combination of them. FFT analysis is performed at each stage to show the frequency contents of the signals under investigation. An economic and fast 3-ended differential protection scheme of the transmission line is proposed to arrest this overvoltage. It is further shown that transmission line protection alone is not sufficient to protect the generators. In addition the generator excitation system has also to be shut down to fully mitigate this problem. Essentially therefore, a coordinated control of excitation system and the main transmission line breakers relaying scheme must be established.
5.8 References


Generation by Induction Generators: Incidence of Self-Excitation Phenomenon,”


CHAPTER 6

Conclusions and Future Work

This thesis deals with diverse power system problems related to wind farm integration and their alleviation through FACTS devices. It begins with a study of inter-area oscillations of multi-machine power systems and various resonance issues encountered in a power system network fed by conventional synchronous generators as well as wind turbine generators. The thesis further deals with the validation of doubly fed wind turbine generators and relevant applications of Flexible AC Transmission System devices to solve some of these problems. FACTS devices are primarily applied as the remedial measures to subsynchronous resonance and inter-area oscillations with local and remote signals acquired by wide area measurements. The contributions of the thesis are summarized at first. Major conclusions drawn from the various system studies reported in this thesis are then outlined. Finally, future directions of research are also suggested.

6.1 Major Contributions

- A weighted sum of the derivative of remote generator bus voltage angle signals is effectively utilized in SVC control for damping inter-area oscillations.

- Remote generator speed signal used for the first time for SSR damping with SVC.

- Subsynchronous resonance is shown to be a potential threat in series compensated wind farms even at realistic series compensation levels.

- Damping of above SSR accomplished both with SVC and TCSC for the first time.
Potential of severe overvoltages demonstrated for the first time in grid interconnection of large wind farms and remedial measures proposed.

GE 1.5 MW Doubly Fed Induction Generator model has been validated through extensive field tests in Hydro One’s network. This study has been done for the first time in HONI network in Ontario.

Recommendations for system performance improvement provided.

6.2 Chapter-wise Summary

6.2.1 Damping of Inter-area Oscillations

Damping of inter-area oscillations by FACTS devices using PMU-acquired global signals is well reported. However, a simple replication of generator rotor speed deviation by means of the derivative of the remote generator bus voltage angles acquired by the phasor measurement units is one of the contributions of this thesis. It is shown that the derivative of the generator bus voltage angle can mimic the generator rotor speed and hence is equally effective in inter-area oscillation damping when used as the input to the power swing damping controller of a static VAR compensator. The effectiveness of the proposed signal is compared with different local signals such as line current or line power and is found to be superior even with a highly stressed network condition subjected to different types of contingencies. Signal transmission delay encountered in wide area measurements is duly taken care of and a lead lag compensator is designed to compensate the delay. The main conclusion from this work is that a weighted combination of global signals performs better than the locally acquired signals in damping low frequency inter-area oscillations as the lightly damped modes contributed by multiple machines are more observable in remote generator speed than many other local signals. Although signal
transmission delay affects the performance of the remote signals, its effects can be minimized through appropriate compensation.

6.2.2 Performance of Remote Generator Speed in the Damping of SSR

Performance of remote signals in damping subsynchronous resonance is not well reported. This thesis proposes to employ remote generator speed as the input to subsynchronous damping controller of a mid-point connected SVC originally meant for voltage control purposes. The study is performed on the IEEE 1st Benchmark Model for SSR studies. The main conclusion is that remote generator speed deviation prominently exhibits all the unstable subsynchronous modes. As a result this signal is capable to damp all four SSR modes for all critical levels of compensations. A single proportional and derivative controller is sufficient to damp the SSR corresponding to first three critical levels of compensation whereas a slight modification of the same controller successfully damps the SSR for most critical level of series compensation. Such studies involving remote generator speed for damping SSR using an SVC have been done for the first time.

6.2.3 SSR in Series Compensated Wind Farms

The possibility of occurrence of SSR in a series compensated transmission line fed by a wind farm and mitigation of the same with FACTS devices are first reported in this thesis with rigorous nonlinear time domain simulations. This study shows that induction generator effects and torsional interactions are likely to occur in a wind farm supplying power to the grid by a series compensated line. Even a realistic series compensation level may cause potential instability of the system due to these two effects. The frequencies of oscillations appearing in various system variables due to these effects are identified by the FFT analysis. The relation between these frequencies and series compensation levels is also justified. Alleviation of this severe system instability is extensively studied using two FACTS devices, static VAr compensator and thyristor controlled series capacitor. A
comparative study of the damping performance of SVC voltage regulator, SVC subsynchronous damping controller and the TCSC current controller proves the superiority of TCSC over the SVC. In short, subsynchronous resonance is a potential problem of a series compensated wind farm and it can be overcome by using additional damping capability of FACTS devices which are installed for other system performance improvement purposes. These studies have also been performed for the first time.

6.2.4 Overvoltages at the Terminal of a Large Wind Farm Connected to a Double Circuit Transmission Line

The potential overvoltages that may occur at the terminal of a wind farm connected to one of the lines of a coupled double circuit transmission corridor is not well discussed in literature. In this unique configuration of wind farm interconnection, ferroresonance and self-excitation can respectively take place once the transmission line which is fed by the wind turbine generators gets disconnected and followed protection initiated isolation of the wind farm from the main step down transformer (which steps down the transmission voltage level to a lower voltage level suitable for collector bus). In this study different wind turbine generator configurations are considered. A potential problem of 2.5-3 pu overvoltage is seen to exist at the terminals of the wind turbine generators due to these two phenomena irrespective of the generator configuration. This overvoltage could be a serious concern to the utilities as it reaches its peak level within 2-3 cycles which is almost equal to or less than the main breaker operation time. The main conclusion of this study is that this detrimental overvoltage can saturate the transformer which is the link between the wind farm and the transmission line. This overvoltage can also be the cause of serious damage to the wind turbine generators and the associated equipment if proper protection is not undertaken. In this configuration the protection task is found to be challenging due to the fact that not only the wind farm and the main transformer have to be isolated from the high tension transmission corridor but also the excitation system of the wind turbine generators has to be shut down to avoid self-excitation. Surge arrestors could be an interim measure to arrest the overvoltage so that it does not reach to a
detrimental value before the protection system operates. This planning study for a large wind farm has also been done for the first time.

6.2.5 Modeling and Validation of GE 1.5 MW Doubly Fed Wind Turbine Generators

Analytical modeling of doubly fed wind turbine generators is widely discussed and reported in literature. However, majority of those analytical models are mainly based on some theoretical approaches and are tested on hypothetical systems. The performance of those models are not normally validated with test results obtained from field experiments conducted in a wind farm which is operational in practice. In this thesis the GE 1.5 MW doubly fed wind turbine generators implemented in PSS/E Wind Software package are extensively validated with field tests which are conducted in AIM Erie Shore wind farm of Hydro One Networks. This wind farm has an installed capacity of 99 MW consisting of 66 GE 1.5 MW wind turbine generators. The simulated system responses of the test events in PSS/E show a good agreement with the actual field test results and thereby validating those wind turbine generator models for transient stability study of bulk power systems. From this study an industry guideline of the wind farm testing has been evolved. Further, it is shown that appreciable improvement in the transient responses of the DFIGs can be achieved by the systematic tuning of the voltage and reactive power controllers of the machines. This field validation performed for the first time in Ontario in the Hydro One power grid.

6.3 Future Directions of Research

The following are some of the problems which could be studied in future based on the work reported in this thesis:

1. The delay encountered in signal transmission from remote location to the site of the FACTS controller is a major concern. The problem becomes severe when
multiple torsional modes of subsynchronous frequencies are excited as in case of SSR and the transmission of the auxiliary signal such as generator rotor speed containing all of the subsynchronous modes is delayed. The delay compensation for such a signal becomes difficult because of the existence of a number of high frequencies and hence larger phase lags need to be compensated in more than one stage. A thorough mathematical modeling of delay and the design of auxiliary controller to compensate the delay for SSR may be a future direction of research.

2. The SSR in wind farm comprising self-excited induction type generators are discussed and solution techniques are proposed. However, this is an entirely new direction of research and a variety of studies can be conducted. First of all, finding the possibility of occurrence of SSR involving other types of wind turbine generators such as doubly fed induction generators, directly connected synchronous machines with stator converter etc., is a vast area of research. Remedial converter control measures for alleviating this problem for such generators need to be devised as well. Further the interaction of neighboring FACTS control systems with those of the wind turbine generator converters is a novel area of research that may be pursued in future.

3. The overvoltages at the terminal of the wind farm connected to one of the lines of a coupled double circuit transmission corridor may be due to either ferroresonance or self-excitation or a complex combination of them. The boundary between these three factors is to be clearly drawn so that it could be easily understood that if the voltage signal at the point of tapping takes a particular shape and magnitude then that can be attributed to one of the specific factors mentioned above. Although this factor is best attempted to be justified in this thesis, modeling of different transformer saturation characteristics and configurations need to be done to verify the demarcation.

4. Modeling and validation of different configurations of wind turbine generator models in nonlinear electromagnetic time domain programs namely
EMTDC/PSCAD or EMTP still need to be done. Although there is a plenty of hypothetical wind turbine generator models implemented in those platforms and reported in literature their performance has to be validated with field test results. EMTDC/PSCAD or EMTP models the power system components to the highest degree of detail and simulations carried out in these platforms are supposed to be the closest representation of the real life scenario. This thesis deals with this problem with the wind turbine generator models available in PSS/E which is primarily a transient stability program and can perform fundamental frequency phasor simulations. The shortcoming for such a validation process is that some of the high frequency switching harmonics appearing in the measurements could not be modeled and studied. Hence validation of the WTG models in EMTDC/PSCAD or EMTP domains need to be undertaken.
APPENDIX A

Field Validation of a Doubly Fed Induction Generator (DFIG) Model and System Performance Improvement

A.1 Introduction

A global hike in wind power penetration is imminent as wind power is increasingly being considered not only an environment friendly way of producing power but also an economic generation alternative in areas with appropriate wind speed [1]. The Canadian wind market has grown by an average of more than 30% over each of the last six years as a result of a combination of federal incentives and initiatives by individual provinces to increase the contribution from renewable energy. Total installed capacity of the wind farms in Canadian provinces has reached 1588 MW out of a proposed target of 2767 MW. In Ontario, between 2009 and December 2011, new interconnections of wind farms having the installed capacity of 1,175 MW will be allowed in selected areas [2].

Improved models for wind turbines and wind farms are absolutely necessary for the overall solution to the transmission challenges imposed by this growing wind power integration. However, as the industry history of modeling conventional generating equipment proves, the process for developing these models and their validation will likely not be short [4]. This requires a comprehensive development of the mathematical models of different classes of wind turbine generators and their controls, implementing these formulations in different computer simulation tools, theoretical validation and
explanation of the performances of these wind turbines when connected to the grid and, at
last, validation of the simulation models with the field measurements. In addition, the
complexity of the models and the rapid advances being made in the technology itself must
be taken into account. As a result it is clear that developing a wind turbine generator
model is a challenge and needs attention to ensure accurate system studies which evaluate
the performance of this new class of generating systems to be integrated with the power
system grid [4, 5].

One of the principal differences between the wind farms and conventional generating
plants is that in most cases wind farms employ induction generators instead of
synchronous generators as an electro-mechanical energy conversion device. Wind turbine
generators are broadly classified into three categories which are:

1. Fixed speed asynchronous wind turbines employing self-excited induction generator
   (SEIG) or wound rotor induction generators (WRIG) with external resistance
   connected to the rotor terminals.
2. Variable speed doubly fed induction generator (DFIG) with back to back voltage
   source power electronic converters.
3. Synchronous generator with full size ac-dc-ac power converter connected to its
   stator.

Various software tools have the capability to model wind turbine generators (WTG) of
these three categories in different domains of analysis. A few such software tools and
WTG models widely used in power industry are mentioned below:

1. Electromagnetic Transient Domain Models of first two categories of wind turbine
generators in EMTDC/PSCAD software [6]
2. Transient stability models of VESTAS V80 1.8 MW wind turbine generator
employing wound rotor induction generator and GE 1.5 MW doubly fed induction
generator (DFIG) in PSS/E software [7]
3. Electromagnetic transient domain and electro-mechanical transient domain models of first two categories of wind turbine generators in SIMPOW [8]

4. Electromagnetic transient domain and electromechanical transient domain models of all three categories of wind turbine generators in DIgSILENT Power Factory [9]

In spite of the availability of the wind turbine generator models in these widely employed power system simulation tools, scant literature is available which reports the validation studies of these models with the field tests. The objective of this work is to evaluate the modeling and validation requirements of a doubly fed induction generator (DFIG) and to establish a thoroughly tested DFIG model which could be used in power system studies.

This study is possibly the first attempt to validate a DFIG model available in a widely used commercial software with the results obtained from the field test conducted in an operational wind farm of Hydro One Network Inc. (HONI).

The organization of the chapter is as follows. Section A.2 describes the wind generating station and the lay out of the studied system. The modeling of the GE 1.5 MW wind turbine generators is briefed in section A.3. Modeling of the test system and the simulation of the test conditions using PSS/E are outlined in section A.4. Section A.5 reports the validation results and some improvements in system responses by varying the controller parameters of DFIG. The possible reasons behind the differences between the simulation and test results are accounted and various issues regarding the test procedure are brought out in section A.6. Based on the conducted studies reported in this chapter some recommendations are made in section A.7 which will ensure more realistic and accurate field tests leading to proper utilization of the invested resources. Section A.8 concludes the chapter.
A.2 Study System

This study is a part of the project undertaken by Hydro One Network Inc. (HONI) in their ongoing efforts to obtain accurate models of wind turbine generators of different configurations. These wind turbines are manufactured by different vendors and their models need to be validated by the utilities who are allowing the customers to connect to their network. The need for establishing accurate models is of paramount importance as these validated models will be extensively used to evaluate the impact of distributed generation sources on the existing power system grid. Although manufacturers may have validated their machine models but the results of their studies are not easily available in literature.

Hydro One has already interconnected wind farms consisting of a large number of GE 1.5 MW wind turbine generators. The GE 1.5 MW wind turbine generators are good examples of this doubly fed configuration and their models are available in PSS/E Wind software. Hence the model of GE 1.5 MW doubly fed asynchronous wind turbine generator implemented in PSS/E software has been tested and validated in this project.

Several tests were carried out by Hydro One, in their AIM Erie Shore Wind Farm at Port Burwell substation. This wind farm is located 25 kilometers south of Tillsonburg, Ontario down the Glen Erie line. It has 66 GE 1.5 MW wind turbine generators, resulting in 99 MW installed capacity, uniformly distributed over a vast geographical terrain near Lake Erie shore. The wind farm along with the network configuration around its near vicinity is taken from the full scale Hydro One system and is shown in Fig. A.1.

Testing of a wind farm sometimes proves to be a time consuming and tedious process due to the random nature of wind. Tests should not be performed until there is enough wind flow and the turbines are producing appreciable power. Besides the wind, substantial manpower is required to perform measurements and document the test results. Involvement of nine organizations for three consecutive days was required to make this test successful.
The participating organizations were as follows:

- AIM PowerGen Corporation
- Stapleton Price Operations Management
- GE Wind Energy
- Kestrel Power Engineering Ltd.
- AMEC Americas Ltd.
- Black & McDonald Ltd.
- Independent Electricity System Operator (IESO)
- The University of Western Ontario
- Hydro One Networks Inc.
The participating organizations were involved in various activities to make the test event successful. AIM PowerGen Corporation and Stapleton Price Operations Management are the owners of the Port Burwell Wind Farm and permitted Hydro One Network Inc. (HONI) to conduct the test. GE Wind Energy, Kestrel Power and Black & McDonald were in charge of the measurements of various parameters at the WTG terminals and at the Port Burwell generating stations. HONI was the main organizer of this test and also was in charge of measurements of several system variables at the Tillsonburg Transformer Station. The substations and the protection equipment necessary to interconnect this wind farm with HONI network were installed by AMEC. The University of Western Ontario and IESO were responsible to conduct the simulation studies in PSS/E for the validation of the DFIG models.

A number of tests were conducted employing a single wind turbine generator as well as multiple wind turbine generators on the same collector feeder. The tests included:

1. Capacitor bank switching on and off at 34.5 kV Port Burwell wind generating station
2. Capacitor bank switching on and off at 115 kV Tillsonburg transformer station
3. Wind farm reference voltage change by ± 2%

Out of these tests only a few events are chosen to validate the PSS/E models of GE 1.5 MW wind turbine generators. The test events are chosen in such a way that they fall into PSS/E recommended transient domain in which these models are supposed to be valid. The study results show good agreement of the PSS/E models with the field measurements.
A.3 DFIG Model

GE 1.5 MW wind turbine generator configuration is shown in Fig. A.2. This model has been implemented in PSS/E to simulate the single rotor branch (single cage) doubly-fed (wound rotor) induction (asynchronous) generator machine by representing mechanical dynamics but neglecting stator and rotor flux linkage dynamics. The model has been significantly modified based on results of studies of weakly interconnected wind farms and the manufacturer’s recommendations. Details of the device dynamics have been substantially simplified. Specifically, the very fast dynamics associated with the control of the generator converter have been modeled as algebraic (i.e. instantaneous) approximations of their response. Representation of the turbine mechanical controls has been simplified as well.

![DFIG configuration in PSS/E](image)

Fig. A.2 DFIG configuration in PSS/E [7, 10]

Voltage and reactive power control in steady state as well as during transient operation are possible in this configuration of doubly fed wind turbine generator. The controller structure and various controller gains, e.g. \(K_{Qh}, K_{Vi}\), are shown in Fig. A.3. The reactive power controller receives the reactive power command from either of the Wind VAR Emulator system, steady state reactive demand or from power factor control system. Wind VAR Emulator system is a supervisory control system which controls and monitors the collector bus voltage of the entire wind farm. On the other hand, power factor control system dynamically maintains the specified power factor at the machine terminal depending on changing active power demand which varies with wind speed as well as with grid requirements. At the time of testing Wind VAR Emulator and power factor
control systems were out of service. Hence the zero reactive power reference to maintain unity power factor at the WTG terminal in steady state is generated from the power flow solver of PSS/E. Modeling of the GE 1.5 MW and 3.6 MW machines with conventional dynamic models for either synchronous or induction machines is, at best, highly approximate and should be avoided. For detailed description of the models including their schematic diagram, structure, representation in power flow as well as in transient stability packages, control strategies and many other details, the reader is referred to [7, 10].

Fig. A.3 Voltage and reactive power control of GE 1.5 MW DFIG

A.4 Modeling of the Test System in PSS/E

GE 1.5 MW wind turbine generators have voltage and reactive power control strategies which employ back to back voltage source converters both at the rotor and the stator sides of the wound rotor induction generator. The power electronic converter control automatically reacts in response to steady state and fast transient (contingencies) changes in system operating conditions. This control strategy is implemented in PSS/E Wind, which is an integral part of the PSS/E software and can be linked to PSS/E main engine, after suitable simplifications appropriate for the transient stability analysis. In PSS/E, GE wind turbine generators can be configured in four control modes [8] as follows:

2. Current North American configuration with WindVAR system out of service.
3. European (Fast Power Factor control) with WindVAR system operational.
4. European (Fast Power Factor control) with WindVAR system out of service.
At the time of field measurements a single feeder was isolated and all the 11 wind turbine generators connected to that feeder were subjected to different test conditions. The total power output from the generators was approximately 10 MW. Wind turbine generators are configured as in mode 2. Correspondingly, in PSS/E the mode 2 was implemented in steady state and in dynamic activities.

The validation studies are conducted in a system which is further reduced but not shown in Fig. A.1. The single line diagram of the study system is shown in Fig. A.4. It mainly encompasses the Port Burwell wind generating station (WGS), Cranberry Junction as the grid or infinite bus, Tillsonburg Transformer Station (TS) and the corresponding TS load.

![Diagram of the study system](image)

Fig. A.4 Study system

Two test conditions are mainly considered for this study. They are:

- An 8 MVAr capacitor is switched on at 34.5 kV collector bus of Port Burwell Substation;
- The same capacitor bank is then switched off from the Port Burwell 34.5 kV bus.

Test conditions were implemented in PSS/E as accurately as possible so that the actual transient events are simulated. Validation results are reported in the next section.
A.5 Validation Results

The entire validation study is carried out in a few stages. Firstly, two different test events mentioned in the previous section are simulated to validate the original GE 1.5 MW DFIG model with its nominal parameters recommended by the manufacturer and implemented in PSS/E Wind software [7, 10]. Secondly, it is shown that the reactive power and hence voltage responses of a DFIG can be substantially improved with proper tuning of controller parameters. The study shows a maximum difference lower than 2% between the simulated and test responses, thus validating the DFIG model.

A.5.1 Test 1: 8 MVAr Capacitor Switch Off at Port Burwell WGS

The figures below show the system responses for 8 MVAR capacitor bank switch off at Port Burwell 34.5 kV collector bus. The signals examined are active and reactive power flows of the wind turbine generators measured on the collector feeder and the collector bus voltage, which are displayed in Fig. A.5 to Fig. A.7. The results show acceptable agreement between the simulated response and the field results. Original model with nominal parameters implemented in PSS/E Wind software is used for this study.

![Fig. A.5 Reactive power flow on collector feeder](image-url)
A.5.2 Test 2: 8 MVAr Capacitor Switch On at Port Burwell WGS

In continuity with the previous test, the same 8 MVAr capacitor is switched on in the next test event. It is to be noted that these two tests are usually done consecutively to keep the other parameters, e.g. wind speed, unchanged. Same signals as reported in section A.5.1 are reported in Fig. A.8, A.9, and A.10 respectively. Reasonable matching is observed between the actual and field test results. This validates the DFIG model used in PSS/E.
Fig. A.8 Reactive power flow on the collector feeder

Fig. A.9 Active power flow of the WTGs

Fig. A.10 Collector bus voltage
A.5.3 Improvement of System Performance by Controller Parameter Tuning

It is apparent from Fig. A.5 and Fig. A.8 that the reactive power response takes several seconds to settle down. This is mainly due to the detuned parameters of the voltage and reactive power controllers. The structure of reactive power and voltage controller of the GE 1.5 MW WTG is shown in Fig A.3. At the time of test the wind turbine generators were operating close to unity power factor and their wind VAR management system was shut down. As a result, neither fast reactive power control nor voltage control was operational. Only steady state reactive power control was enabled and hence $K_{Qi}, K_{Vi}$ are the only controller gains which could be controlled. Similar operating scenario is simulated in PSS/E. A systematic tuning procedure based on trial and error is adopted for its ease of implementation. At first $K_{Vi}$ is kept constant and $K_{Qi}$ is varied and next the reverse procedure is adopted. The reactive power responses for these two control parameters variations are reported in separate subsections. It is to be noted that parameters are tuned only for one test event which is an 8 MVAr capacitor switch off at Port Burwell WGS. Similar results are obtained for capacitor switch on but are not reported to avoid repetition.

A.5.3.1 Variation in $K_{Qi}$

A wide range of values of $K_{Qi}$ is selected from $K_{Qi} = 0.05$ to $K_{Qi} = 5$. The $K_{Vi}$ is kept fixed at 40. The reactive power responses are shown in Fig. A.11.

From Fig. A.11 it is evident that corresponding to $K_{Qi} = 0.5$, although the measured reactive power deviates from that of simulated quantity, the settling time of the signal becomes less than 3s compared to 8s for $K_{Qi} = 0.05$. However, further increase in $K_{Qi}$ makes the response gradually oscillatory which is also vividly illustrated in this figure.
Fig. A.11 Reactive power response for varying $K_{Qi}$
A.5.3.2 Variation in $K_{VI}$

Similar to $K_{QH}$, $K_{VI}$ is also varied within a wide range. It is found from Fig. A.12 that the reactive power response is insensitive to $K_{VI}$ compared to $K_{QH}$. So it is recommended that $K_{VI}$ could remain at its nominal value recommended by the manufacturer.
Fig. A.12 Reactive power response for varying $K_{Vi}$
A.6 Comparison of the Test Results and Simulated Responses

It is shown in section A.5.1 and A.5.2 that the reactive power responses match very closely with the test results. However, there are some differences in power flow and voltage response signals. This is shown in this section by zooming in the plots of those signals for the two test events simulated.

A.6.1 Test 1: 8 MVAr Capacitor Switch Off at Port Burwell WGS

Figs A.13 and A.14 show the expanded plots of voltage and power flow signals during this test event. Following observations are made:

- The simulated steady state value of the collector bus voltage is within 2% of the value obtained in actual test. This is a very good correlation considering the facts listed below:
  - The most simplified configuration of the WTG to get an insight of its operating principles
  - The wind VAR emulator system was out of service at the time of testing.

- The voltage overshoot is larger in actual test than in simulation. It is also observed from Fig. A.5 that the overshoot in reactive power is less in actual field test data than that in simulation. The overshoot magnitude depends on several factors such as system strength or short circuit capacity, power output levels from the wind generators and so on which always vary at every instant in real system. But the settling time of voltage and reactive power response remains same as it depends on system damping. This settling time is very close between the actual and simulated response and is quite apparent from Fig A.5 and Fig. A.13.
Similarly, the differences in power flow signal are as follows:

- There are some high frequency components in the measured power flow signal which are absent in the simulated power output from the WTGs. These high frequency components may not be obtained through PSS/E simulations as this software is essentially for positive sequence phasor time domain simulations. These could be however, obtained through electromagnetic transient simulations. Fig. A.15 shows Fast Fourier Transform (FFT) plots of the measured power flow signal during the capacitor switch off. This plot confirms the existence of high frequency components of the power flow signal. In addition to that the FFT plot also demonstrates some subharmonic components. The exact reasons of appearance of these additional frequency contents are difficult to find out because of the DFIG and system modeling limitations in PSS/E mentioned before. The probable causes of these harmonic components may be attributed to several reasons, namely, power electronic interface, transformer and network reactances, etc. The FFT plot quantifies the frequencies of the harmonics. Due to the presence of harmonics, power output from the wind turbine generators does not exactly match with the simulated response.

- In spite of the presence of high frequency harmonics as well as subharmonics, it should be emphasized that Fig. A.14 shows the measured and simulated power flows from the wind turbine generators in a much expanded scale. The difference is actually less than 5-6% (less than 0.6 MW). Moreover, from the frequency contents of the power flow signal it is apparent that the magnitude of high frequency and subharmonic contents is much less than the DC value of the power and hence their presence may not be of that importance in practice.
There is a dip in power flow signal both in measurements and in simulation once the capacitor is switched off. The dip in power is larger in actual test. This dip is expected as there is an abrupt dip in voltage at the instant of capacitor switch off.

Fig. A.13 Collector bus voltage at Port Burwell (zoomed in)

Fig. A.14 Power flow from the generators (zoomed in)
A.6.2 Test 2: 8 MVAR Capacitor Switch On at Port Burwell WGS

In this study same observations are made as mentioned in section A.6.1. The difference in voltage is again within 2% and is apparent from Fig. A.16. The difference in power flow signal is also similar as that of section A.6.1 at the instant of capacitor switch on which is depicted in Fig. A.17. In simulation the power output from the WTGs is found to increase at the time of the capacitor switch on. This is expected as the voltage at collector bus also jumps at the instant of capacitor switch on. The frequency content of the power flow signal for capacitor bank switch on is shown in Fig. A.18.
In short, in this test also reasonable match between the field test and simulation results is observed in reactive power, voltage and power flow signals. The extent of mismatch is within an acceptable band and the validity of the model is once again confirmed.

A.7 Recommendations for Wind Farm Testing

Based on the studies reported in this chapter a number of recommendations are made which will help utilities to conduct more accurate tests in near future. A tremendous coordination of several agencies and investment in terms of time, money and manpower are
required for organizing a field test. Hence all efforts should be made to ensure that the field testing is a success. The recommendations to achieve this goal are as follows:

- As mentioned in section A.2, at the time of testing several other experiments are carried out. However, those test results are either difficult to simulate in PSS/E or may not be theoretically explained. It should therefore be made mandatory to extensively simulate the test conditions according to the test plan for the wind farm for all likely wind speeds and the system conditions expected at the time of field testing. This will give prior idea of how the system responses should be before the tests are conducted. If the field results do not correspond to simulation results the possible reasons of mismatch should be identified onsite and necessary corrections may be done in field testing.

- Based on simulations if it can be shown that modifications in WTG control may substantially improve system performance, an agreement may be reached a priori with the representatives of the manufacturers so that the field tests may be repeated with improved WTG control parameters. This will ensure optimum system performance.

A.8 Conclusions

From this study it is concluded that the GE 1.5 MW wind turbine generator model implemented in PSS/E shows reasonable accuracy with actual field measurements. It is also shown that the system performance can be significantly improved with proper tuning of controller gains. The mismatches between the test and simulation results are compared and possible explanations are provided. Presence of high frequency harmonics in measured power flow signals has been found and their frequency ranges are shown by FFT analysis. These high frequency harmonics may be investigated only by detailed electromagnetic transient simulations through EMTDC/PSCAD or EMTP software. However, the DFIG models for electromagnetic transient analysis are not readily
available. These field validation studies have been done for the first time in the electrical network of Hydro One in Ontario. These studies have further provided useful insights in the operation of the WTGs.

A.9 References


APPENDIX B

Data of IEEE First Benchmark System for SSR Studies

A. Generator Data:

Generator and network data are taken from [11].

System Base MVA = 892.4 MVA, Base Voltage = 500 kV

B. SVC Data:

SVC rating: \( Q_L = 300 \text{ MVAr} \) and \( Q_C = 340 \text{ MVAr} \).

Slope \( K_{SL} = 3\% \)

Voltage regulator parameters: \( K_p = 1.0; K_I = 100 \).

SSDC parameters:

(a) \( X_c = 0.47; K_I = 2.45; K_d = 0.0196 \).

(b) \( X_c = 0.38; K_I = 0.5; K_d = 0.004 \).

(c) \( X_c = 0.285; K_I = 0.5; K_d = 0.004 \).

(d) \( X_c = 0.185; K_I = 0.5; K_d = 0.004 \).
APPENDIX C

Data for the Wind Farm

A. *Self-Excited double-cage Induction Generator (SEIG) Data:*

- Power Rating = 1000 HP; \( V_{LL} = 26.0 \text{ kV} \);
- \( R_s = 0.015 \text{ p.u.} \) \( X_{Ls} = 0.091 \text{ p.u.} \) \( R_{r1} = 0.0507 \text{ p.u.} \)
- \( R_{r2} = 0.0095 \text{ p.u.} \) \( X_{L1} = 0.0 \text{ p.u.} \) \( X_{L2} = 0.0539 \text{ p.u.} \)
- \( X_{ml2} = 0.1418 \text{ p.u.} \) \( H_G = 0.5 \text{ p.u.} \)

Higher generator power output is obtained by choosing an appropriate number of machines acting coherently.

B. *Torsional System Data:*

- Power = 100 MW; \( H_T = 12.5 \text{ p.u.} \) \( H_G = 0.5 \text{ p.u.} \) \( K_{GT} = 0.15 \text{ p.u.} \)

C. *SVC Data:*

- 100 MW Power Transfer:
  - \( Q_c = 150 \text{ MVAr} \) \( Q_L = 100 \text{ MVAr} \)
- 500 MW Power Transfer:
  - \( Q_c = 300 \text{ MVAr} \) \( Q_L = 200 \text{ MVAr} \)

Voltage Regulator: \( K_P = 0.0 \) \( K_I = 200 \).

SSR Damping Controller: \( K_{aux} = 100 \) \( K_w = 1.0 \) \( T_w = 10.0 \text{ s.} \)

SVC slope = 3%.

D. *TCSC Data:*

- \( p = \) Percentage series compensation \( X_C/X_{\Sigma} = 90\%, 65\%, 50\% \)
- \( X_L = \) Calculated from (4.5) to avoid multiple resonances in TCSC reactance-firing angle characteristics.

TCSC Current Controller: \( K_P = 0.0 \) \( K_I = 200 \).
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