

Analysis and Control of Power System with Wind Generation

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Abstract

The objective of this work is to study the impact of large scale wind integration in the dynamic performance of power system. The variable nature of wind generation has been driving power system operating conditions from a largely predictable one to highly variable and stochastic. Such changes will have huge impact in the dynamic performance of the system.

The limitation in dynamic performance is one of the constraints for effective utilization of available transmission and generation resources. The thesis draws a qualitative behavior of inter-area mode damping with increased wind penetration. The factors such as changes in power flow and displacement of conventional generators, resulting from large scale integration of wind are considered. Another consequence of wind variability is the changes in controllability and observability in the context of power system damping control when operating conditions vary significantly. The modal controllability and observability decide the controller performance, large variation of which can result in inefficient control effort and poor stability margin. A controller design methodology using robust signal selection is presented for power systems with increased variability in operating conditions. The core of this method is based on stochastic error co-variance matrix of modal residue due to large variation in operating condition. The work further explores possibility of using wind farms for damping control using active and reactive power modulation. Interaction of damping controller with torsional mode of wind turbines is analyzed and a signal selection criteria is presented to reduce the interaction. Also, selection of active or reactive power modulation of wind farm for damping control is discussed. The outcome of this research offers deeper insight into the power system dynamic problem in the presence of large asynchronous generation such as wind.

*Dedicated to
My parents, wife and our son, Layan*

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Declaration

I hereby declare that the work presented in this thesis is my own work, and, wherever appropriate, contributions from other people have been acknowledged.

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List of Symbols

A	State matrix in state space representation
B	Input matrix in state space representation
B_C	Susceptance of capacitor
B_L	Susceptance of reactor
B_{svc}	Susceptance of SVC
c	drive train damping coefficient
C	Output matrix in state space representation
C_p	Performance coefficient of wind turbine
D	Damping coefficient of generator
D	Feedthrough matrix in state space representation
e	Residue error
e'_{ds}	Direct axis components equiv. source behind transient impedance
e'_{qs}	Quadrature axis components equiv. source behind transient impedance
E'_d	Transient emf due to flux linkage in q-axis damper coil
E_{FD}	Synchronous machine field voltage
E'_{dc}	Transient emf due to flux linkage in dummy rotor coil
E'_q	Transient emf due to field flux linkage
f	Vectors of differential equations
g	Vectors of algebraic equations
G(s)	Plant transfer function
h	Vector of output equations
H	Inertia of synchronous generator
H_g	WTG generator inertia
H_t	WTG turbine inertia
H(s)	Controller transfer function
I	Current
I	Vector of current injection at buses
i_{di}	Direct axis component of stator current

i_{ds}	Direct axis components of stator current
$i_{dq} = i_q + ji_d$	Current in Park's reference frame
i_{dr}	Direct axis components of rotor current
i_{qi}	Quadrature axis component of stator current
i_{qr}	Quadrature axis components of rotor current
i_{qs}	Quadrature axis components of stator current
$i_{DQ} = i_Q + ji_D$	Current in Kron's reference frame
j	Imaginary number
k	Drive train shaft stiffness
K	Controller gain
k_c	Percentage compensation of TCSC
k_{c-ref}	Reference setting of TCSC
k_{c-ss}	Supplementary signal of TCSC
$\mathbf{K}$	Controller transfer function
K_A	Excitation system regulator gain
K_E	Excitation system exciter gain
K_F	Excitation system stabilizer gain
n	Number of states
N	Number of operating conditions
P	Active power
P_r	Rotor active power
P_s	Stator active power
$\mathbf{P}_i^k$	Residue error covariance matrix
$\mathbf{P}_i^{rel,k}$	Relative residue error covariance matrix
p	Poles of transfer function
pf_{ki}	Participation factor corresponding to k th state variable in i th mode
P_t	WTG turbine power
Q	Reactive power
Q_{GSC}	Grid side converter reactive power
Q_r	Rotor reactive power
Q_s	Stator reactive power
R	Resistance
R	Blade length
R_i	Residue corresponding to i th pole
$ R_i^{mk} $	Magnitude of residue with respect to the m th operating scenario corresponding to the k th signal, of the i th mode

S_E	Excitation system saturation
T	Mechanical input torque of generator
T_A	Excitation system regulator time constant
T_B	Excitation system transient gain reduction block time constant
T_C	Excitation system transient gain reduction block time constant
T_e	Electrical output torque of generator
T_E	Excitation system exciter time constant
T_F	Excitation system stabilizer time constant
T_t	WTG turbine torque
T_{tcsc}	Time constant of TCSC
T'_c	Open circuit transient time constant along dummy coil
T'_d	Open circuit transient time constant along d-axis
T'_q	Open circuit transient time constant along q-axis
$\mathbf{u}$	Vectors of input variable
V	Voltage
$\mathbf{V}$	Vector of bus voltages
V_I	Excitation system input voltage
v_{dr}	Direct axis components of rotor voltage
$v_{dq} = v_q + jv_d$	Voltage in Park's reference frame
v_{ds}	Direct axis components of stator voltage
$v_{DQ} = v_Q + jv_D$	Voltage in Kron's reference frame
v_{qs}	Quadrature axis components of stator voltage
v_{qr}	Quadrature axis components of rotor voltage
v_w	Wind velocity
$\mathbf{x}$	Vectors of state variable
$\dot{\mathbf{x}}$	$\frac{d}{dt}\mathbf{x}$
x_d	Synchronous reactance along d-axis
x'_d	Transient reactance along d-axis
x_q	Synchronous reactance along q-axis
x'_q	Transient reactance along q-axis
X_C	Capacitive reactance
X_L	Inductive reactance
$\mathbf{y}$	Vectors of output variable
$\mathbf{z}$	Vectors of algebraic variable
z	Zeros of transfer function
$\mathbf{Z}$	Network Impedance Matrix

Z_{th}	Thevenine Impedance
$ \cdot $	Magnitude operator
$\angle \cdot$	Angle operator
β	WTG blade pitch angle
δ	Rotor angle of generator
λ	Tip speed ratio
λ	Eigenvalue
μ_i	Mean of random variable
$\mathcal{N}(0, 1)$	Standard normal distribution with zero mean and unit variance
ω_{elB}	Base speed
ω_r	WTG rotor speed
ω_t	WTG turbine speed
ω_s	Synchronous speed of generator
ω	Speed of generator
ω	Frequency in rad/sec
ϕ	Power factor angle
ϕ	Right eigenvector
ψ	Left eigenvector
ρ	Air density
θ	Voltage angle
θ_{tw}	Equivalent twist angle of drive train shaft
θ_i^{mk}	Angle of residue with respect to the m th operating scenario corresponding to the k th signal, of the i th mode.
σ	Standard deviation
σ	Real part of eigenvalue
σ^2	Variance
ζ	Damping ratio

List of Abbreviations

AC	Alternating Current
GB	Great Britain
DAE	Differential algebraic equation
DC	Direct Current
DFIG	Doubly-Fed Induction Generators
ECM	Error Covariance Matrix
FACTS	Flexible AC Transmission Systems
FC	Full converter, representing variable speed generator with full converter interface
GE	General Electric
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IAM	Inter-area Mode
LM	Local Mode
NETS	New England Test System
NYPS	New York Power System
PSLF	Positive Sequence Load Flow
PSS	Power System Stabilizer
SMES	Superconducting Magnetic Energy Storage
SMIB	Single Machine Infinite Bus
SEP	Stable Equilibrium Point
PMU	Phasor Measurement Unit
RSC	Rotor Side Converter
TCPAR	Thyristor Controlled Phase Angle Regulator
TCSC	Thyristor Controlled Series Capacitor/ Compensator
TM	Torsional Mode
UPFC	Unified Power Flow Controller

UK	United Kingdom
SVC	Static var Compensator
WAMS	Wide Area Measurement System
WECC	Western Electricity Coordinating Council
WTG	Wind Turbine Generator System

Chapter 1

Introduction

Ensuring secure and affordable energy while minimizing the impact on environment is the major challenge faced by countries around the world. Depleting oil and gas reserve, political instability in countries enriched with natural resources and need to reduce damaging emissions have forced many governments to look for alternative energy sources within their borders. Electricity generation from renewable sources has got increased attention in this context. Various renewable generating technologies such as solar, wind, wave, tidal, hydro, bio energy, fuel cell etc. are being developed.

Out of many, the wind energy continues to be the fastest growing renewable generating source. According to World Wind Energy Association's 2012 half yearly report, the total worldwide wind turbine installed capacity has reached 254GW [1]. Countries such as China, USA, Germany, Spain, India, Italy, UK, Denmark, Netherlands etc. are few to take lead in the area [1]. A significant portion of their electricity demand will be met by wind or other renewable resources in the near future.

However, the non-dispatchable nature of wind power due to the variation and uncertainty in wind causes significant problems in large scale wind integration into the electricity network. Since electricity is supplied on demand, sufficient reserve capacity should be maintained at all time. Due to variability in wind power output, power system require higher generation reserve which is generally ensured by running conventional generating stations. It is shown that the variability in wind output increases the variability in conventional generation output [2, 3]. Smart grid can also help to tackle the issues related to wind variation by controlling demand [4].

Diversification of renewable portfolio and interconnection of different grids are means to increase wind energy utilization and reduce reserve capacity requirement. Large scale transmission system expansion is required to facilitate this. The capacity improvement of existing lines and addition of new lines are being carried out in

various power systems. According to [5], Europe require to upgrade 34 existing high voltage AC (HVAC) interconnections, build or upgrade 17 High Voltage DC (HVDC) lines and need up to 11 new long distance HVDC supergrid connections in order to achieve their renewable targets. The proposed North Sea grid can facilitate sharing of electricity generated by wind, solar and tidal power between the neighboring countries [5]. The wind power produced by UK during low demand periods can be stored as hydro potential in Norway and released during peak hours. Similarly, the proposed pan-European electricity Supergrid will connect offshore wind farms from the Baltic Sea to the Mediterranean, via the North Sea and the Atlantic, with major load centers in Europe enabling higher utilization of wind power [6]. The network will allow free movement of electricity securing higher revenue for wind farm operator which will eventually challenge the technical limitations of the network. Future generation and transmissions lines need to be highly flexible in order to meet these challenges.

One of the important constraints in providing flexibility for transmission network is the electromechanical stability of existing AC systems which are generally stability limited. Historically, inter-area oscillations are responsible for transmission line bottlenecks and many power system back outs [7]. In some systems the number of recorded yearly inter-area oscillation related incidents grew from dozens to hundreds [8] in recent years. It is very important to ensure sufficient damping to inter-area modes in order to fully utilize the renewable resources.

Real challenge to the system operator comes from the obscure nature of inter-area mode. The power system does not exhibit any problem until its stability limit is reached and once there, a disturbance in the system can cause poorly damped or some times undamped oscillations. There is no tool available for the system operator to judge the damping level of an operating scenario. Hence the operators generally load the system well below its thermal limit.

However such simple criteria cannot be applied to future power systems as the operating conditions will be continuously evolving with weather and market conditions, and the network is expected to provide the flexibility. Not all of these resulting operating conditions or power flow patterns will be familiar to operator and/or are sufficiently stable. In the new world order where technology follow market, power system networks should ensure sufficient damping to all oscillatory modes for all possible operating conditions. The thesis will analyze the behavior of inter-area oscillation and explore the possibilities of robust damping controller design for power systems with increased wind penetration.

1.1 Objective of the thesis

The objectives of this thesis are:

- *To analyze the impact of increased wind penetration on inter-area mode damping of power system.* Studies based on systems with large scale wind integration show that, the inter-area oscillation involves only synchronous machines interconnected through ac transmission lines, and wind generators do not participate in this mode. However, with large scale wind penetration damping of the mode changes. Many literatures report both positive and negative impact of large scale wind penetration on inter-area mode damping, but they do not show how it will be affected. The thesis tries to draw up a qualitative behavior of inter-area mode damping with wind penetration. Different possible operating conditions for two test systems, a two area system and a representative GB test system, are generated to analyze the damping behavior. The damping behavior with different inter-area power flow scenarios and displacement of different synchronous generators are studied.
- *To investigate the importance of feedback signal selection for Flexible AC Transmission Systems (FACTS) based damping controllers.* Supplementary controls of FACTS devices are found to provide additional damping for inter-area oscillations if placed at suitable locations. However, FACTS controllers are placed considering their primary objectives such as power flow and voltage control. It is shown that judicious selection of feedback signal can enhance the damping control potential of FACTS devices [9]. Signal having higher magnitude of residue, product of modal controllability and modal observability, can be used to design a controller with low control effort. However, the magnitude and angle of residue varies in wide range for power systems with significant variation in operating conditions. The variation of which can cause poor performance of the controller. The thesis proposes a set of signal selection criteria where by feedback signals having less variation in residue are selected. The proposed signal selection method ensures robust controller performance for large number of operating conditions.
- *To explore damping control capability of wind generators.* Modern wind turbine generators (WTGs) have capability to independently control the active and reactive power output. The thesis investigates the potential of modulating

active and reactive power output of WTGs to improve damping. Issues such as torsional interaction and selection of actuator location are examined.

1.2 Outline of the thesis

Following this introduction, **Chapter 2** discusses various issues related to inter-area oscillations and their significance in future power system. In **Chapter 3** a simple modeling framework for multimachine power system with synchronous machines and FACTS devices is presented. Various control system tools are explained and a two-area system simulation is presented to relate these tools to stability analysis. This is followed by modeling of wind farms in **Chapter 4**. Modeling using detailed machine model and generic WTG model are explained with simulation results. **Chapter 5** discusses the impact of wind penetration on inter-area oscillation damping. In first part, a two-area test system is used to build up the concept. A representative model of the Great Britain transmission network is developed. The wind penetration issues are further explored using the GB test system. **Chapter 6** discusses the feedback signal selection for FACTS based damping controller design and a signal selection algorithm is presented. A simulation study using sixteen machine five area test system is presented to validate the proposed approach. It is shown that the controller using proposed signal selection method achieve required damping for large number of operating conditions. Damping controller design using wind farm is discussed in **Chapter 7**. **Chapter 8** lists the conclusions and future work.

1.3 Contribution of the thesis

- Impact of increased wind penetration on inter-area mode oscillations in power system is analyzed and a qualitative behavior of the damping of inter-area mode is presented.
- A feedback signal selection method for inter-area mode damping controller is presented. It is shown that the proposed method simplifies controller design and ensure robust damping for large number of operating scenarios
- The damping control capability of wind turbine through active and reactive power modulation is presented. The impact of damping controller on torsional mode oscillation and location dependance on the choice of active or reactive power modulation are analyzed.

- A dynamic model of representative GB transmission grid is developed to replicate the well known 0.5Hz Scotland-England inter-area mode. The model can be used to analyze impact of wind penetration on future GB network.
- A programming guide for multimachine power system modeling for small signal stability studies is presented.

Chapter 2

Inter-area oscillations in power system

Inter-area oscillations are inherent in interconnected AC systems. This type of oscillations limit power transfer capacity of tie line between different areas and can sometime cause power system black out. Any improvement in damping of these oscillations have significant economic benefit. This chapter discusses the characteristics of these oscillations and their significance in future power system.

2.1 Nature of inter-area oscillations

Synchronous generators in power system produce torque depending on the relative angular displacement between their rotors in order to maintain their synchronism. If due to a disturbance the angular difference increases, the torque will be produced in generators to reduce the difference and bring the system to steady state. In this process, the generator rotors will oscillate at its natural frequency. Generally such oscillations decay and disappear within few seconds. However it is observed that, beyond a particular loading limit (stability limit) the oscillations in power system will grow and eventually trip generators and transmission lines. The reason being insufficient damping to these oscillations. The oscillations are named inter-area oscillations when generators from more than one distinct area participate.

The inter-area oscillation is a complex phenomenon which depends on many factors such as system structure, operating condition, nature of load, distribution of load, presence of automatic voltage controllers, and generator and transmission line loading. For example, damping is found to decrease as the tie line power transfer increases [10] and it is improved with tie line strength. In a power system these

factors are subjected to continuous changes, and hence the damping and frequency of inter-area mode vary. Some modes may disappear or their frequencies may vary with the system operating conditions. Furthermore several other devices such as Thyristor controlled series capacitor (TCSC), Static var compensator (SVC), HVDC systems etc influence the damping of inter-area mode. Number of such devices are installed in power systems in recent years. This increasing complexity of inter-area mode characteristics make their damping control a challenging task for power system designers.

Another characteristic of this oscillation is that no noticeable problem can be observed in power system until the stability limit is reached. Once stability limit is reached, a disturbance in system can cause poorly damped or some times undamped oscillations. An operator cannot judge for sure if a particular operating condition may cause undamped oscillation. In a power system with continuously changing operating conditions, the inter-area oscillations pose a major challenge to system operator.

2.1.1 Cost of inter-area mode oscillations

Inter-area oscillations were observed when generators from different areas are interconnected in order to improve reliability of power system. The oscillators were controlled by limiting power transfer through the tie-lines. However, with large scale inter-connection of power systems and power system restructuring, the annual number of inter-area events has increased significantly in recent years. In some systems the number of recorded yearly inter-area oscillation related incidents grew from dozens to hundreds [8]. The economic cost of such oscillations can be two folds. In modern world where day to day life is heavily dependent of electricity, a power system black out due to inter-area oscillation is a disaster. Several incidences have been reported in different parts of the world that caused huge loss to the economy [11, 12]. Secondly, due to lack of monitoring and early warning system, the system operators limit loading of transmission lines well below their thermal limit. This is to avoid any system separation or possible black out, which results in underutilization of generation and transmission capacity.

2.1.2 Solutions to stability issues

Initial reaction to these oscillations were to either change control settings or restrict operation of the tie-line until the development of power system stabilizers (PSS). Power system stabilizers are the most cost-effective and successful damping controllers

used in power system [13]. They were used from very early stages of development of inter-connected systems [14, 15]. PSS modulates excitation system voltage reference input such that the generator produces damping torque in phase with speed changes. Generally local signals are used as feedback signals for PSS although recent literatures suggest remote signals as alternatives [16]. One of the early PSSs used shaft speed (Delta-Omega) as input signal [17]. However this type of controller when used for thermal units were found to have number of limitations which complicated its design and restricted its effectiveness. In order to overcome this limitation, Delta-P-Omega stabilizer, which use shaft speed and electric power as input signal, is developed in 1978 [18]. They were very successful in improving damping of the oscillations. An additional reactive power input to Delta-P-Omega controller can further enhance performance of PSS for long distant power transmission [19]. Presently PSS is an essential controller in modern power systems.

Introduction of FACTS devices in power system opened a new avenue to inter-area oscillation damping. Though primary purpose of these devices is to support power flow and voltage control, the potential of improving damping using supplementary control can be easily realized [20]. Devices such as TCSC [9, 21], SVC [22], Unified power flow controller (UPFC) [23, 24], High voltage DC system (HVDC) [25], Super conducting magnetic energy storage (SMES) devices [26], and Thyristor controlled phase angle regulator (TCPAR) [27] are suggested as actuator for damping control.

2.1.3 Actuator location and feedback signal selection

Once damping capability of the FACTS devices are evident, the pressing question is how to find best location for installing them? In case of PSS, an obvious location is the generator with highest speed participation in the mode [16]. Speed participation factor indicates the sensitivity of a mode to addition of mechanical damping at the generator shaft [13]. If speed participation of a generator is zero, it will not be able to contribute to damping improvement of the mode. Another approach is to use residue [28], where generator location providing largest magnitude of residue for the transfer function between automatic voltage regulator reference and the feedback signal is selected. If the residue is very small, that generator will not be able to contribute to the damping of the mode. The residue concept is proposed for selecting FACTS device location where the residue of the transfer function between reference input of FACTS controller and feedback signals is used [28]. Initially, locally available signals were used to design damping controllers. However, recent introduction of Wide Area Measurement System (WAMS) enables the use of signals from remote locations in

the system [9, 29].

It is to be noted that, FACTS devices are installed to support power flow or voltage control. Hence rather than finding best location for FACTS controller, the real issue is whether existing/ proposed FACTS controller can be used to damp the mode. Availability of remote signal can enhance performance of a FACTS controller which otherwise may not be effective for damping control. Different methods have been proposed to select the most appropriate feedback signal for damping controller. The modal residue based approach is widely used for obtaining the device location and feedback signal for the FACTS controllers [16, 28, 30]. The feedback signal having the largest magnitude of the residue makes the controller very effective with low control effort [31, 32]. The selection of signals based on the geometric approach of modal observability and modal controllability is presented in [33, 34, 35]. In [35], the authors compare the geometric approach with modal residue based approach. It is found that both approaches depend on the orthogonality between the eigenvectors and the output and input vectors, however the residue approach is independent of scaling. Though simulation results show some advantages of geometric approach over residue approach yet the residue approach is widely followed by the community. Furthermore the angle of the residue is not taken into consideration for comparison with geometric approach. In [36], the authors present a method based on the Hankel Singular Values [37]. [38] discusses the importance of transfer function zero in feedback signal selection. A good separation between critical poles and zeros is required in order to obtain adequate eigenvalue movement. Suitable zero placement can be achieved by modifying local signals [38] or changing dynamics of other parts of the system [39, 40]. These methods select signal based on nominal operating condition or few worst operating conditions with an assumption that modal observability and controllability i.e. residue does not vary significantly. However, for power systems with large variation in operating condition, this may not be true [41]. The changes in residue will make the signal ineffective for control. It is required to select a signal with least variation in residue. In [42], the authors discuss the effect of variation in the angle of the residue corresponding to the feedback signals under various operating conditions and [43] presents a signal selection criteria based on minimum variation in the magnitude of residue. The method is appropriate for selecting a feedback signal for damping a single mode.

2.1.4 Controller design methodologies

Continuous variation in operating condition of power system poses further challenge to damping controller design. Research efforts were focused on designing a robust

controller for many operating conditions [44, 45]. With more PSS available in a system, a coordinated design and tuning of these controllers are considered [32, 46, 47, 48]. The coordinated design of PSS and FACTS devices [49, 50], and coordinated design of different FACTS devices [51] are found to further improve the damping of inter-area oscillations. However, increasing complexity of power system, large variation in operating conditions and subsequent variation in residue will increase challenges for power system damping controller design.

Also these studies use few worst case operating scenarios for the controller design which may not represent critical conditions for inter-area oscillation studies [7]. For power systems with wide variation in operating condition, which is expected in future power system, designing a robust damping controller is a challenging task.

2.2 Recent changes in power system

Power systems around the world are experiencing its biggest transformation of all times with changes in its three constituent parts such as generation, transmission and distribution. It is expected that such changes will shift system operation from a more or less predictable one to random and stochastic. This section will examine the possible changes in power system and its implication to stability of the system.

2.2.1 Changes in generation

During last two decades contribution from renewable generating sources for electricity generation has increased significantly due to environmental and political reasons. In 2007, the European Union has set a binding target of 20% of energy to source from renewable generation by 2020 [52]. In United Kingdom, this target translate to 15% of renewable generation by 2020, most of which will come from electricity generation. Various renewable technologies such as solar, wind, wave, tidal, hydro, bio energy, fuel cell, and nuclear [53, 54] are developed. UK is planning to increase the wind generation from 3.8GW in 2010 to 26.8GW in 2020. Other countries are also pursuing similar ambition [52]. Apart from nuclear generation, all other types of renewable generation depend on weather condition and are subject to variation in electrical output. Solar generation is only available during the day time and varies with cloud movement [55] whereas wind generation varies with prevailing weather condition [2]. The following discussion concentrates on the impact of wind generation on system operation. However, the issues are similar with other types of renewable

generations.

Characteristics of wind

The wind generators typically produce useful output between wind velocities of 3ms^{-1} and 25ms^{-1} , of which it gives rated output above $\approx 13\text{ms}^{-1}$. Study based on UK wind resources have shown that wind generators operates 90% of all hours in below rated speed. This result in an annual average capacity factor for wind turbines substantially below what is typically achieved by conventional generators. It is reported that annual capacity factor of UK wind power varies from 14% to 31% with a long term average of 27% [56]. The important feature of wind as far as power generation is concerned is its variability. The speed and direction of wind fall on a turbine vary depending on prevailing weather condition. It shows annual, monthly and diurnal variability. In UK, wind output is higher during winter months compared to summer months, and higher wind output during day light hours compared to night. Though very rare, it is possible to have no wind and very high wind events in some part of the country making wind generator output zero [57]. It is found that the correlation of wind speed between two generators reduces as the distance increases. Hence diversification of wind generation sites will help to reduce variability in overall wind generation of the country [56].

Changes in generation scheduling

Changing generation mix and more emphasis on renewable generation will have significant impact on generation scheduling. The increased penetration of wind generation will reduce the load factor of thermal generation [57] and at the same time, the outputs of thermal generators will vary with variations in wind output [3]. Fig. 2.1(a) shows the hourly despatch by generation type for the WestConnect study area in April 2006, when no wind or solar generation is present [2]. The coal and nuclear generation form base load. The fall in nuclear generation on the 15th and 16th is due to planned maintenance activity. The combined cycle plants are used in base load/ intermediate mode and, the hydro generator is used to support hourly variation in load. Fig. 2.1(b) shows operation of the system with 35% renewable penetration. The combined cycle units are almost completely off, gas turbine output has increased, and the coal plants are cycling significantly. The nuclear generators show dip in output which is more than likely to indicate a need to spill some of the wind generation, as it is difficult to change nuclear output for such a short time period.

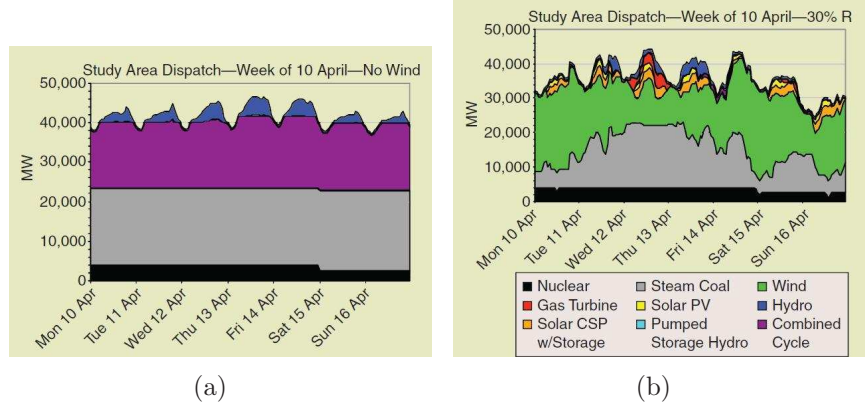


Figure 2.1: Generation dispatch in WestConnect study area in April 2006. Source [2] (a) with no new renewable generation and (b) with 35% renewable generation

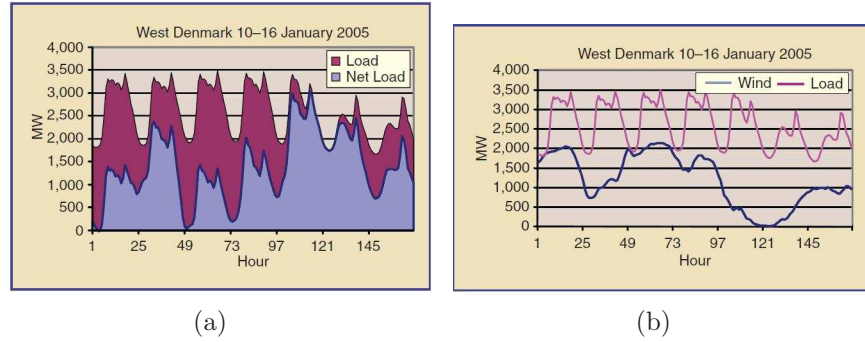


Figure 2.2: Effect of wind penetration in West Denmark Grid during 10 to 16 January 2005 (source: Energinet.dk) [58] (a) load and net load (load less wind) (b) load and wind

Fig. 2.2 presents a study on the West Denmark electricity network [58]. Fig. 2.2(a) shows the actual load and the net load for a week in the West Denmark. The net load is total load less wind generation and the difference between these traces is the wind generation. Fig. 2.2(b) compares the load and wind during this period. During hours close to 49 wind is able to cater full load with less conventional generation as shown in Fig. 2.2(a) whereas no wind generation is available close to hour 121 as shown in Fig. 2.2(b). The generation profile in the network changed in approximately 70 hours from less conventional generation to 100% conventional generation. Also the wind induces steep change in conventional generation output in both direction which call for high flexibility in existing generators.

Fig. 2.3 presents a forecast of operating scenario of the GB network for year 2020 [57]. Fig. 2.3(a) shows the GB demand profile for January 2010, together with a scaled January 2010 wind generation. The blue line demonstrates the variability of the wind generation, with load factors ranging from 5% to 80%. The demand

profile is more consistent in respect of diurnal shape, but with lower levels across weekend and holiday periods. Assuming the same wind profile for January 2021 and an installed wind generation capacity of 26.7GW, Fig. 2.3(b) shows the expected variation in thermal generation output. Approximately 30GW change in thermal generation is expected within two days time frame. Additional thermal generation capacity must be allotted as reserve to cater for the variability in wind output. Fig. 2.4 shows the break up reserve requirement for secure operation of the system with the expected wind variability. Basic reserve, the reserve for forecast error and conventional generation capacity loss, and reserve for response, the reserve to support any in feed loss are common in power system operation. Variability in wind call for additional reserve capacity in conventional generating stations as indicated by blue shade. Higher reserve for response is also required to cater for sudden loss of large off-shore wind farms, towards the end of this decade.

Studies presented so far show that the flexibility required for generating stations is significantly higher compared to that of present day power system.

2.2.2 Changes in transmission system

A good transmission system is key to integration of renewable generation such as wind and solar. These resources are generally located in remote areas and weak transmission system can be a barrier to higher utilization of these resources [59, 60, 61]. Transmission system of various countries are transforming with installation of new HVDC lines and FACTS devices, and capacity improvement of existing lines to support power flow with increase in generation [62]. In UK, the majority of wind resource are located in Scotland whereas main load centers are located in England. Two HVDC lines are proposed along the Scotland-England transmission corridor to improve transfer capacity of the system [63]. Transmission lines connecting different energy resources can improve utilization of multiple energy resources depending on their output schedule. A meshed DC grid in the North Sea is found to result in increased utilization of wind and hydro capacity in the Norway and wind in the North Sea [5]. Also an ambitious plan to build a European supergrid is also under consideration [6] which will interconnect renewable resources in many countries with major load centers, enabling secure spread of electricity between the countries. An interconnection between different grids will reduce overall conventional reserve requirement in the system.

Another important development in recent years is the introduction of WAMS. Using signals sent by the Global Positioning System satellites and Phasor measurement

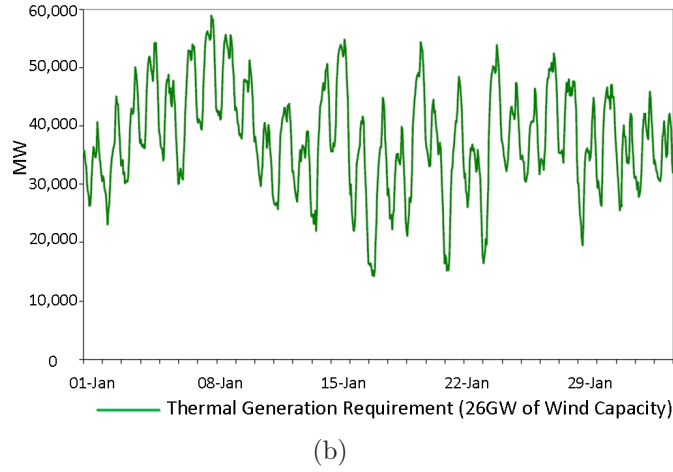
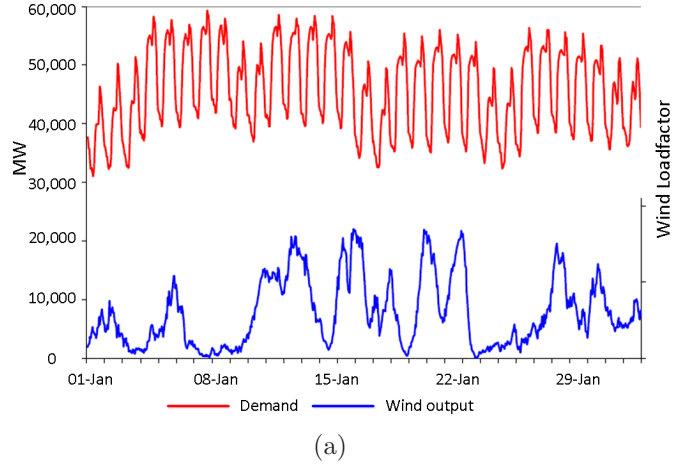


Figure 2.3: Effect of wind penetration on thermal generation scheduling in GB network (a)GB demand and wind generation profile of January 2010 and (b) Thermal generation requirement for 2020. Source: [57]

units (PMU), WAMS can collect synchronized measurements from different parts of transmission network [64]. At present these measurements are use for post event analysis. However researchers are working towards using these measurements for real time monitoring and control of power system [65, 66]. WAMS will give a boost to development of more flexible transmission line operation.

2.2.3 Changes in distribution system

Distribution system is expecting a radical change in coming years with a shift from its passive nature of operation [67]. Using small scale wind turbines and solar panels at roof top, more customers will be producing part of their electricity by their own [68, 69]. Plug in electric vehicles and advanced home automation devices will further change the characteristics of distribution system. Future home will be more energy

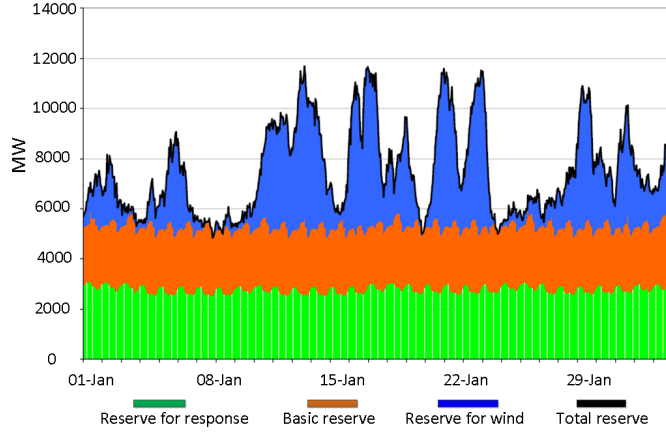


Figure 2.4: Effect of wind penetration on operating Reserve Requirement in GB network for January 2020. Source: [57]

efficient. Moreover smart metering, and communication and computing capacity will be available to actively interfere in the system operation [70]. Using demand side management system the utilities can actively control system load [71]. The result will be a more stochastic nature in distribution system operation.

2.3 Chapter summary

The inter-area oscillations in power system depends on the operating condition of the system. Power system operation typically ensures that generator and transmission lines are loaded well below stability limit. However, for future power systems governed by market forces, power flow pattern will be decided by the price signals and weather conditions rather than technical boundaries. Integration of renewable generation will add additional stress into the system due to increased variability in operating conditions. Weather dependent nature of wind generation will increase operating reserve requirement and increase variability in conventional generation output. Since wind at different sites are less correlated as distance between sites increases, diversification of wind resources will reduce variability in total wind generation and as a result reduce variability in conventional generation. But it will increase the variation in power flow pattern in the system. The network must be flexible enough to face these scenarios. Transmission capacity enhancement is essential to provide the operating flexibility. Power systems around the world are installing many HVDC and FACTS devices to cope up with the changing operating conditions, which will increase the complexity of the network. The interaction of these devices when placed at close proximity, needs in depth study. The changes in

distribution system operation from its passive to active nature will add additional randomness in the system. The characteristics of evolving distribution system load and its effect on stability is not well understood. The increased complexity in network and variability in operating conditions will increase challenges for ensuring stability of the system for all operating conditions.

Chapter 3

Modeling and analysis of multimachine power system

Modeling plays an important role in power system stability studies. Various components of the system should be modeled with sufficient accuracy to simulate the underlying physical phenomenon. This chapter details the modeling of power system from the perspective of small signal stability studies. Models of various power system components are adopted from [10, 72, 73]. The modeling details are limited to the context of this research work. The programming is carried out using MATLAB and Simulink software. The chapter also explains modal analysis and various control system tools used in stability analysis. A two-area test system is used to relate various terms used in the context of small signal stability.

3.1 Dynamic modeling of power system

A model of power system is an integration of several dynamic models such as synchronous generators, asynchronous generators, load, FACTS devices, etc. Fig. 3.1 shows a top level view of the model, where various dynamic models are connected to a network model. The output of the network model is fed back to dynamic models making it a closed loop system. The network model consists of all transmission network components except the components modeled separately. It is represented using an algebraic equation $\mathbf{V} = \mathbf{Z}\mathbf{I}$, where $\mathbf{V}$ is a vector of bus voltage, $\mathbf{I}$ is a vector of injected current at each bus and $\mathbf{Z}$ is a matrix representing the impedance of transmission line and other components not modeled separately. The output of the network block, bus voltage, is fed to dynamic models. The dynamic models consists of differential and algebraic equations (DAE), and the outputs are injected current

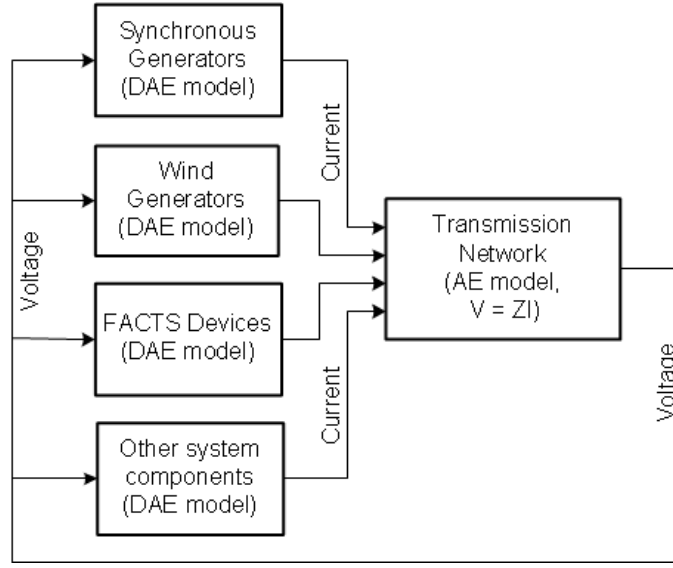


Figure 3.1: Overview of power system simulation program

at corresponding buses.

The power system networks used in this work contain dynamic models such as wind farms, synchronous generators, TCSC and SVC. The DAE equations for later three are listed in this chapter. Wind farm modeling is discussed in Chapter 4. Static load is assumed for all test systems as the objective of the work is to analyze impact of variable operating conditions resulting from large wind penetration on system stability. It is thought that this assumption will not cause significant error in the results and reduce complexity of the model. However, it is worth noting that the type and location of load will influence stability of power system and it is important to model dynamic load for accurate assessment of power system stability [10].

3.1.1 Synchronous machines

The modeling of synchronous generator is a subject matter of many text books and literatures [72, 73, 74]. The models of varying degree of complexity are reported. The modeling complexity required depends on the type of phenomena being studied and the available computational resource. This work uses transient model which is explained in this chapter. The model is sufficient for large system small signal stability studies if the model data is correctly determined [73]. However, subtransient model is required to analyze the behavior during subtransient period, and sub-subtransient model is important to analyze the effect of eddy current and asynchronous torque[75]. However for inter-area mode damping studies the use of these two models do not offer

significant improvement in accuracy compared to transient model [10]. Since the work is related to small signal stability studies in transient time period, the transient model having a field coil on d-axis and damper coil on q-axis is used. The governor is modeled using a reheat type turbine governor system and excitation system is represented using either a IEEE-DC1A or a IEEE-ST1A models.

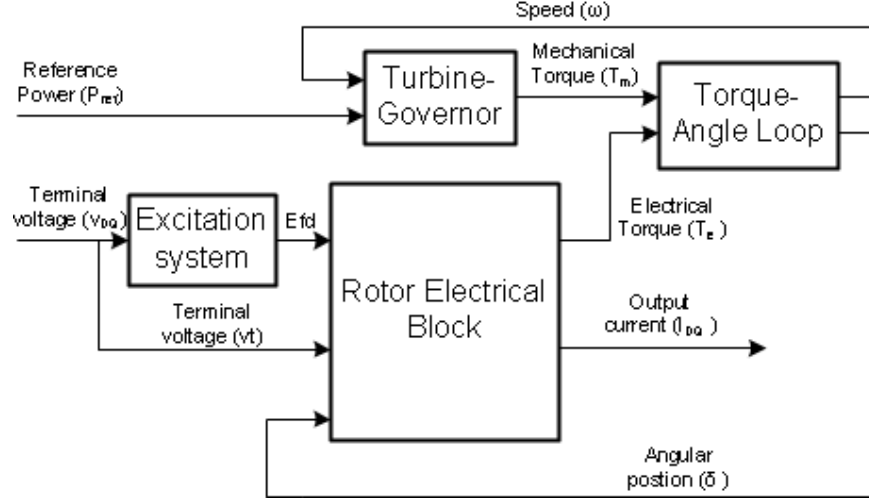


Figure 3.2: Block diagram representation of synchronous machine model

Fig. 3.2 shows internal block representation of a synchronous machine model. The DAE equations corresponding to individual blocks are listed below. The input to synchronous machine model is bus voltage v_{DQ} in (3.3) obtained from network block. The output of the model is current i_{DQ} in (3.9) which is fed to the network block. A brief note on translating the differential equations or transfer functions to Simulink blocks is given in Appendix A. The various blocks are assembled to form synchronous machine model and later complete power system simulation program.

Equations for torque-angle loop block

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (3.1)$$

$$\frac{d\omega_i}{dt} = \frac{\omega_s}{2H_i} [-D_i(\omega_i - \omega_s) + T_{mi} - T_{ei}] \quad (3.2)$$

for $i = 1, 2, 3 \dots m$, where,

m : total number of generators,

δ_i : rotor angle of i^{th} generator

ω_i : Speed of i^{th} generator
 ω_s : Synchronous speed of generator
 H_i : Inertia of i^{th} generator
 D_i : Damping coefficient of i^{th} generator
 T_{mi} : mechanical input torque of i^{th} generator
 T_{ei} : electrical output torque of i^{th} generator

Equations for rotor electrical block

$$(v_{qi} + jv_{di}) = v_{DQi}e^{-j\delta_i} = (v_{Qi} + jv_{Di})e^{-j\delta_i} \quad (3.3)$$

$$\frac{dE'_{qi}}{dt} = \frac{1}{T'_{di0}}[-E'_{qi} + (x_{di} - x'_{di})i_d + E_{fdi}] \quad (3.4)$$

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{qi0}}[-E'_{di} - (x_{qi} - x'_{qi})i_{qi}] \quad (3.5)$$

$$\frac{dE'_{dci}}{dt} = \frac{1}{T_{ci}}[-E'_{dci} - (x'_{qi} - x'_{di})i_{qi}] \quad (3.6)$$

Equation (3.6) represents a dummy rotor coil used to handle transient saliency. A detailed discussion on treating saliency is available in [73].

$$(i_{qi} + ji_{di}) = \frac{1}{(R_{ai} + jx'_{di})}[E'_{qi} + j(E'_{di} + E'_{dci}) - (v_{qi} + jv_{di})] \quad (3.7)$$

$$T_{ei} = E'_{di}i_{di} + E'_{qi}i_{qi} + (x'_{di} - x'_{qi})i_{di}i_{qi} \quad (3.8)$$

$$i_{DQi} = (i_{Qi} + ji_{Di}) = (i_{qi} + ji_{di})e^{j\delta_i} \quad (3.9)$$

$v_{qdi} = v_{qi} + jv_{di}$: voltage in Park's reference frame
 $v_{QDi} = v_{Qi} + jv_{Di}$: voltage in Kron's reference frame
 $i_{QDi} = i_{Qi} + ji_{Di}$: current in Kron's reference frame
 E'_{qi} : transient emf due to field flux linkage
 E'_{di} : transient emf due to flux linkage in q-axis damper coil
 E'_{dci} : transient emf due to flux linkage in dummy rotor coil
 i_{di} : d-axis component of stator current
 i_{qi} : q-axis component of stator current

x_{di}, x'_{di} : synchronous and transient reactance along d-axis, respectively
 x_{qi}, x'_{qi} : synchronous and transient reactance along q-axis, respectively
 $T'_{qi}, T'_{di}, T'_{ci}$: open circuit transient time constant along q-axis, d-axis and dummy coil, respectively

Excitation system block

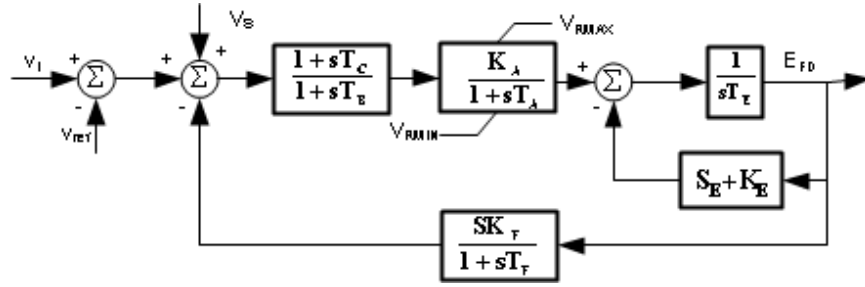


Figure 3.3: Block diagram representation of excitation system model

The block diagram representation of DC type-1 excitation system is shown in Fig. 3.3 [72, 73]. V_I and E_{FD} are input, the measured voltage and output, the field voltage respectively. The constants K_E and T_E relate to exciter gain and time constant, respectively. The regulator transfer function has single time constant T_A and positive gain K_A . The feedback transfer function with constants K_F and T_F represent excitation system stabilizer, and the lead/lag block represent transient gain reduction. The figure can represent the static excitation system by setting the parameters, S_E, K_E, K_F , and T_F to zero.

Turbine governor block

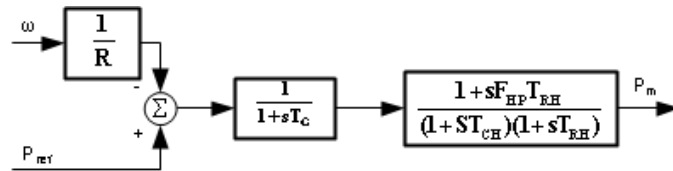


Figure 3.4: Block diagram representation of turbine governor system model

Block diagram representation of governor with reheat steam turbine is shown in Fig. 3.4 [72]. The gain $\frac{1}{R}$ and the first order transfer function represent governor model and the other block represents reheat steam turbine model. The value of R determines the steady state speed versus load characteristic of generating unit.

3.1.2 Thyristor controller series compensator (TCSC)

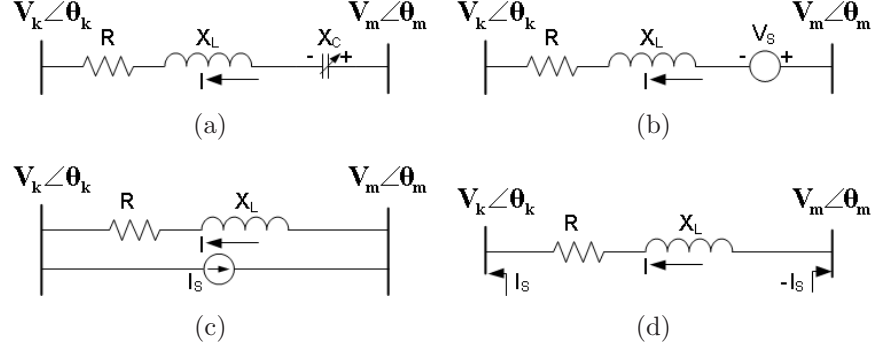


Figure 3.5: Various schematic representations of TCSC

A TCSC is formed of a Thyristor controlled reactor (TCR) connected in parallel with a fixed capacitor to provide rapid and continuous variation of transmission line series reactance. Fig. 3.5(a) shows a schematic representation of a transmission line with a TCSC, in which variable capacitor represents the TCSC. The compensated impedance of the transmission line is given by, $Z_{th} = R + jX_L(1 - k_c/100)$, where $k_c = \frac{X_C}{X_L}100$ represents percentage compensation.

In dynamic modeling of the system, a TCSC can be represented using current injection model. The transformation of TCSC model from a variable series capacitor to injected current at terminal buses is depicted in Fig. 3.5(a) through Fig. 3.5(d) [12].

Let I be the current flowing from bus m to bus k . The TCSC having capacitive reactance X_C can be represented by a voltage source $V_S = -jX_C I$ as shown Fig. 3.5(b). The voltage source V_S in Fig. 3.5(b) is replaced with a current source $I_S = V_S/(R + jX_L)$ in Fig. 3.5(c). Further the current source I_S is split into two current injections at terminal buses k and m as shown in Fig. 3.5(d).

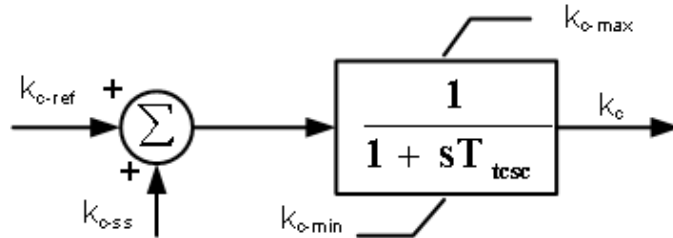


Figure 3.6: Small signal dynamic model of TCSC

For small signal stability studies, the dynamic characteristics of TCSC can be modeled using a single time constant T_{tcsc} as shown in Fig. 3.6 [12]. Where, T_{tcsc} is

response time of TCSC, k_{c-ref} is reference setting of TCSC and k_{c-ss} is supplementary signal for damping control.

3.1.3 Static Var compensator (SVC)

Static var compensator is a shunt connected device which provides reactive power support to control dynamic voltage variations in the network. It consists of parallel combination of thyristor controlled reactor and fixed capacitors. The reactive power injection of a SVC at a bus k is given as,

$$Q_k = V_k^2 B_{svc} \quad (3.10)$$

where $B_{svc} = B_C - B_L$, and B_C and B_L are the susceptance of the fixed capacitor and thyristor controlled reactor, respectively. The corresponding current injection at bus k is,

$$I_k = jV_k B_{svc} \quad (3.11)$$

The small signal dynamic model of SVC is given in Fig. 3.7 [72]. Where, T_{SVC} is the response time of the switching circuitry, T_M is the time constant representing delay in measurement and T_{v1} and T_{v2} are the time constants of the voltage regulator block.

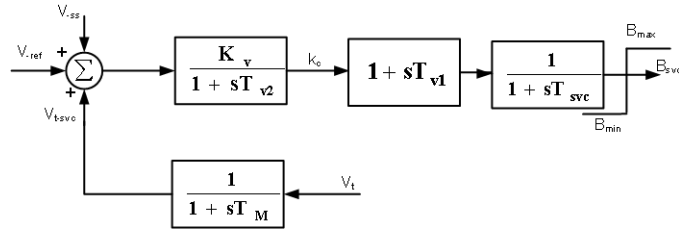


Figure 3.7: Small signal dynamic model of SVC

3.1.4 Initialization

The power system model presented above consists of non-linear equations which calls for a numerical solution. It is assumed that, the system is under stable equilibrium point (SEP) at time $t = 0$ and disturbance happens at $t \geq 0$. To start the simulation, it is necessary to calculate the initial value of states, x_0 at time $t = 0$.

The primary step in initializing the model is to obtain a power flow solution of the network. The power flow solution gives real and reactive power output of generators

(P_g and Q_g), and terminal voltage magnitude and angle (V_t and θ_t) at buses. At SEP, the change in value of the states with time is zero which means, the $\frac{d}{dt}$ term in all differential equations can be set to zero and initial value of states can be deduced. A step by step procedure for initial value computation for synchronous machine specific to this work is listed below. A more detailed explanation is available in [73]. The subscript 0 in the following equations meaning initial value or steady state value of the state variables.

- Run power flow model and obtain P_g , Q_g , V_{g0} and θ_{g0} for the generator bus.

- Compute output current, $I_{g0} \angle \phi_0 = \frac{P_g - jQ_g}{V_{g0} \angle \theta_{g0}}$

- Compute E_{q0} and δ_0 from, $E_{q0} \angle \delta_0 = V_{g0} \angle \theta_{g0} + (R_a + jx_q) I_{g0} \angle \phi_0$

- Compute

$$i_{d0} = -I_{g0} \sin(\delta_0 - \phi_0)$$

$$i_{q0} = I_{g0} \cos(\delta_0 - \phi_0)$$

$$v_{d0} = -V_{g0} \sin(\delta_0 - \phi_0)$$

$$v_{q0} = V_{g0} \cos(\delta_0 - \phi_0)$$

- Compute

$$E_{fd0} = E_{q0} - (x_d - x_q) i_{d0}$$

$$E'_{q0} = E_{fd0} + (x_d - x'_d) i_{d0}$$

$$E'_{d0} = -(x_q - x'_q) i_{q0}$$

$$T_{e0} = E'_{q0} i_{q0} + E'_{d0} i_{d0} + (x'_d - x'_q) i_{d0} i_{q0} = T_{m0}$$

The above steps will initialize rotor electrical block. Other blocks contain simple transfer function structure. A brief description of programming and initialization of transfer function blocks in MATLAB and Simulink is given in Appendix A.

Another important issue associated with simulating the model is occurrence of algebraic loop. An algebraic loop occurs when an input port with direct feedthrough is driven by the output of the same block, either directly, or by a feedback path through other blocks which have direct feedthrough, as shown in Fig. 3.8 [76]. This means, the output of the block at time t depends on the same output. When this occurs, Simulink invokes algebraic loop solver which will attempt an iterative solution of the equations. Hence, the simulation will get slowed down and some times stop abruptly. Different ways of avoiding algebraic loop is presented in [77]. For this

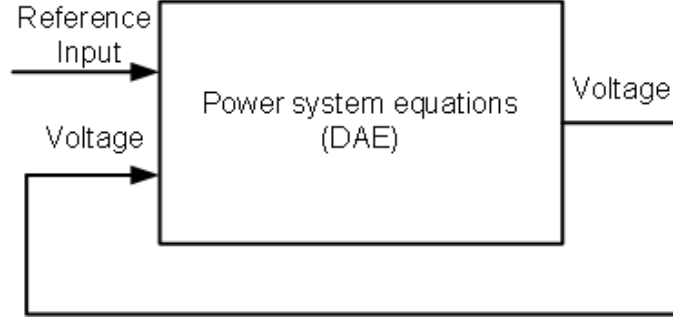


Figure 3.8: Algebraic loop representation

work, whenever algebraic loop creates trouble in running the simulation, the initial condition (IC) block in the Simulink [78] is placed in the input voltage signal of dynamic blocks. The IC blocks specifies the initial value of voltage obtained from power flow which can then be used by Simulink to start the simulation.

3.2 Linear analysis

The power system models presented so far contains non-linear equations and it can be summarized in the following form,

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{z}, \mathbf{u}) \\ 0 &= \mathbf{g}(\mathbf{x}, \mathbf{z}, \mathbf{u}) \\ \mathbf{y} &= \mathbf{h}(\mathbf{x}, \mathbf{z}, \mathbf{u})\end{aligned}\tag{3.12}$$

where $\mathbf{f}$ and $\mathbf{g}$ are vectors of differential and algebraic equations, and $\mathbf{h}$ is a vector of output equations. The notations $\mathbf{x}$, $\mathbf{z}$, $\mathbf{u}$, and $\mathbf{y}$ represent vectors of state variable, algebraic variable, inputs and outputs, respectively.

For power system stability studies, which is the main focus of this thesis, the linear analysis of the system is sufficient. By Linearizing (3.12) and eliminating the vector of algebraic variables $\mathbf{z}$, we can obtain a state space representation of power system as,

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} &= \mathbf{Cx} + \mathbf{Du}\end{aligned}\tag{3.13}$$

where $\mathbf{A}$ is state matrix, $\mathbf{B}$ is input matrix, $\mathbf{C}$ is output matrix, and $\mathbf{D}$ is feedthrough matrix. From MATLAB/Simulink model of the power system the state matrices are obtained using the command *linmod* [79]. (3.13) can be represented in transfer function form as,

$$G(s) = \frac{k(s - z_1)(s - z_2)\dots(s - z_m)}{(s - p_1)(s - p_2)\dots(s - p_n)} \quad m < n \quad (3.14)$$

where p and z are poles and zeros of the transfer function, respectively.

3.2.1 Eigenvalues

Eigenvalues of $\mathbf{A}$, $\{\lambda_i = \sigma_i \pm j\omega_i\}_1^n$ is be obtained using the command *eig*. This is same as the poles of (3.14). However, both terms eigenvalue and pole, and their symbols, λ and p are used in this thesis depending on the context. For a stable system all eigenvalues have negative real part. Eigenvalues may be both real and complex. The complex eigenvalues determines oscillatory behavior of power system where ω relates to frequency of oscillation. In this thesis, the word *mode* is used to represent a complex eigenvalue characterizing electromechanical oscillation. The damping ratio and frequency of oscillation in Hz, of a mode or eigenvalue is given as,

$$\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (3.15)$$

$$f = \frac{\omega}{2\pi} \quad (3.16)$$

3.2.2 Eigenvectors

The right eigenvector for λ_i is a n -column vector ϕ_i which satisfies the relation;

$$\mathbf{A}\phi_i = \lambda_i\phi_i, \quad i = 1, 2, 3, \dots, n \quad (3.17)$$

Similarly, left eigenvector ψ_i satisfies the equation;

$$\psi_i\mathbf{A} = \lambda_i\psi_i, \quad i = 1, 2, 3, \dots, n \quad (3.18)$$

The right and left eigenvectors are normalized such that,

$$\psi_i\phi_i = 1 \quad (3.19)$$

In MATLAB the command, *eig* gives eigenvalues and eigenvectors.

3.2.3 Mode shape

The right eigenvector represents mode shape, which is relative activity of a state variable when a particular mode is excited [72]. The magnitude of the elements of ϕ_{ni} give extents of the activities of n th state variables in i th mode, and the angles of the elements give phase displacements of the state variables with regard to mode. Mode shape can tell us whether a mode is local mode or inter-area mode. Local modes have eigenvectors that are dominated by a few variables associated with one generator or a group of closely connected generators. Inter-area modes have eigenvector components distributed more equally throughout areas of the system [13]. For inter-area mode, the phase displacement of δ and ω states of generators in different areas will be close to 180 degrees.

3.2.4 Participation factor

The normalized participation factor is given as [12],

$$pf_{ki} = \frac{|\phi_{ik}||\psi_{ki}|}{\sum_{k=1}^{k=n} |\phi_{ik}||\psi_{ki}|} \quad (3.20)$$

pf_{ki} represents relative participation of k th state variable in i th mode, and vice versa. For inter-area mode analysis, participation factor is a simple indicator to identify the generators participating in the mode.

3.2.5 Residue

Residue is a powerful tool for output feedback controller design, and it is extensively used in this thesis. These are the constant numerators of the transfer function in (3.14) when it is written in following form,

$$G(s) = \frac{R_1}{s - p_1} + \frac{R_2}{s - p_2} + \dots + \frac{R_n}{s - p_n} \quad (3.21)$$

A more detailed discussion of the residue concept is presented in Chapter 6.

3.3 Model validation

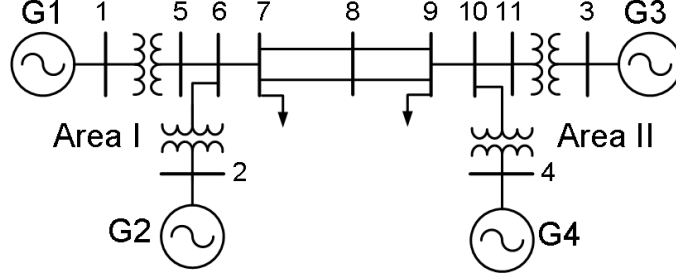


Figure 3.9: Four machine two-area test system

A MATLAB and Simulink based program is developed to simulate power system using the approach presented so far. Time domain simulation results and linear analysis results obtained from the program is compared with results presented in [72, 73] using a four machine two-area test system shown in Fig. 3.9. All machines are equipped with static excitation system and the loads are represented using constant power model. The system data is adopted from [73] and listed in Appendix B.

3.3.1 Time domain simulation

The time domain simulation results of the two-area test system are presented here. The system is initially in steady state. At time $t=1\text{sec}$, a three phase ground fault is applied at bus #7 and the fault is cleared after 100msec. The response of the system following the fault is plotted in Fig. 3.10, Fig. 3.11, and Fig. 3.12.

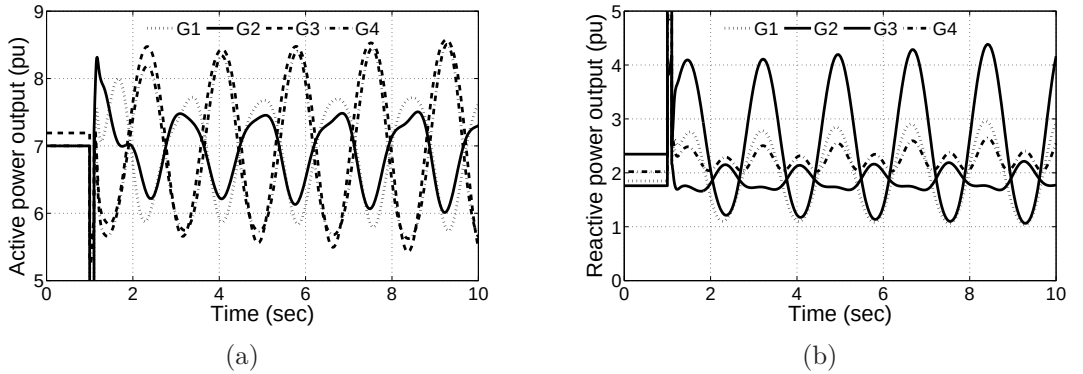


Figure 3.10: Four machine two-area test system time domain simulation results; (a) Generator active power outputs and (b) generator reactive power outputs, following the disturbance

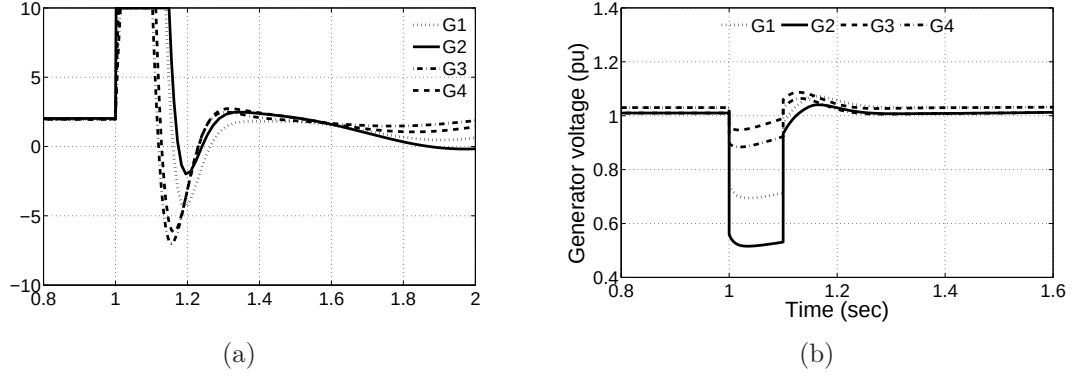


Figure 3.11: Four machine two-area test system time domain simulation results; (a) Excitation system output and (b) terminal voltage of synchronous generators, following the disturbances

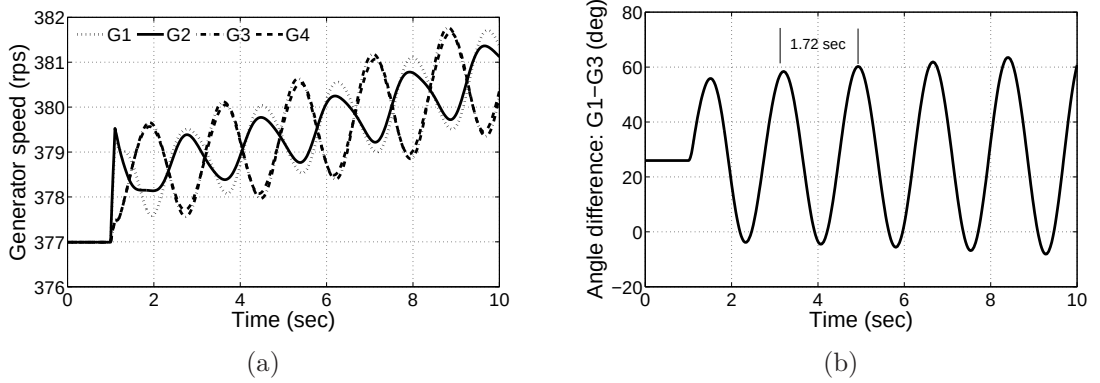


Figure 3.12: Four machine two-area test system time domain simulation results; (a) Generator speeds, and (b) angle difference between G1 and G3, following the disturbances

Fig. 3.10(a) and Fig. 3.10(b) show the active power output and reactive power output of synchronous generators following the disturbance. The growing oscillations indicate that the system is unstable. Also the output of generators in one area move together which form coherent group of generators. In the two-area system, the generators G1 and G2 form one group, and G3 and G4 form another group. The plot of reactive power output of generators is shown in Fig. 3.10(b). The output of G2 is much larger than the other generators due to closeness of the generator to the ground fault. The excitation system outputs and terminal voltages are plotted in Fig. 3.11. The drop of terminal voltage of each generator is proportional to its electrical distance from the fault.

Fig. 3.12(a) shows the speed of the generators. The instability of the system is visible in the increasing amplitude of oscillations after every cycle. Fig. 3.12(b) shows the angle difference between generators G1 and G3. This is one of the best signals

to view inter-area mode as the generators are part of two coherent groups. The plot shows an oscillation of frequency 0.58Hz.

3.3.2 Modal analysis

The linear state space model of the two-area system is obtained using the *linmod* command. The eigenvalues of the state matrix $\mathbf{A}$ are listed in Table. 3.1 which matches closely with previously published results [72, 73]. Few differences are due to different excitation system parameter values used. The table also shows the dominant states of complex eigenvalues having normalized participation factor more than 0.1.

The system has got five pairs of complex eigenvalues. The eigenvalue pairs #7,#8 and #9,#10 represent excitation modes of the system which have participation from E'_q and E_{fd} states of all generators. The mode in #13 to #14 has higher participation from δ and ω modes of G1 and G2 which are in Area #1. This is called local electromechanical mode of Area #1 (LM1). Similarly, the mode in #15 to #16 has higher participation from δ and ω modes of G3 and G4 which is local electromechanical mode of Area #2 (LM2). The mode in #17 and #18 has participation from δ and ω states of all generators in both the areas, hence called inter-area mode oscillation(IAM). In this particular system, the generators G1 and G3 have more participation compared to generators G2 and G4, respectively. This observation is important while discussing the effect of wind penetration on inter-area mode in Chapter 5.

The frequency of inter-area mode is 0.59Hz which is same as the oscillation frequency observed in time domain simulation result shown in Fig. 3.12(b). The mode shape of the inter-area mode is shown in Table. 3.2. The difference between mode shape of participating generators at two areas is close to 180 degree.

3.3.3 Damping controller design

In order to demonstrate the damping controller performance, a SVC is placed in the bus #8. A damping controller is designed using the SVC as actuator and the active power flow signal between buses #9 and #10 as feedback signal. The controller design is discussed in Section 6.2.1.

Fig. 3.13 shows the inter-area mode with three operating conditions: without SVC, with SVC but no damping controller, and with SVC and damping controller. The plot with $\circ$ show the eigenvalue of the system without SVC in which the inter-area mode damping is negative. With the SVC added, plot with $\times$, the system is

Table 3.1: Eigenvalues of the four machine two-area test system

Serial No.	Eigenvalue	Frequency (Hz)	Damping ratio (%)	Dominant states
1	-74.70	-	-	-
2	-74.35	-	-	-
3	-60.06	-	-	-
4	-57.76	-	-	-
5	-37.99	-	-	-
6	-38.41	-	-	-
7,8	$-22.82 \pm 21.25i$	3.38	73.17	$Eq'(0.7) \& Efd(0.63)$ G1 $Eq'(0.9) \& Efd(0.81)$ G2 $Eq'(0.83) \& Efd(0.75)$ G3 $Eq'(1) \& Efd(0.9)$ G4
9,10	-24.06 ± 15.60	2.48	83.9	$Eq'(1) \& Efd(0.94)$ G1 $Eq'(0.88) \& Efd(0.83)$ G2 $Eq'(0.84) \& Efd(0.79)$ G3 $Eq'(0.80) \& Efd(0.75)$ G4
11	-12.85	-	-	-
12	-12.41	-	-	-
13,14	-0.64 ± 7.08	1.13	9.03	$\omega(0.83) \& \delta(0.83)$ G1 $\omega(1) \& \delta(1)$ G2
15,16	-0.62 ± 6.52	1.04	9.50	$\omega(0.82) \& \delta(0.82)$ G3 $\omega(1) \& \delta(1)$ G4
17,18	0.03 ± 3.70	0.59	-0.75	$\omega(1) \& \delta(1)$ G1 $\omega(0.62) \& \delta(0.62)$ G2 $\omega(95) \& \delta(0.95)$ G3 $\omega(0.61) \& \delta(0.61)$ G4
19,20	(0,0)	-	-	-
21	-4.43	-	-	-
22	-4.27	-	-	-
23	-4.31	-	-	-
24	-4.55	-	-	-

Table 3.2: Mode shape of inter-area mode in two-area test system

State	δ_{G1}	δ_{G2}	δ_{G3}	δ_{G4}
Mode shape	-73.37	-64.08	120.47	118.47

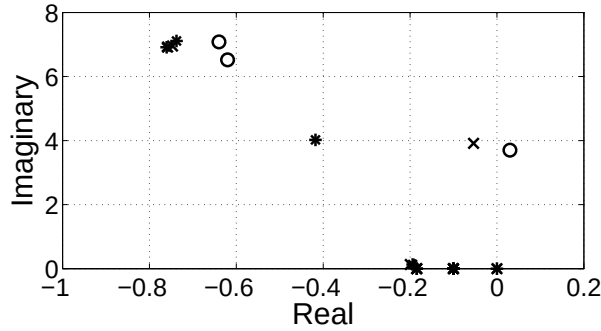


Figure 3.13: Eigenvalues of four machine two-area test system with SVC; [o] without SVC, [x] with SVC but no damping control and [*] with SVC and damping controller

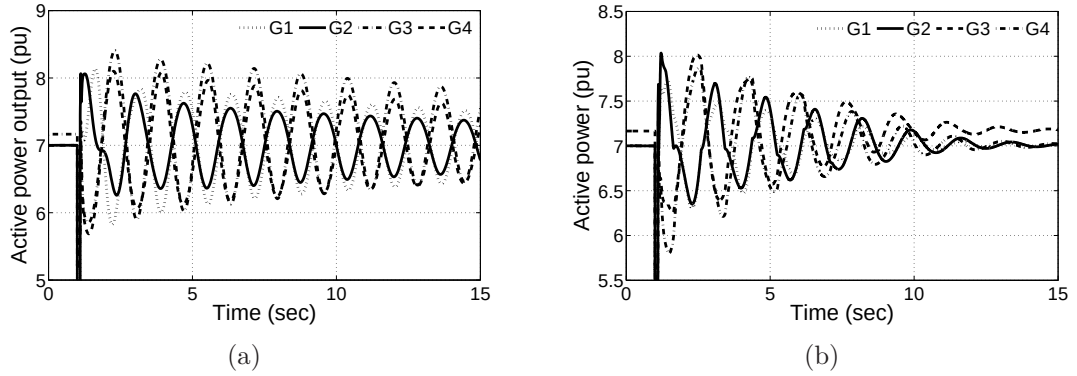


Figure 3.14: Four machine two-area test system time domain simulation results with SVC based damping controller; Generator active power outputs (a) with SVC but no damping controller and (b) with SVC and damping controller

stable compared to system without SVC installation. This shows the ability of SVC to improve the inter-area damping. However, the damping ratio is not sufficient for a secure operation of the system. With supplementary damping controller, the plot with *, the stability of the system improves further.

The time domain response with and without supplementary damping controller is plotted in the remaining figures in this chapter. The active power output of the generators with SVC and no supplementary damping controller is shown in Fig. 3.14(a). Compared to Fig. 3.10(a) which is without SVC, the plot show a damped oscillation. Fig. 3.14(b) shows the response with supplementary damping controller in action which shows a good damping performance. The plot of generator speed without and with damping controller is shown in Fig. 3.15(a) and Fig. 3.15(b), respectively. The SVC bus voltage and SVC susceptance are plotted in Fig. 3.16(a) and Fig. 3.16(b), respectively. The flat top of susceptance plot is due to the limit of SVC. The angle difference between the generators G1 and G3 is plotted in Fig.

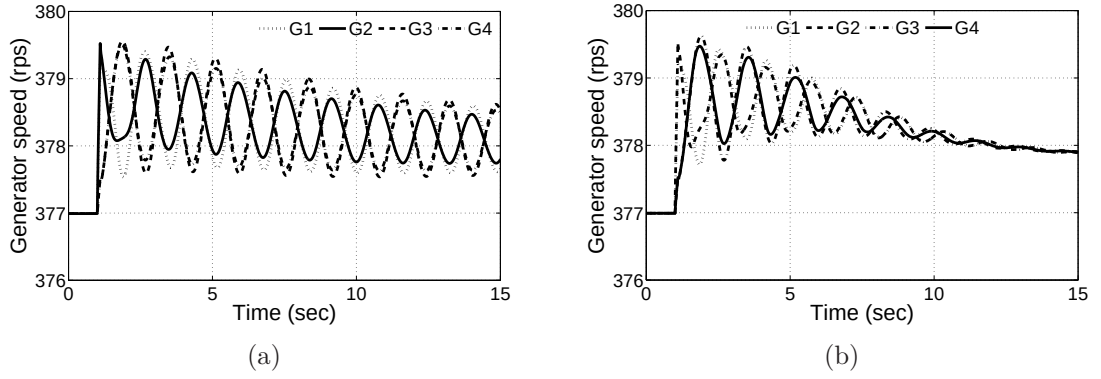


Figure 3.15: Four machine two-area test system time domain simulation results with SVC based damping controller; Speed of generators (a) with SVC but no damping controller and (b) with SVC and damping controller

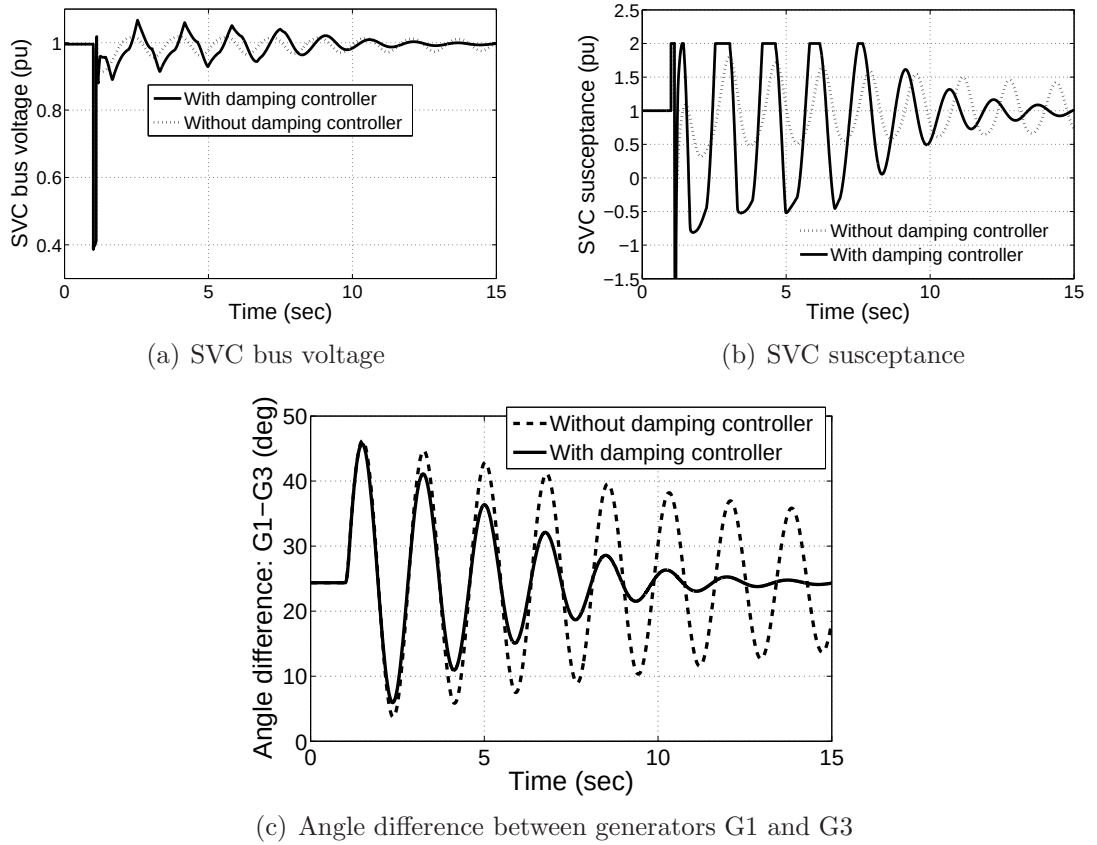


Figure 3.16: Four machine two-area test system time domain simulation results with SVC based damping controller; for cases with SVC but no damping controller, and with SVC and damping controller

3.16(c) which shows the improved damping of inter-area mode.

3.4 Chapter summary

Simulation software is vital for power system stability studies. In this research work, a program is developed in Matlab/Simulink instead of using commercial software packages. The building blocks and programming approach is presented in this chapter. The models and parameters for various dynamic components are adopted from [12, 72, 73]. The results match closely with one available in [72, 73]. There are slight differences in the results due to differences in network structure and excitation system parameters used¹.

¹A comparison with results available in page 815 of [72] and page 328 of [73], for their respective parameters were carried out separately and obtained a one to one match.

Chapter 4

Modeling of wind turbine generator system

This chapter discusses different modeling principles for wind turbine generator (WTG) systems used in this work. The WTG systems in service can be classified into four main types,

- Type-1 : fixed speed induction generator
- Type-2 : variable rotor resistance induction generator
- Type-3 : variable speed, doubly fed induction generator (DFIG)
- Type-4 : variable speed generator with full converter interface (FC)

The earlier wind generators were Type-1 machines formed of fixed speed squirrel cage induction generator and operate at fixed speed. The output power beyond rated speed is regulated using either stall or pitch control. The Type-2 machines are made of wound rotor type induction machines with variable rotor resistance. They can operate over larger slip range compared to Type-1 machines. Both for Type-1 and Type-2, machines capacitor banks are provided to support reactive power requirement.

Large scale wind farms use Type-3 or Type-4 WTG system which are variable speed machines. Power electronics converters play a major role in operation of these machines. In future, majority of power produced through wind will be supplied by these machines. Hence the work presented in this thesis uses Type-3 and Type-4 machines for dynamic simulation.

Fig. 4.1 shows schematic representation of Type-3 and Type-4 WTG systems. **Type-3** machines consist of a doubly fed induction generator with wound rotor. The rotor is fed with a non-zero voltage at slip frequency through an ac-dc-ac voltage

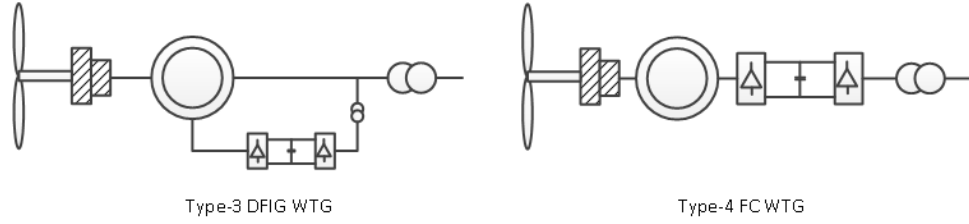


Figure 4.1: Schematic diagram of Type-3 and Type-4 WTG systems

source converter to achieve variable speed operation. The stator is directly coupled to power system. The rotor side converter (RSC) provides decoupled control of stator active and reactive power. It is rated only for part of the stator power as the rotor power is proportional to the slip which is around 30%.

The dynamics performance of the system is governed by the dynamics of the induction generator and the converters. Since the converters respond much faster than the machine during transient time period, the converter dynamics dominates the WTG performance characteristics from the grid perspective. But stator dynamics are important for unbalanced fault response.

Type-4 machines are connected to power system through a full converter which shields the generator speed from system frequency. Hence a wide range of operating speed is possible for this type of machines. Generally permanent magnet synchronous machines are used in Type-4 WTGs. The converters in Type-4 machine need to be rated to 100% since full stator power passes through the converter. Like Type-3 machines, the dynamic performance of Type-4 machines is dominated by the converter dynamics in transient time period.

4.1 Wind farm modeling

Unlike conventional generators, a wind farm consists of many small wind turbine generators connected to main grid through a collector system network. A complete wind farm modeling involves representation of individual WTGs and collector system which can be used to study issues of local interest [80]. However, such model will be too complex to use for stability studies. In order to reduce complexity, wind farm can be represented using one or few WTGs. This type of modeling, aggregate modeling, is found to be adequate for studying integration of large wind farms into the power system replicating a general dynamic behavior of a wind farm at the connection point [81, 82]. Wind characteristics and wind farm structure play a major role in the complexity of wind farm model. Due to the wake effect, the change in wind

speed at a turbine due to preceding turbine, output of different WTGs in a wind farm differs. WTGs of similar output can be aggregated and represented as a single machine. It is shown that more than one WTG may be needed to represent wind farm dynamics depending on wind speed and wind direction [83, 84] to account for the wake effect. Also for large wind farms, feeder length from the point of common coupling to individual WTGs can be significantly different which can cause differences in response of individual WTGs to system fault. A single machine representation may not be adequate in such situations. However in this thesis, single generator representation is used for wind farm to reduce the complexity of model. This assumption will limit the applicability of model only for events in the network, and it cannot reproduce power system dynamics for events inside wind farm or in the grid very close to wind farm. It is thought that, for inter-area mode analysis this assumption will not introduce significant error. In practical scenarios each wind farm modeling requires further analysis of wind characteristics and feeder structure to make a valid and simplified model.

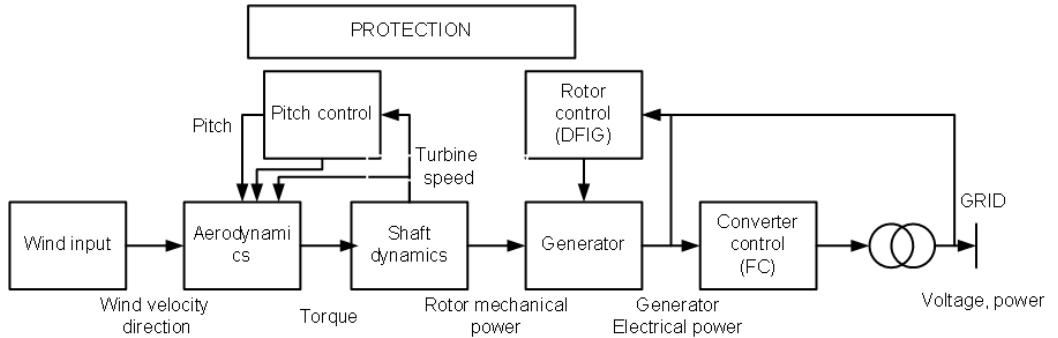


Figure 4.2: Block diagram representation of wind turbine generator system

Fig. 4.2 shows detailed schematic block diagram of a wind turbine generator system. The wind input is a time series representation of wind velocity. Aerodynamics model includes structure of wind farm, wake effect model, C_p curve of wind turbine and turbine blade dynamics. Shaft dynamics is represented using a two mass model or single mass model of turbine generator system. Generator block includes detailed flux dynamic equations of generator. Either rotor control block for DFIG or converter control block for FC is used. Protection logic may be included depending on the simulation objectives. Depending on the application, complexity of the model can be reduced by removing or simplifying some blocks.

Two types of modeling approaches are discussed in this chapter. First one is a detailed model where machine flux dynamics of induction generator is modeled. The model is useful to study the interaction of WTG with power system. Since

the model includes representation of induction generator flux dynamics, they are very complex. Including several such models to represent each wind farm will make the program computationally intensive. Hence their use in this thesis is limited to system having one WTG. The modeling details and parameters for this model are adopted from [85]. The results obtained from MATLAB/Simulink are compared with reported results in [85]. Second model is generic WTG model which uses an algebraic representation of the machine. These are simple models which are used when several wind farms are present in a system. It can be used for large scale system integration studies and dynamic stability analysis. Since machine flux dynamics are not included, these models cannot represent WTG internal dynamics. Two types of generic models, Type-3 and Type-4, representing DFIG and FC type WTG, respectively are explained. The modeling details for generic WTG models are adopted from [86]. The MATLAB/Simulink program results for generic WTG models are compared with time domain simulation results obtained from GE's PSLFTM software which uses the same model.

Test systems

The WTG models are programmed using MATLAB/Simulink. The results are presented using two test systems, a SMIB system and two-area test system shown in Fig. 4.3 and Fig. 4.4, respectively. The generic WTG model results using MATLAB/Simulink are compared against GE's PSLFTM software. In PSLFTM simulation set up, the infinite bus generator is represented using GENSAL model with predefined voltage and frequency, and for two-area system the synchronous generators were represented using GENROU model [87]. The parameters of the WTG are detailed in Appendix D.

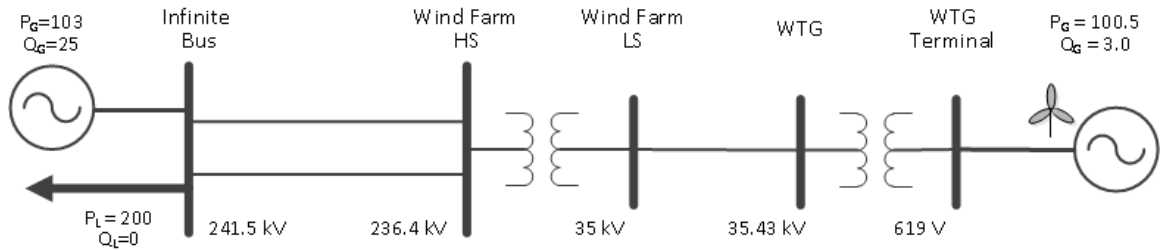


Figure 4.3: Single machine infinite bus test system

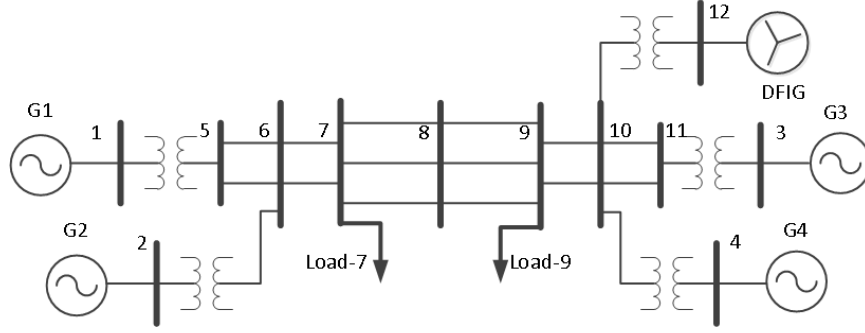


Figure 4.4: Two-area system with wind farm

4.2 Detailed WTG model

A detailed model of Type-3 WTG system is presented in this section. The system contains a doubly fed induction generator directly coupled to the grid. The primary purpose of the model is to assess the impact of WTGs on inter-area mode damping. The wind velocity, hence the mechanical input power, is assumed to be constant during the course of simulation. This assumption will not effect the stability characteristics of power system. However, the program cannot simulate the effects of sudden variation in wind velocity. Also, the grid side converter is assumed to have unity power factor such that no reactive power is exchanged through the grid side converter to power system.

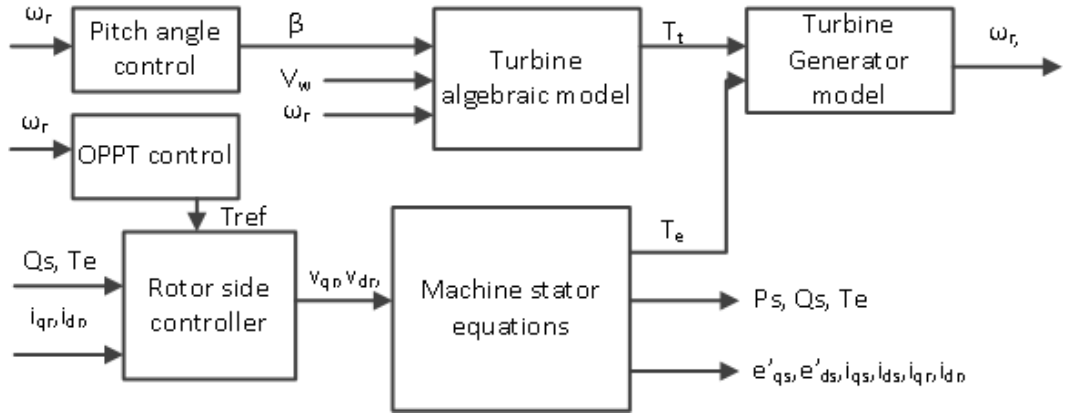


Figure 4.5: Block diagram representation of Detailed WTG model

4.2.1 DAE equations

Fig. 4.5 shows the internal block diagram of WTG system simulation. The modeling approach and equations are adopted from [85].

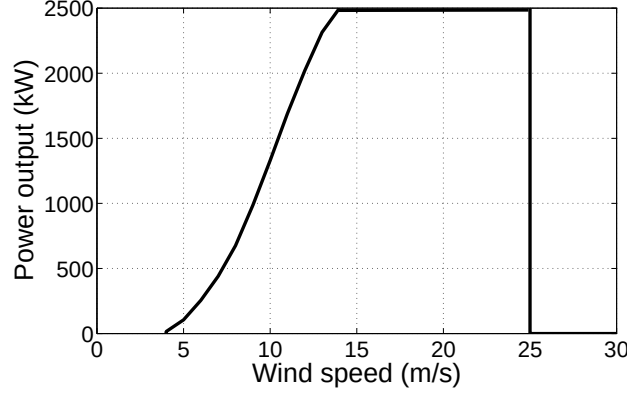


Figure 4.6: Wind speed-power output curve of WTG system

Fig. 4.6 shows typical wind speed vs. output power curve of a WTG system which operates in specific speed ranges. Extractable power is produced between cut in wind speed and cut out wind speed. The cut in wind speed is the speed at which turbine starts to rotate and produce power. This is around 3ms^{-1} . As wind speed increases WTG output increases until it reaches rated power output at around 13ms^{-1} . This region is called sub-rated regime of operation and the turbine blade pitch angle is held to zero during this region to extract maximum wind power. Above this wind speed is called rated regime, WTG produces rated output power and turbine blade pitch angle is controlled to regulate turbine speed. WTG can safely operate until cut out wind speed of around 25ms^{-1} at which point it is shut down to protect it from structural damage.

The DAE equations of the WTG are listed below in the order of block in the Fig. 4.5. The control structure of pitch angle controller and actuator is shown in Fig 4.7. Where, ω_r and β represent rotor speed and pitch angle respectively. The pitch angle regulator is activated during the rated regime of operation. During sub-rated regime the pitch angle of blade is set to zero in order to extract maximum wind power.

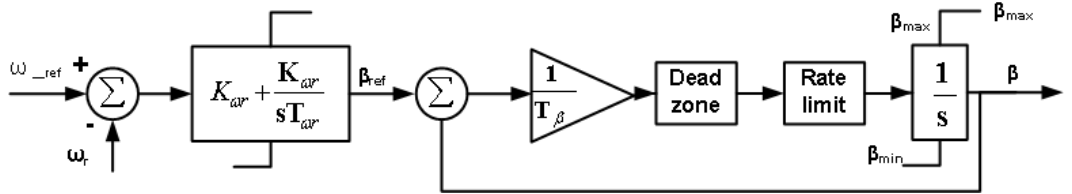


Figure 4.7: Pitch control and actuator model of WTG

The turbine algebraic loop computes mechanical torque produced by wind turbines using (4.2).

$$P_t = 0.5\rho\pi R^2 C_p (\lambda, \beta) v_w^3 \quad (4.1)$$

$$T_t = \frac{P_t}{\omega_t} \quad (4.2)$$

The C_p is the performance coefficient of turbine and for accurate results manufacturers supplied curves should be used. However for academic purposes (4.3) can be used. R , ρ , λ , ω_t and v_w represent blade length, air density, tip speed ratio, turbine speed and wind velocity respectively.

$$C_p (\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda + c_8\beta} - \frac{c_2 c_9}{\beta^3 + 1} - c_3\beta - c_4\beta^{c_5} - c_6 \right) \quad (4.3)$$

$$\exp \left(\frac{-c_7}{\lambda + c_8\beta} + \frac{c_7 c_9}{\beta^3 + 1} \right) + c_{10}\lambda$$

$$\lambda = \frac{\omega_t R}{v_w} \quad (4.4)$$

The turbine generator model represents torque-angle loop of the turbine generator system. In this thesis, it is represented using a two mass model. A single mass model representation is also reported in the literature. Equations (4.5) to (4.7) represents this block.

$$\frac{d}{dt}\omega_r = \frac{1}{2H_g}(k\theta_{tw} + c\frac{d}{dt}\theta_{tw} - T_e) \quad (4.5)$$

$$\frac{d}{dt}\theta_{tw} = \omega_{elB}(\omega_t - \omega_r) \quad (4.6)$$

$$\frac{d}{dt}\omega_t = \frac{1}{2H_t}(T_t - k\theta_{tw} - c\frac{d}{dt}\theta_{tw}) \quad (4.7)$$

where,

T_e : electrical torque

T_t : turbine torque

θ_{tw} : equivalent twist angle of drive train shaft

H_g : WTG generator inertia

H_t : WTG turbine inertia

ω_{elB} : WTG base speed

K : drive train shaft stiffness

c : drive train damping coefficient

The optimum power tracking control is active during sub-rated regime of operation. The reference torque is related to rotor speed by 4.8).

$$T_{e,ref} = K_{opt} w_r^2 \quad (4.8)$$

$$K_{opt} = 0.5 \rho \pi R^5 C_{pmax} / \lambda_{opt}^3 \quad (4.9)$$

The equations (4.11) to (4.27) represent the machine stator equations.

$$\frac{L'_s}{\omega_{elB}} \frac{d}{dt} i_{qs} = -R_1 i_{qs} + \omega_s L'_s i_{ds} + \frac{w_r e'_{qs}}{\omega_s} - \frac{e'_{ds}}{w_s T_r} - v_{qs} + K_{mrr} v_{qr} \quad (4.10)$$

$$\frac{L'_s}{\omega_{elB}} \frac{d}{dt} i_{ds} = -R_1 i_{ds} - \omega_s L'_s i_{qs} + \frac{w_r e'_{ds}}{\omega_s} + \frac{e'_{qs}}{w_s T_r} - v_{ds} + K_{mrr} v_{dr} \quad (4.11)$$

$$\frac{L'_s}{\omega_{elB}} \frac{d}{dt} e'_{qs} = R_2 i_{ds} - \frac{e'_{qs}}{w_s T_r} + (1 - \frac{\omega_r}{\omega_s}) e'_{ds} - K_{mrr} v_{dr} \quad (4.12)$$

$$\frac{L'_s}{\omega_{elB}} \frac{d}{dt} e'_{ds} = -R_2 i_{qs} - \frac{e'_{ds}}{w_s T_r} - (1 - \frac{\omega_r}{\omega_s}) e'_{qs} + K_{mrr} v_{qr} \quad (4.13)$$

where,

i_{qs} and i_{ds} , quadrature and direct axis components of stator current

i_{qr} and i_{dr} , quadrature and direct axis components of rotor current

v_{qs} and v_{ds} , quadrature and direct axis components of stator voltage

v_{qr} and v_{dr} , quadrature and direct axis components of rotor voltage

e'_{qs} and e'_{ds} , quadrature and direct components equiv. source behind transient impedance

$$R_1 = R_s + R_2$$

$$R_2 = K_{mrr}^2 + R_r$$

$$K_{mrr}^2 = \frac{L_m}{L_{rr}}$$

$$i_{qr} = -\left(\frac{e'_{ds}}{X_m}\right) - K_{mrr} i_{qs} \quad (4.14)$$

$$i_{dr} = \left(\frac{e'_{qs}}{X_m}\right) - K_{mrr} i_{ds} \quad (4.15)$$

$$(4.16)$$

$$P_s = v_{qs}i_{qs} + v_{ds}i_{ds} \quad (4.17)$$

$$P_r = v_{qr}i_{qr} + v_{dr}i_{dr} \quad (4.18)$$

$$P_{tot} = P_s + P_r \quad (4.19)$$

$$Q_s = -v_{qs}i_{ds} + v_{ds}i_{qs} \quad (4.20)$$

$$Q_r = -v_{qr}i_{dr} + v_{dr}i_{qr} \quad (4.21)$$

$$Q_{tot} = Q_s + Q_{GSC} = Q_s \quad (4.22)$$

$$T_e = L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \quad (4.23)$$

where,

P_s and P_r stator and rotor active power

Q_s and Q_r stator and rotor reactive power

Q_{GSC} grid side converter reactive power

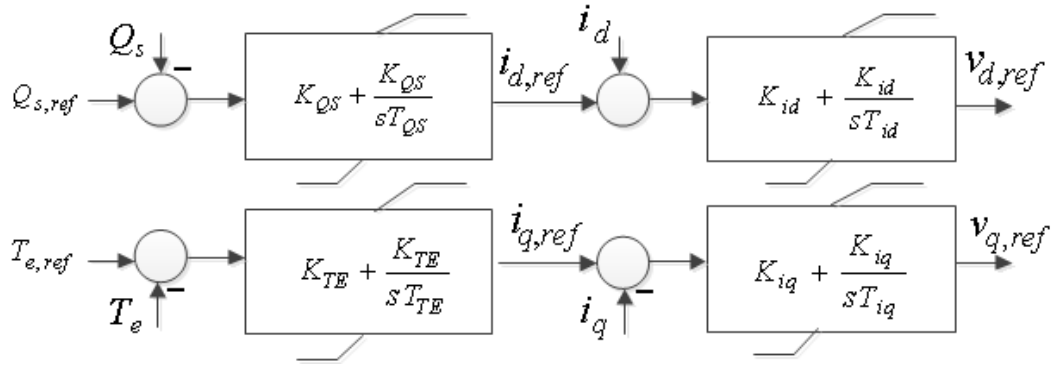


Figure 4.8: Schematic diagram of rotor side converter of WTG

The rotor side converter consists of two decoupled loops with each loop made of two PI controllers in cascade as shown in Fig. 4.8. The slower outer loop does electrical torque and reactive power control, and produces set point for faster inner loop control. Either reactive power control or terminal voltage control can be achieved by changing the input accordingly in the RSC.

4.2.2 Initialization and simulation

The steady state equations of the machine given by (4.24) to (4.27) are derived from the DAE equations by setting derivative terms to zero. This set of equations along with (4.19), (4.20), and (4.23) are used to find the initial condition of WTG model. The steps for the machine stator equation block initialization are listed below.

The other blocks contain simple first order or second order equations which can be initialized using the procedure explained in Appendix A.

$$v_{qs} = -R_s i_{qs} + \omega_s (L_{ss} i_{ds} + L_m i_{dr}) \quad (4.24)$$

$$v_{ds} = -R_s i_{ds} - \omega_s (L_{ss} i_{qs} + L_m i_{qr}) \quad (4.25)$$

$$v_{qr} = -R_r i_{qr} + s\omega_s (L_{rr} i_{dr} + L_m i_{ds}) \quad (4.26)$$

$$v_{dr} = -R_r i_{dr} - s\omega_s (L_{ss} i_{qr} + L_m i_{qs}) \quad (4.27)$$

- From power flow solution, find $v_{qs} = V_g$, $v_{ds} = 0$, $P_{tot} = P_g$, and $Q_{tot} = Q_s = Q_g$. The grid side converter is assumed to have unity power factor and no reactive power is exchanged through it, i.e. $Q_{GSC} = 0$.
- If the machine is operating in sub-rated condition, solve (4.24) to (4.27) together with (4.19), (4.20), and (4.23). The electrical torque is given by the (4.8). This forms a set of 7 equations with 7 unknowns ($i_{qs}, i_{ds}, i_{qr}, i_{dr}, v_{qr}, v_{dr}, \omega_r$). .
- If the machine is operating in rated condition, solve (4.24) to (4.27) together with (4.19) and (4.20). The speed $\omega_r = \omega_{rated}$. This forms a set of 6 equations with 6 unknowns ($i_{qs}, i_{ds}, i_{qr}, i_{dr}, v_{qr}, v_{dr}$).

4.2.3 Simulation results

This section presents time domain results for the DFIG model using two test systems. Fig. 4.9, Fig. 4.10, and Fig. 4.11 show response of DFIG connected to an infinite bus to various system faults. Fig. 4.9 shows response of DFIG to a step change in the infinite bus voltage. The subplots are DFIG terminal voltage, infinite bus voltage, DFIG active power output and DFIG reactive power output. As the DFIG terminal voltage falls, the voltage control loop comes into action and tries to restore the voltage by injecting additional reactive power. The response time depends on the RSC parameters. The active power output show only a small change which account for change in terminal voltage. This shows the decoupled control of active and reactive power of the machine.

Fig. 4.10 shows the response of DFIG voltage controller. The terminal voltage reference input is changed from 1.03pu to 1.05pu at time $t=1\text{sec}$. The infinite bus voltage is held constant during this simulation. The DFIG bus voltage changes to new value within 1sec by injecting additional reactive power output. In this case also, active power output is not affected significantly.

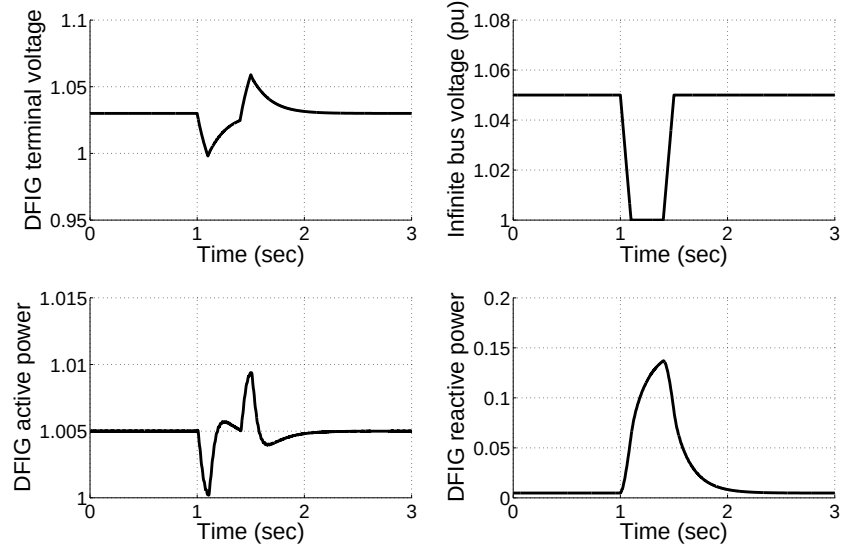


Figure 4.9: Simulation results of SMIB system using detailed WTG model: Response to step change to infinite bus voltage. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output

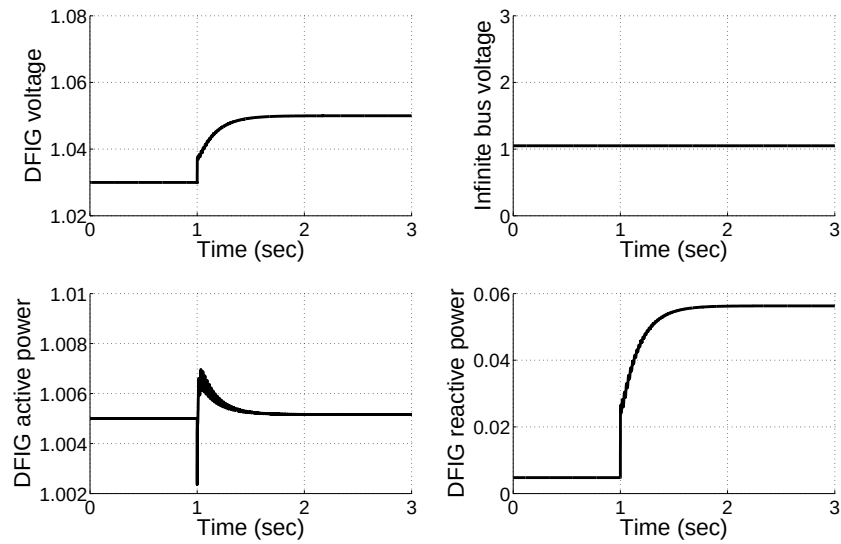


Figure 4.10: Simulation results of SMIB system using detailed WTG model: Response to step change to voltage reference input. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output

Fig. 4.11 shows the response of the DFIG following a three phase to ground fault at infinite bus. Because of the ground fault, the voltage at infinite bus goes to zero which brings DFIG terminal voltage to around 0.5pu. The voltage controller comes into action and injects additional reactive power to restore the voltage. Also the active power output follows voltage variation. The three simulation cases shows the effect of decoupled control of DFIG.

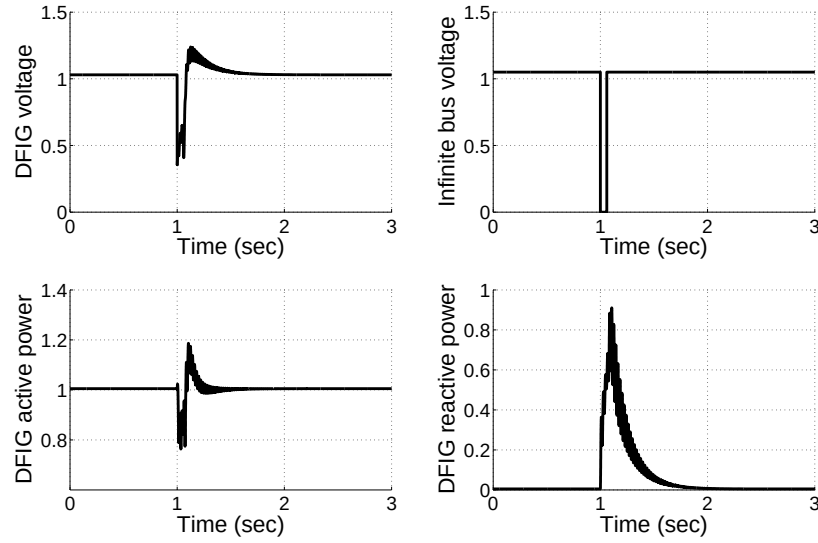


Figure 4.11: Simulation results of SMIB system using detailed WTG model: Response to a three phase fault at infinite bus. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output

Fig. 4.12 and Fig. 4.14 show time domain response of a two-area test system with DFIG. One of the synchronous machine, G4 is removed from the network for this simulation. A three phase to ground fault is applied at time $t=1\text{sec}$ for a duration of three cycles, at bus #7. The active and reactive power output of three synchronous generators and the DFIG are shown the figures. During the fault, a sudden change is observed in the outputs indicated by the spikes. However, that time scale is not important in this study. Following the disturbance, a damped oscillation is visible in active and reactive power outputs of synchronous machines. No oscillations are observed in DFIG output as it is controlled by the converter. The inter-area oscillation is captured in the rotor angle between generator G1 and G3 as shown in Fig. 4.14 with a frequency close to 0.68Hz. The results follow closely with previously published results [85].

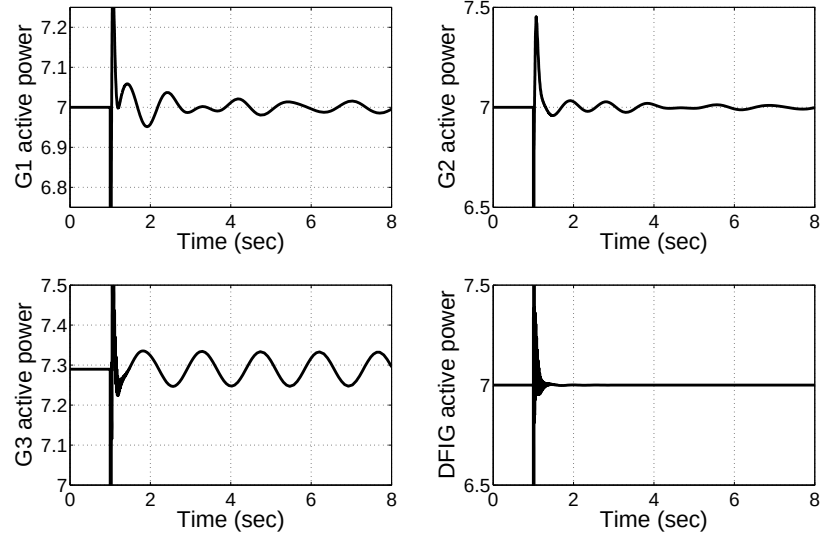


Figure 4.12: Response of two-area test system using detailed WTG model to a three phase fault: Active power output of generators.

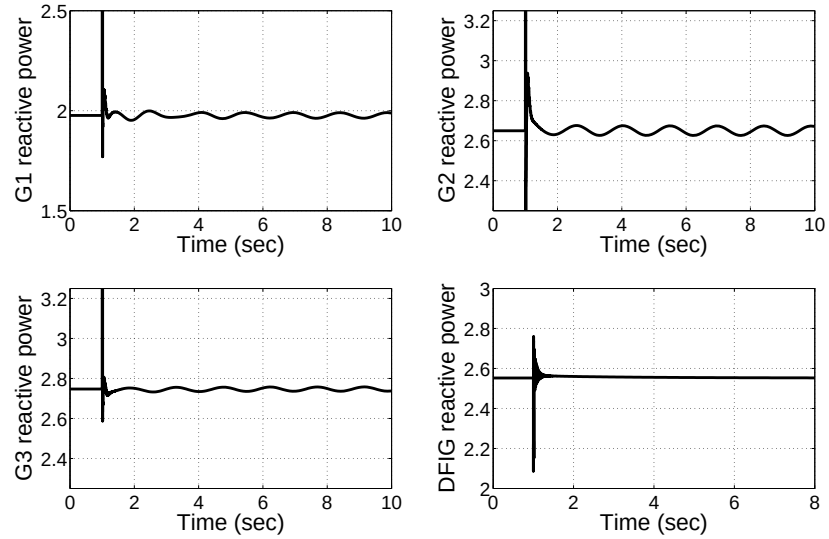


Figure 4.13: Response of two-area test system using detailed WTG model to a three phase fault: Reactive power output of generators.

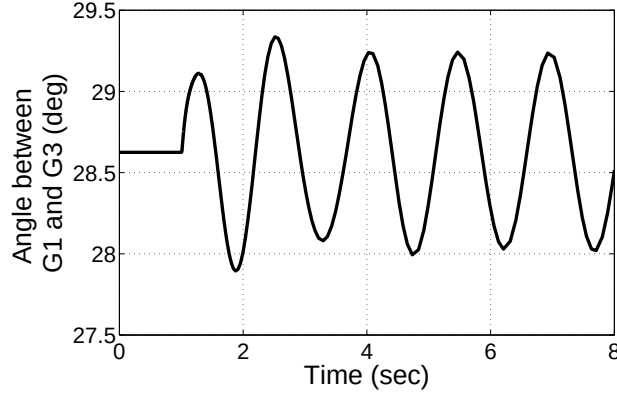


Figure 4.14: Response of two-area test system using detailed WTG model to a three phase fault: Angle difference between G1 and G3

4.2.4 Modal analysis

The state space representation of the two-area system with the DFIG is obtained from MATLAB/Simulink program. The Table 4.1 shows the complex eigenvalues of the state matrix, along with frequency, damping ratio and dominant states participating in the mode. The states having normalized participation factor of more than 0.1 is included in the list. The system has six pairs of complex eigenvalues. The participation factor analysis shows that, two of the complex eigenvalues are related to DFIG whereas other four are related to synchronous machines. No eigenvalues has participation from both type of generators.

The mode #1 with a frequency close to 50Hz is related to rotor electrical dynamics of DFIG. Its damping ratio is highly dependent on the rotor controller parameters. The mode #2 and #3 are the excitation modes of synchronous machines. The mode #4 is another mode which is related to DFIG dynamics. The states which have higher participation to this mode are ω_r & θ_{tw} , and the mode is named as torsional mode of DFIG. The other modes, local and inter-area mode, are related to synchronous machine similar to the one described in the previous chapter. The important point to note is the absence of one of the local modes and improved damping of inter-area mode frequency. It is to be noted that, the inter-area mode continues to be a characteristic of synchronous machine. Though the damping ratio changed in presence of DFIG, it has participation only from the states of synchronous machines. This is because the fast converter dynamics in DFIG effectively shields the machine dynamics from the rest of the power system.

This follows that the DFIG type WTG system does not participate in the inter-area mode damping. However their presence influence the damping ratio of this mode.

Table 4.1: Complex eigenvalues of two-area test system with detailed WTG model

Serial No.	Eigenvalue	Frequency (Hz)	Damping ratio (%)	Dominant states
1	$-12.8 \pm 328i$	52.24	3.9	E'_{qs} & E'_{ds} , DFIG
2	$-23.4 \pm 19.7i$	3.14	76.38	E'_q & E'_{fd} of G1 to G3
3	$-24.3 \pm 13.2i$	2.11	87.79	E'_q & E'_{fd} of G1 to G3
4	$-2.14 \pm 11.2i$	1.78	18.82	ω_r & θ_{tw} of DFIG
5	$-6.3 \pm 6.7i$	1.07	9.32	ω & δ of G1 to G2
6	$-0.003 \pm 4.32i$	0.68	0.001	ω & δ of G1 to G3

Hence it is not necessary to model the machine dynamics of WTG system in order to study inter-area oscillations. The modeling details of more generic Type-3 and Type-4 WTG system are explained below.

4.3 Generic wind turbine models

In previous section, it is shown that the wind farm does not participate in the inter-area oscillation mode. The response of the wind farm to external disturbances in transient time period is dominated by the power converter dynamics with independent control of active and reactive power. It also aids the machine to operate in wide range of speed. Hence it is not essential to model the wind generator in details in order to analyze the inter-area oscillation mode. Also, the detailed model requires internal data of generators and turbines which are not readily available. Hence it is difficult to match the model results with actual wind farm dynamics.

An alternative is the generic WTG model proposed by WECC which can be used to model wind farms of different manufacturers [86]. These are reduced order positive sequence models intended to study the response of the system for faults happening in the grid. The machine flux dynamics are not included in this model but emulates the performance of a wind farm to external disturbances. However the model is not suitable for studying dynamics of power systems to events inside the wind farm or interaction of DFIG machine and the power system. The modeling of Type-3 and Type-4 WTG system is described here.

4.3.1 Type-3 WTG model: doubly fed asynchronous generator with rotor side converter

Fig. 4.15 shows the functional blocks of Type-3 WTG model namely [86],

- Generator converter model
- Converter control model
- Wind turbine model
- Pitch control model

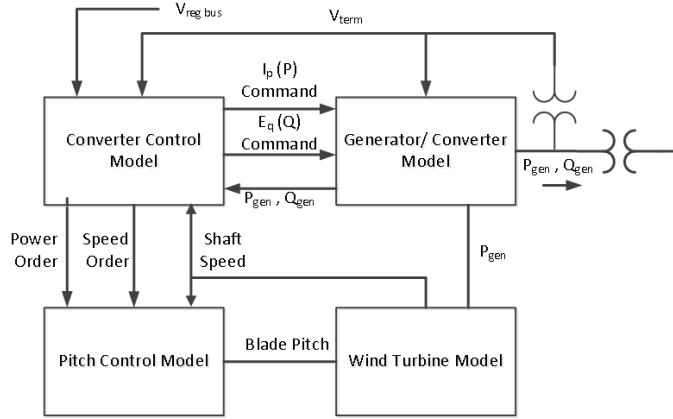


Figure 4.15: Schematic representation of generic Type-3 WTG model

The Generator converter model represents the generator and power converter of the wind farm. Unlike conventional models, this model does not contain any flux dynamics or rotor dynamics. The rotor dynamics is represented in wind turbine model. The resulting model represents an algebraic controlled current source that computes the required current injection into the network in response to the flux and active current commands from the converter control model. Fig. 4.16 shows the internal block diagram of the model. The converter control model contains decoupled active and reactive power control loops. Fig. 4.17 shows the reactive power control loop with wind farm reactive power control emulator and power factor control regulator. Depending on the settings of *varflg* wind farm can be operated in constant reactive power mode, constant power factor angle mode, or voltage regulation mode by a wind farm reactive power controller. The V_{aux} input can be used to modulate the wind farm voltage control reference input for damping improvement.

Fig. 4.18 shows the active power control loop of the wind farm. The non-linear function, $f(P_{gen})$ is used to model desired WTG speed as a function of the power level. In this thesis (4.28) with upper and lower limits is used to represent $f(P_{gen})$.

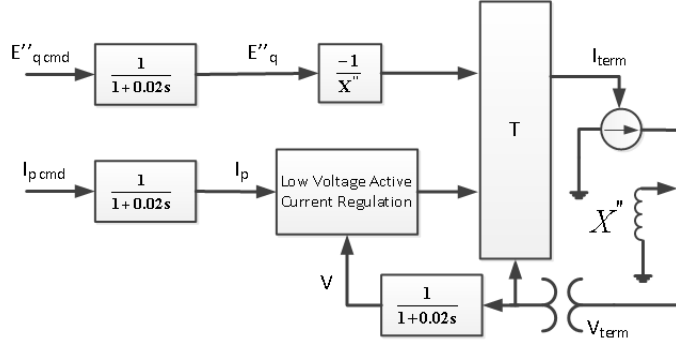


Figure 4.16: Generator converter model of generic type-3 WTG model

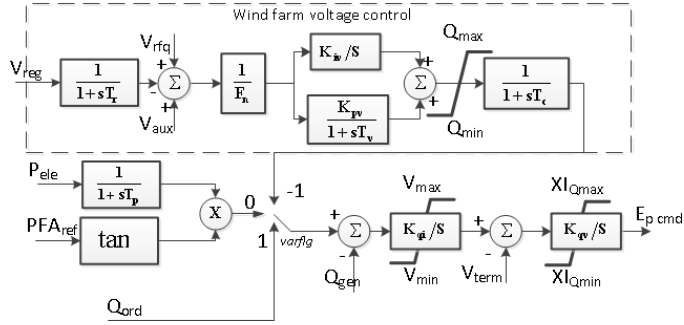


Figure 4.17: Reactive power control loop of generic type-3 WTG model

$$\begin{aligned} \omega_{ref} &= f(P_{gen}) = -0.6052P_{gen}^2 + 1.3416P_{gen} + 0.5369 \\ &\quad \text{if } \omega_{ref} > 1.2 \quad \omega_{ref} = 1.2 \\ &\quad \text{if } \omega_{ref} > 0.76 \quad \omega_{ref} = 0.76 \end{aligned} \quad (4.28)$$

This approximation means that, the simulation may not give correct results if the wind speed, hence generator output, is close to cut in speed.

Fig. 4.20 and Fig. 4.19 show the wind turbine model and pitch control model. The parameters of wind farm model used in this thesis are listed in Appendix D.

4.3.2 Simulation of SMIB system with Type-3 WTG

The model is implemented using MATLAB and Simulink software, and combined with other power system models to develop the multimachine simulation program. The time domain response obtained from the program is compared with GE's PSLFTM, a commercial software. For Simulink program the infinite bus in the SMIB system is assumed as a load bus. Whereas in PSLFTM it is represented using GENSAL model with a predefined bus voltage and frequency [87].

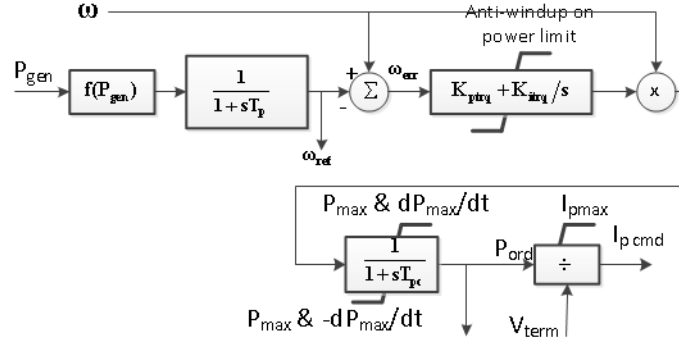


Figure 4.18: Active power control loop of generic type-3 WTG model

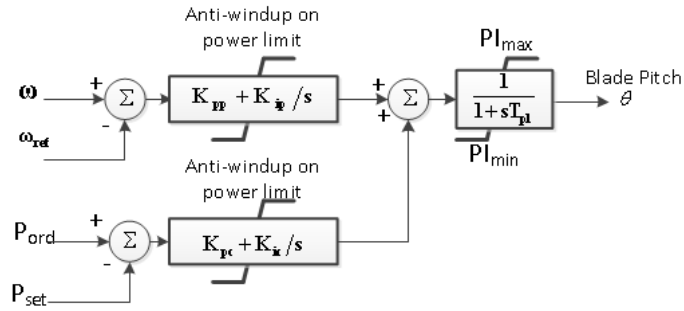


Figure 4.19: Pitch angle control loop of type-3 WTG model

Fig. 4.21 to Fig. 4.23 shows the results of SMIB simulation under the following test conditions.

- Fig. 4.21 Step change in infinite bus voltage
- Fig. 4.22 Step change in DFIG voltage reference input
- Fig. 4.23 Three phase fault at infinite bus

The dotted line shows PSLFTM simulation results and solid line shows the MATLAB simulation results. A small off-set is provided for PSLFTM plots to distinguish from the other plot. The plots are alike except for the three phase fault in Fig. 4.23. In this case, because of sudden dip in terminal voltage, converter protection logic come into play. However, the programming logic used for this protection function in the PSLF is not included in MATLAB program and PSLF simulation has synchronous generator at infinite bus where as in MATLAB it is load bus. This causes a difference in plots during and shortly after the fault. This time period is not important for the small signal stability analysis and the results matches for transient time period. Hence program developed in MATLAB can be used to small signal stability analysis.

It can be seen that, both the plots are alike with one to one correspondence.

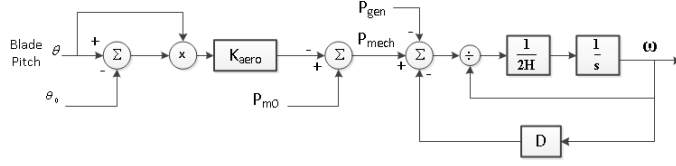


Figure 4.20: Turbine model of type-3 WTG model

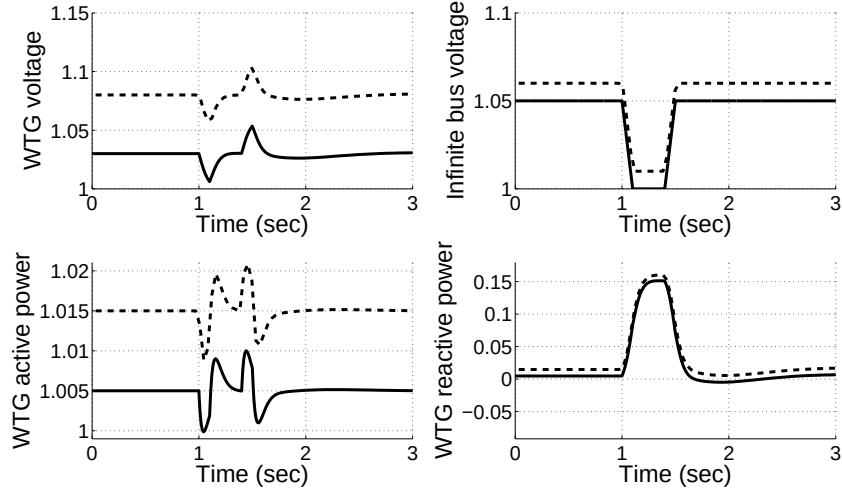


Figure 4.21: Simulation results of SMIB system using detailed WTG model: Response to step change in infinite bus voltage. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output. Dotted line-PSLFTM result, solid line-MATLAB results. A dc off-set is given to PSLFTM results to distinguish between the two plots.

4.3.3 Type-4 WTG model: Variable speed generators with full converter interface

Fig. 4.24 shows the functional blocks of Type-4 WTG model with two internal blocks namely,

- Converter model
- Converter control model

The details of this model is shown in Fig. 4.25 to Fig. 4.20. The model has only slight difference to Type-3 model. The input to generator converter model is active and reactive current command whereas Type-3 model has flux command. The reactive power control loop in converter control model is more or less similar in Type-3 and Type-4 model. However active power control model is different in Type-4 which includes models to emulate turbine performance.

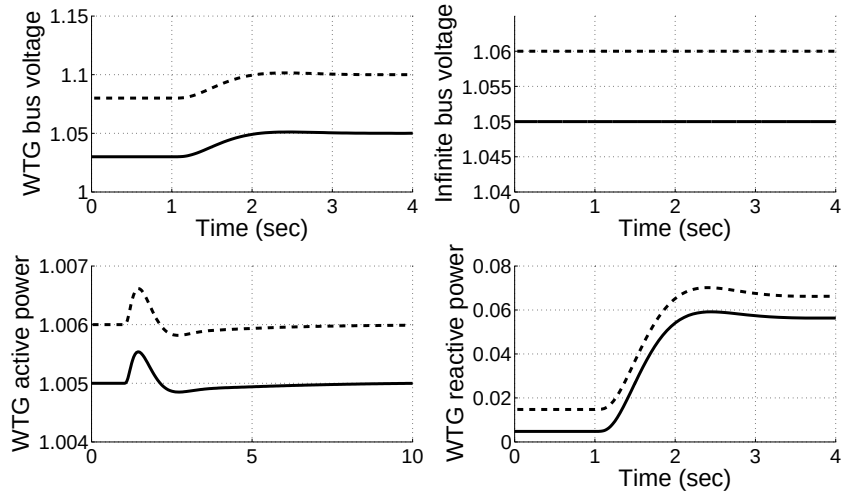


Figure 4.22: Simulation results of SMIB system using detailed WTG model: Response to step change in terminal voltage controller reference input. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output. Dotted line-PSLFTM result, solid line-MATLAB results. A dc off-set is given to PSLFTM results to distinguish between the two plots.

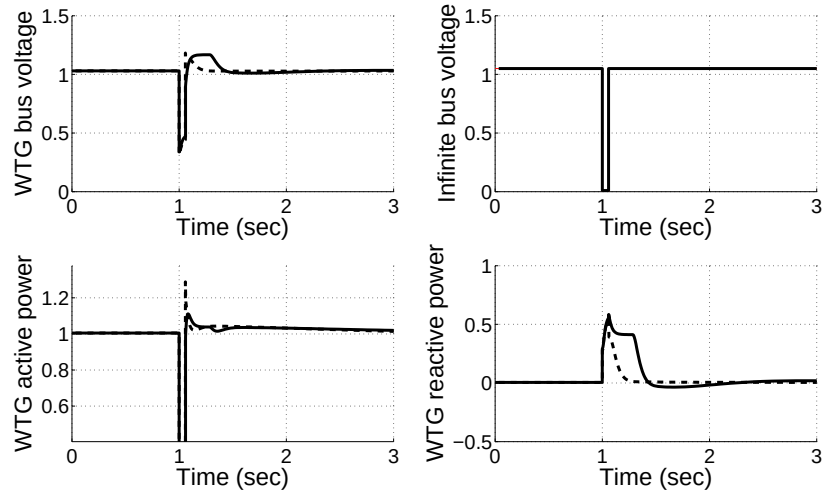


Figure 4.23: Simulation results of SMIB system using detailed WTG model: Response to a three phase fault at infinite bus. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output. Dotted line-PSLFTM result, solid line-MATLAB results. A dc off-set is given to PSLFTM results to distinguish between the two plots.

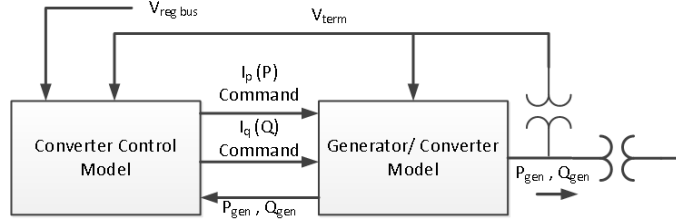


Figure 4.24: Schematic representation of generic Type-4 WTG model

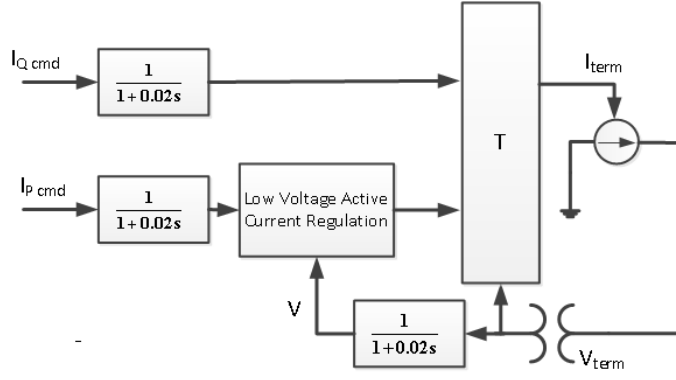


Figure 4.25: Generator converter model of generic Type-4 WTG model

4.3.4 Simulation of SMIB system with Type-4 WTG

Fig. 4.28 shows the SMIB simulation result of Type-4 model using MATLAB and PSLFTM. A step change is applied to the infinite bus voltage from time $t=1\text{sec}$ to $t=1.5\text{sec}$. As the system recovers, the terminal voltage controller reference input is changed from 1.03pu to 1.05pu at time $t = 5\text{sec}$. Both MATLAB and PSLFTM simulation show similar results during the simulation.

4.3.5 Two-area system with WTG

A WTG is connected to the two-area test system as shown in Fig. 4.4. The generator G4 is removed from the network to balance the load. The synchronous machines are represented using transient model in MATLAB/Simulink program. However, a directly comparable model is not available in PSLFTM library. The GENROU model (Solid rotor generator represented by equal mutual inductance rotor modeling) is used for synchronous machines [87]. Hence, a point to point comparison of two time domain simulation results for multi-machine case is not accurate. However, a qualitative comparison is still possible.

The Fig. 4.29 shows the result obtained from the two-area test system with the DFIG represented using Type-3 WTG model. The active power output of the

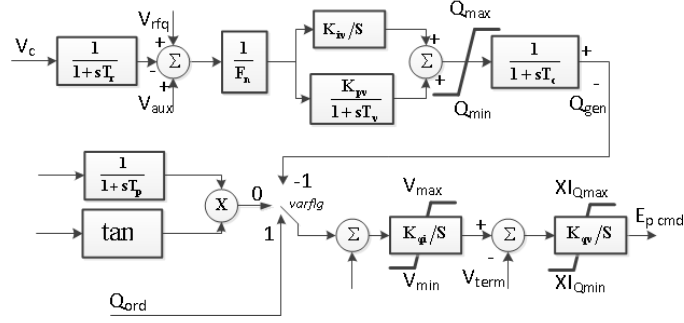


Figure 4.26: Reactive power control loop of generic Type-4 WTG model

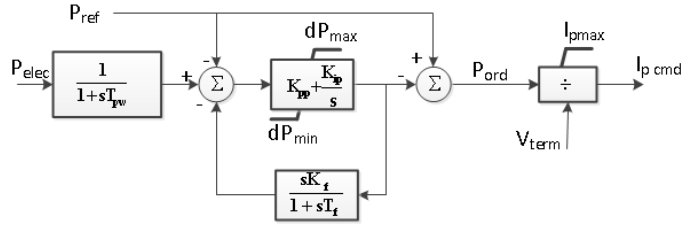


Figure 4.27: Active power control loop of generic Type-4 WTG model

three synchronous generators and the DFIG following a disturbance are shown in the figure. As noted before, the time domain simulation results using MATLAB program and PSLFTM are not similar. However, a similar behavior in transient time period is observed. Oscillations in inter-area mode frequency region is observed only in synchronous generator outputs. The oscillations in both simulation results damp more or less in similar time. The DFIG output is held constant soon after the fault because of the converter control action. A magnified view of the plot during the fault is shown in Fig. 4.30. Though MATLAB simulation using transient model is not accurate during this period, they both show a similar trend. The important point to note here is the response of DFIG which shows no oscillatory behavior once the fault is removed. Only the synchronous generators participate in some kind of oscillations.

Modal analysis

State space representations of two-area test system with a wind farm using both Type-3 and Type-4 WTG model are obtained from MATLAB simulation. The synchronous generator G4 is removed from the network in order to balance the load. The Tables 4.2 and 4.3 show the complex eigenvalues of the state matrix of the system using Type-3 and Type-4 WTG model, respectively. Modes #1 to #3 in both tables are excitation modes of the generators. The modes also have participation from reactive power control loop of WTG generators. Mode #4 is local mode of area #1 and mode #5 is the inter-area mode. The mode #6 in Table 4.3 relates to reactive power

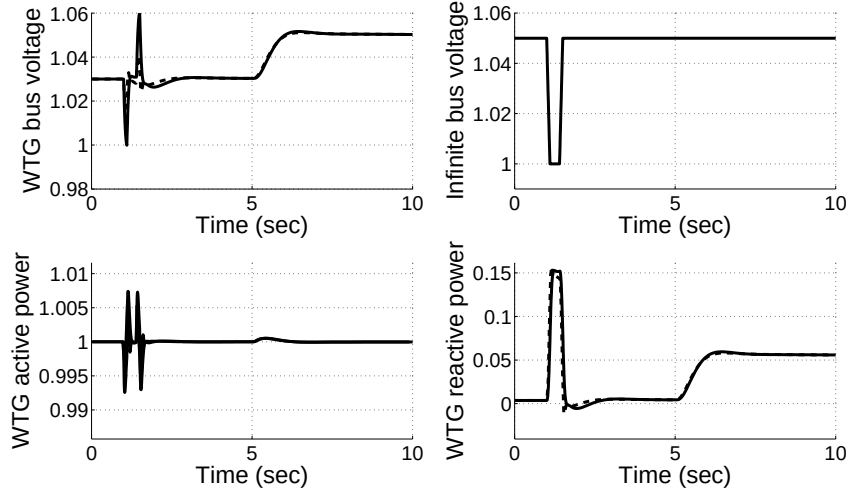


Figure 4.28: Simulation results of SMIB system using Type-4 WTG model: Response to a step change in infinite bus voltage and a step change in voltage controller reference input. Plots show DFIG bus voltage, infinite bus voltage, DFIG active power output, and DFIG reactive power output. Dotted line-PSLFTM result, solid line-MATLAB results.

control loop of WTG. It is observed that the electromechanical modes (mode #4 and #5) have participation only from synchronous machines. Also note the equal damping ratio of the inter-area mode in two tables. It show that the damping ratio is independent of DFIG model used.

4.4 Chapter summary

This chapter presents different WTG modeling approaches such as detailed and generic WTG models. Both the models are programmed using MATLAB/Simulink software. The results for generic WTG modes are compared with the results obtained from GE's PSLFTM software. The detailed model having machine flux dynamics is useful to study the interaction of WTG with system. It is, however a complex model which will increase the computational cost if system contains many wind farms. The generic wind turbine model, simple but does not include machine flux dynamics, is useful to study very large systems with many wind farms. They can represent general behavior of wind farm to power system events but cannot simulate interaction of WTG with system. The simulation results presented in this chapter show that the WTGs does not participate in inter-area mode oscillations. However their presence influence the damping of inter-area mode due to change in dynamic characteristics of power system. It is also noted that the use of Type-3 or Type-4 WTG for simulation does not affect the damping characteristics of the system significantly.

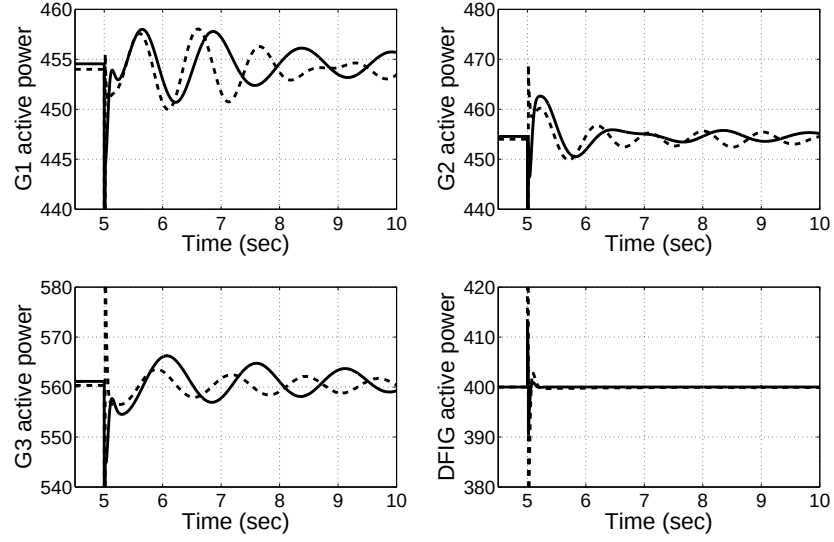


Figure 4.29: Response of two-area test system using detailed WTG model to a three phase fault at bus #7: Active power output of generators. Dotted line-PSLFTM result, solid line-MATLAB results

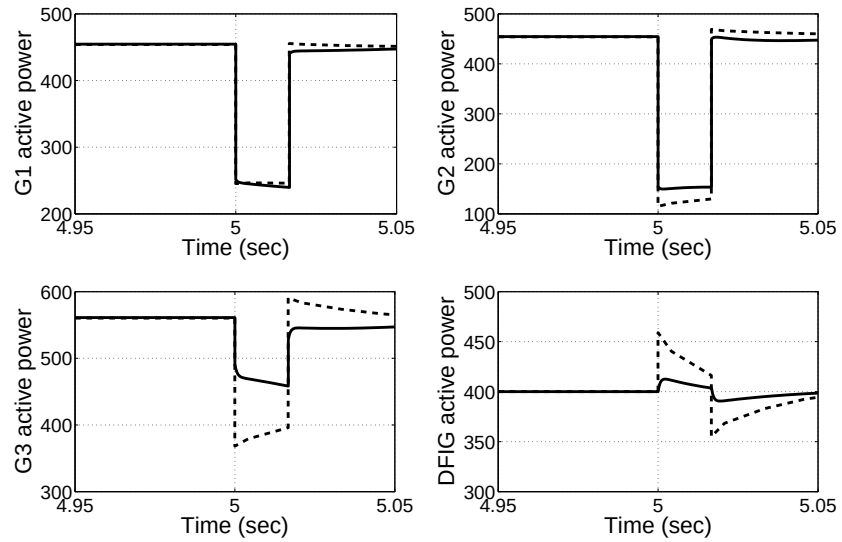


Figure 4.30: Magnified view of Fig. 4.29 showing response during fault

Table 4.2: Complex eigenvalues of two-area test system with a Type-3 WTG

Serial No.	Eigenvalue	Frequency Hz	Damping ratio (%)	Dominant states (Normalized PF)
1	-23.0 ± 23.2	3.7	70	E'_q G3 (1), E_{fd} G3(0.9) E'_q WTG (0.66), S_0 WTG(0.61) E'_q G2 (0.59), E_{fd} G2(0.54) E'_q G1 (0.54), E_{fd} G1(0.50)
2	-24.0 ± 15.8	2.52	86	E'_q G1 (1), E_{fd} G1(0.94) E'_q G3 (0.88), E_{fd} G3(0.83) E'_q G2 (0.64), E_{fd} G2(0.61) E'_q WTG (0.45), S_0 WTG(0.42)
3	-14.1 ± 2.38	0.38	98	E'_q G3 (1), S_1 WTG(0.93) E'_q WTG (0.51), E_{fd} G3(0.39)
4	$-1.12 \pm 5.9i$	0.95	18.8	$\omega \& \delta$ of G2 (1) $\omega \& \delta$ of G1 (0.8)
5	$-0.25 + 4.5i$	0.71	5.55	$\omega \& \delta$ of G3 (1) $\omega \& \delta$ of G1 (0.3) $\omega \& \delta$ of G2 (0.12)

Table 4.3: Complex eigenvalues of two-area test system with a Type-4 WTG

Serial No.	Eigenvalue	Frequency Hz	Damping ratio (%)	Dominant states (Normalized PF)
1	$-21.4 \pm 45.7i$	7.28	42.5	E'_q (1) & S_0 (0.93) of WTG
2	-24.2 ± 18.5	2.95	79	E'_q G1 (1), E_{fd} G1(0.95) E'_q G2 (0.81), E_{fd} G2(0.77)
3	-18.2 ± 3.49	0.55	98	E'_q G3 (1), E_{fd} G3(0.58) S_1 WTG (0.46)
4	$-1.19 \pm 6.5i$	1.03	18.0	$\omega \& \delta$ of G2 (1) $\omega \& \delta$ of G1 (0.81)
5	$-0.25 + 4.56i$	0.72	5.49	$\omega \& \delta$ of G3 (1) $\omega \& \delta$ of G1 (0.31) $\omega \& \delta$ of G2 (0.16)
6	$-2.66 + 2.03i$	0.32	79	V_{ref} (1) & Q_{cmd} (0.68) of WTG (1)

Chapter 5

Effect of large scale wind integration on small signal stability

The wind integration in power systems across the world is not demand driven but is carried out to increase the contribution of renewable energy in total energy mix. Since an efficient system for storing electricity is yet to be developed, conventional generating stations are removed from network or their output is reduced to balance load. Also the wind farms are located based on wind availability, generally far away from load center and spread in different parts of the network. This will cause large variation in power flow pattern in the network depending on the weather conditions. The chapter discusses the impact of such operating conditions on power system stability.

Many studies have been reported on the impact of wind penetration on system damping. These studies are however conducted on various systems and operating conditions, and hence reports differing view on the impact. Studies in [88, 89, 90] argue that in general large scale wind integration has no noticeable effect on inter-area mode stability. The study in [88] uses a New Zealand system, which is relatively small network. However, some operating conditions are identified that can cause network congestion leading into deterioration in damping. Study in [89] uses two-area test system and conclude that the wind integration is not worsening the damping of inter-area mode. However, the authors express concern about the structural changes in power system leading to poor damping. The work in [90] uses a 18 node 7 generator network and shows that the inter-area modes are largely unaffected by the increased wind integration, with the modal characteristics being almost unchanged. It also shows that local and plant level control of wind farm influence damping. Studies in [91, 92] using IEEE 9 bus system and a 11 bus test system, respectively, show that

the damping improved with increased wind penetration whereas [93, 94] show that damping is decreased with increased wind penetration. An Australian test system is used in [94]. However, [95, 96] present results which show both positive and negative impact due to wind penetration. A study system with 22000 buses is used in [95]. The work presented in [97] discusses the influence of wind farm reactive power control scheme on rotor angle stability of synchronous generators.

These differences are expected as the wind generator's influence on damping depends on many factors such as location of wind farm, its internal control systems, power flow in the network, and whether synchronous generators are replaced and did they have PSS. However a more clear understanding is essential to control the inter-area mode oscillations. This study attempts to make qualitative understanding about the impact of wind generators on the damping. The chapter is organized into two sections. In the first section, the two-area test system with an additional wind generator is used. Different possible operating scenarios of the system are generated, and model analysis is carried out to study the inter-area mode. The variation in damping of inter-area mode with different factors in the network is analyzed. In the second section, a reduced GB network model is used to further emphasize the conclusions made in the first section.

The Type-3 DFIG model is used to represent WTG in this chapter. However, as discussed in the previous chapter, choice of the model does not change the behavior of the system towards inter-area oscillation mode. Studies using other models also give similar results.

5.1 Study of two-area system

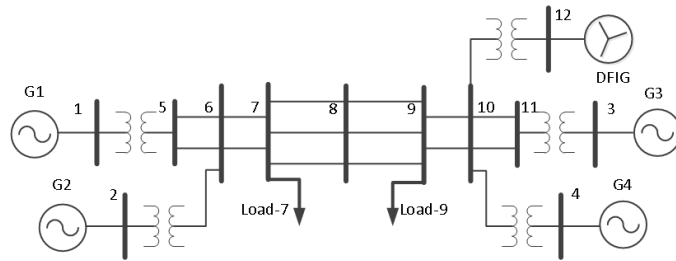


Figure 5.1: Overview of two-area system with wind farm

The two area system used in this chapter is shown in Fig. 5.1. The details of the model are same as the four machine system except an additional wind farm in Area-2. The wind farm has a capacity of 700MW. The wind farm consisting of several WTGs

and collector system is represented using a single machine aggregate model with a transformer. However, single machine model may not be sufficient for representing such large wind farms for all wind velocities and wind directions. However in the absence of those information, a single machine model can be used with caution [98]. Wind farm parameters in pu are included in Appendix D.

5.1.1 Wind farm having equal capacity as one of the synchronous generators

The wind farm used in this study have the same capacity as the synchronous generators. This means that one of the synchronous generators can be replaced when wind farm is operating in its full capacity. Different possible operating scenarios are generated by varying output from generators. Table. 5.1 lists nine possible operating cases generated with 100% wind generation and different thermal generation output. The load remain constants for all the operating conditions.

The table lists these operating conditions of the system with their inter-area mode and local mode characteristics. Case-1 is the base case which is the original four machine two-area system without DFIG. Case-2, Case-3, Case-4 and Case-5 have DFIG with four synchronous generators. The output of synchronous generator is reduced to balance the load. For remaining four cases, one of the synchronous generators is removed to balance the load.

Case-1 represents the base case having an inter-area mode with negative damping. The participation factor analysis shows a higher participation from generators G1 and G3 compared to generators G2 and G4. The base case inter-area power flow is, $P_{IA} \approx 4pu$ (+ve for area-1 to area-2). In **Case-2**, the DFIG injects power in area-2 and the load is balanced by reducing synchronous generator output from G2 and G4 in both areas. This reduces the inter-area power flow to $P_{IA} \approx 0.6pu$ and the inter-area mode damping improves. The **Case-3** is similar to Case-2, but the outputs of generators G1 and G3 are reduced. The damping is further improved, though the inter-area power flow is almost same as the previous case. This is because, in Case-3 the generators having more participation to inter-area mode, G1 and G3, has less generation.

For **Case-4**, the load is balanced by reducing the output from generators G1 and G2, which will reverse the inter-area power flow, $P_{IA} \approx -2.5$. In this case, all synchronous generators in area-1, especially G1 is running half of its capacity. The damping of inter-area mode is improved compared to the base case. The **Case-5**

Table 5.1: Impact of wind penetration on the stability of two-area test system; wind farm capacity equals one of the synchronous generators'. Inter-area and local modes of two area test system for nine operating conditions generated by increasing wind penetration and varying synchronous generator output.

Cases	Generators	IAM		LM, A-1		LM, A-2	
		Frequ- ency (Hz)	Damp- ing ra- tio (%)	Frequ- ency (Hz)	Damp- ing ra- tio (%)	Frequ- ency (Hz)	Damp- ing ra- tio (%)
Case-1	G1, G2, G3, G4 (7pu) no DFIG	0.622	-0.31	1.039	9.54	1.036	8.84
Case-2	G1, G3 (7pu), G2, G4 (3.5pu) DFIG (7pu)	0.629	3.97	0.965	16.14	1.057	14.13
Case-3	G1, G3 (3.5pu) , G2, G4 (7pu) DFIG (7pu)	0.621	5.62	0.993	14.38	1.066	13.11
Case-4	G1, G2 (3.5pu) , G3, G4 (7pu) DFIG (7pu)	0.584	5.09	0.891	22.84	1.132	8.31
Case-5	G1, G2 (7pu), G3, G4 (3.5pu) DFIG (7pu)	0.602	3.30	1.039	9.60	0.984	20.20
Case-6	G1 (0pu) , G2 (7pu), G3, G4 (7pu) DFIG (7pu)	0.710	4.02	-	-	1.132	8.34
Case-7	G1 (7pu) G2 (0pu) , G3, G4 (7pu) DFIG (7pu)	0.675	1.11	-	-	1.132	8.13
Case-8	G1, G2 (7pu), G3 (0pu) , G4 (7pu) DFIG (7pu)	0.739	2.02	1.041	9.54	-	-
Case-9	G1, G2 (7pu), G3 (7pu), G4(0pu) DFIG (7pu)	0.702	0.38	1.039	9.55	-	-

is similar to the Case-4, but the generators in area-2 is producing less power. The inter-area power flow is $P_{IA} \approx 4pu$. In this case, though generators in one area relieved significantly, the inter-area power flow is high and same as that of Case-1. Hence it did not achieve similar improvement in damping as with Case-4. In all these four cases, the effective inertia is same as the base case and hence, inter-area mode frequency is almost constant. The local mode damping is improved with reduction in corresponding generator output.

In the remaining four cases, one of the synchronous generators is removed and an increase in the inter-area mode frequency is observed. This is due to the drop in the effective inertia of the system, as the DFIG practically offers no inertia. In **Case-6**, the generator G1 is removed from the network. The inter-area power flow is reversed due to lower generation at the area-1. The damping is improved in this case. **Case-7** is very similar in power flow with Case-6, but G2 is removed instead of G1. The damping is not as good as in Case-6. This is because in Case-6, generator G1 which has higher participation to the inter-area mode is removed, whereas in Case-7 it is not the case. A similar behavior can be observed with **Case-8** and **Case-9**. The Case-8, where generator G3 having higher participation to inter-area mode is removed, has higher damping ratio compared to Case-9, where generator G4 is removed. The damping of Case-8 and Case-9 are comparatively less than that of Case-6 and Case-7, respectively, due to higher inter-area power flow.

To summarize compare between Case-2 and Case-3, Case-6 and Case-7, and Case-8 and Case-9. All these pairs have similar power flow between each other. However the damping ratio of Case-2, Case-6 and Case-8 are higher in their respective pairs, for different generation profile. This is because, the generators affected in these case have higher participation compared to other cases. Similar comparison is made for the frequency of inter-area mode between pairs Case-6 and Case-7, and Case-8 and Case-9, having similar power flow. The frequency is higher for Case-6 than for Case-7 and for Case-8 than for Case-9. In Case-6 and Case-8, generators having higher participation to IAM is removed from the network. This shows a significant influence of scheduling of generators with higher participation to IAM in the damping.

In order to get a better understanding, a series of analysis with step increase in wind generation is carried out. Following section explains the methodology and outcome of this analysis.

5.1.2 Analysis of two-area system with incremental change in wind generation

In this section, six sets of analysis (let us call *Exp*) are carried out with different levels of wind penetration. Each set consists of 12 operating conditions where DFIG output varies from 0.25pu to 3pu in steps of 0.25pu. Under each operating condition, modal analysis is carried out to obtain eigenvalues. For Exp-1, as the DFIG output increases, G1 output is reduced to balance the load. Similarly, for Exp-2, Exp-3 and Exp-4, output of G2, G3 and G4 is reduced, respectively. For Exp-5 and Exp-6, synchronous generator output is held constant. Instead, the load is increased with increased wind generation. For Exp-5 and Exp-6, the load at Bus 7 and Bus 9 are increased, respectively. The inter-area mode variation for all these operating conditions are plotted in Fig. 5.3.

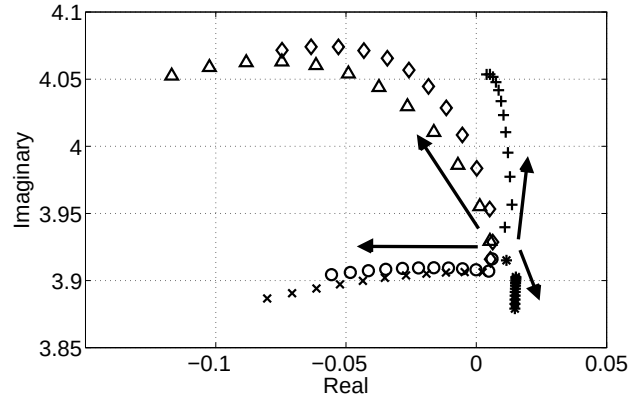


Figure 5.2: Inter-area mode shift for incremental change in wind penetration in the two area test system. $\triangle$: Exp-1, $\diamond$: Exp-2, $\times$: Exp-3, $\circ$: Exp-4, $+$: Exp-5, and $*$: Exp-6.

In **Exp-1**, the generator G1's output is reduced to allow increased DFIG generation for the same load, which results in drop in inter-area power flow. Also note that, G1 is one of the generators having higher participation to the inter-area mode. As seen from the eigenvalue plot ($\triangle$'s), the damping of the mode improves with increase in wind penetration. The **Exp-2**'s pattern of inter-area power flow ($\diamond$'s) is almost similar to Exp-1. But the improvement in damping for Exp-2 is not as good as Exp-1. The participation of G2 in the inter-area mode is less than that of G1. This result reiterates the conclusion made in the previous section. However in Exp-1 and Exp-2, inter-area power flow changes in each steps which will also influence damping.

For **Exp-3** ($\times$'s) and **Exp-4** ($\circ$'s), the inter-area power flow does not change significantly. The improvement in damping is due to relief on the synchronous

generator participating in the mode. As seen from the figure, Exp-3, where G3 output is reduced, gives a better damping than Exp-4, where G4 output is reduced.

Two factors are important here. (1) the effect of change in inter-area power flow, and (2) effect of change in generation participating in the IAM. If Exp-1 and Exp-2 are compared with Exp-3 and Exp-4, respectively, effect of these two factors can be separated. It is concluded that, the change in output of generators participating in inter-area mode will shift inter-area mode in horizontal direction and a change in inter-area power flow will shift the eigenvalues in vertical direction, in eigenplane. However, increasing the wind penetration in practical systems will affect these factors in different proportions.

In the last two cases, **Exp-5** and **Exp-6** the synchronous generator outputs are held constant while the extra generation from the wind is used to cater for an increased load. For Exp-5 (+’s), load at Bus-7 is increased which reduces the inter-area power flow and for Exp-6, load at Bus-9 is reduced which keeps the inter-area power flow almost constant. The movement of eigenvalues in both the cases are in opposite direction which reiterates the possible increase in inter-area mode frequency (shift in vertical direction) with increase in inter-area power flow.

The results show that, the effect of increased wind penetration on the inter-area mode is a complex phenomenon. Three factors are discussed in this section; change in output of generators participating in IAM, change in inter-area power flow, and the removal of synchronous generators from the network. With large scale wind penetration, these factors can occur concurrently, hence it will be difficult to quantify the change in damping. In the Section 5.3, the conclusions made so far are evaluated using a reduced GB network mode.

5.1.3 Effect of wind integration on power system damping controllers

As discussed in previous section, increased wind integration is associated with changes in scheduling of conventional generator output which may result in widely varying operating conditions in the system. This section discusses the effect of such changes in the effectiveness of damping controller.

In Chapter 3, a damping controller is designed for two-area test system using the SVC as actuator and active power flow through line connecting buses 9 and 10 as input. The residue for the transfer function between the controller input and actuator reference input is an important factor in controller design.

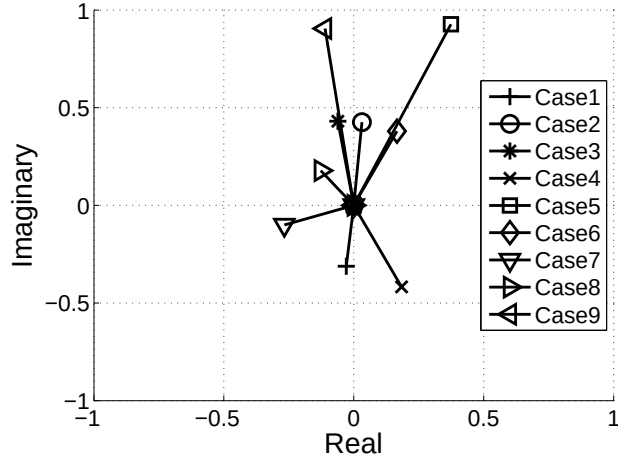


Figure 5.3: Impact of wind penetration on modal residue; Representation of residue for the transfer function between the SVC reference input and output signal, active power flow signal between buses #9 and #10, for nine operating conditions of two-area system

Fig. 5.3 represents the residue for the nine operating conditions discussed in Table 5.1. The length of line is proportional to the magnitude of residue in each case and direction of line shows the angle of residue. The magnitude and angle of the residue vary considerably for different operating conditions¹. In damping controller design it is assumed that the angle of residue may not change significantly [99]. Hence, the phase angle of the controller is designed initially and controller magnitude is optimized to suit all possible operating condition[32, 47]. With increased penetration of asynchronous generators and removal of synchronous generators from the system, this assumption may not be valid for future power systems. If a fixed parameter controller with constant phase angle is designed for the power system, it will not give suitable performance, if not detrimental performance. Motivated from this observation, a robust damping controller approach is presented in Chapter-6 where robustness is ensured by selecting suitable feedback signals.

¹It should be noted that, the variation in residue for two-area system is too large to be comparable with practical power system. This is because, the system is very simple with wind farm of capacity 25% of total load. However, the result points towards possible variation in residue in future power system.

5.2 Dynamic modeling of GB system

5.2.1 Overview of GB network

The electricity transmission network in Great Britain is owned by three entities viz. National Grid Electricity Transmission plc (NGET) in the England and Wales, Scottish Power Transmission Limited (SPTL) in the south of Scotland and Scottish Hydro Electric Transmission Limited (SNET) in the north of Scotland. These three network forms the Onshore Transmission System. National Electricity Transmission System (NETS) comprises of the Onshore Transmission System and the Offshore Transmission system, which NGET operates.

In general, the Onshore Transmission system is operated in three voltage levels such as 400kV, 275kV and 132kV. Apart from this, the system is connected to networks in France, Netherlands, and Northern Ireland through asynchronous link. It has 85.3GW installed capacity with a peak ACS¹ demand of ≈ 56 GW in 2010 [57].

Table 5.2: National grid forecast for GB electricity generation under “Gone Green” scenario. Source National Grid, [57]

Generation Type	Capacity (GW)		Group
	2010/11	2020/21	
Coal	28.2	14.5	Thermal
Coal (CCS)	0.0	0.6	Thermal
Nuclear	10.8	11.2	Thermal
Gas	31.9	34.7	Thermal
Oil	3.4	0.0	Thermal
Pumped storage	2.7	2.7	Hydro
Wind	3.8	26.8	Wind
Interconnectors	3.3	5.8	Thermal
Hydro	1.1	1.1	Hydro
Biomass	0.0	1.6	Thermal
Marine	0.0	1.4	Hydro
Total	85.3	100.5	

5.2.2 Future scenarios in GB network

The GB has ambitious plans for renewable generation for future in order to match the renewable obligations under EU treaty. A majority share of new renewable generation will come from renewable generators, mainly from wind, CCGT plants and nuclear.

¹Average cold spell correction

Table 5.3: Change in generation across different group of generators in GB system

Generation/Load	National Grid Data(GW)			Reduced Grid Data (GW)	
	2010/11	2020/21	Ratio	2010/11	2020/21
Thermal	77.6	68.4	0.88	69.82	61.54
Hydro	3.8	5.2	1.36	2.65	3.63
Wind	3.8	26.8	7.05	2.53	17.85
Total Generation	85.3	100.5	1.17	75.01	88.37
Peak Demand	56	57.3	1.02	59.14	60.51

The total wind generation will grow from 3.8GW in 2010 to 26.8GW in 2020, of which majority share will come from Scotland. Again majority of wind generation will be off-shore far away from the main grid. Some of the thermal generating stations which are close to their working life will be shut down. During this period, the National grid forecast only small increase in peak ACS demand from ≈ 56 GW to ≈ 57.3 GW. Table 5.2 summarizes the National grid forecast for the generation change in the ten years [57].

Significant amount of power will be exported through the Scotland-England transmission corridor which is presently stability limited. A number of reinforcement projects are being proposed to enhance the capacity of this transmission corridor. This includes two HVDC transmission lines [63]. In this research project a dynamic model of representative GB network model is developed. It can provide a qualitative behavior of the inter-area mode of GB system for 2020 operating scenario.

5.2.3 Representative GB network model

The Fig. 5.4 shows one-line diagram of the representative GB transmission network model which was developed at the University of Strathclyde (UoS) [100, 101]. It consists of 29 nodes, inter-connected through 98 transmission lines in double circuit configuration, and one single circuit transmission line. These network branches are intended to represent the main routes on which power flows across the GB transmission system and over which power is exchanged between the seven year statement's (SYS) "Study Zones" and have realistic parameters including thermal ratings. It is claimed that, the model is based on and has been validated against a solved AC Load Flow reference case that was provided by the NGET [101].

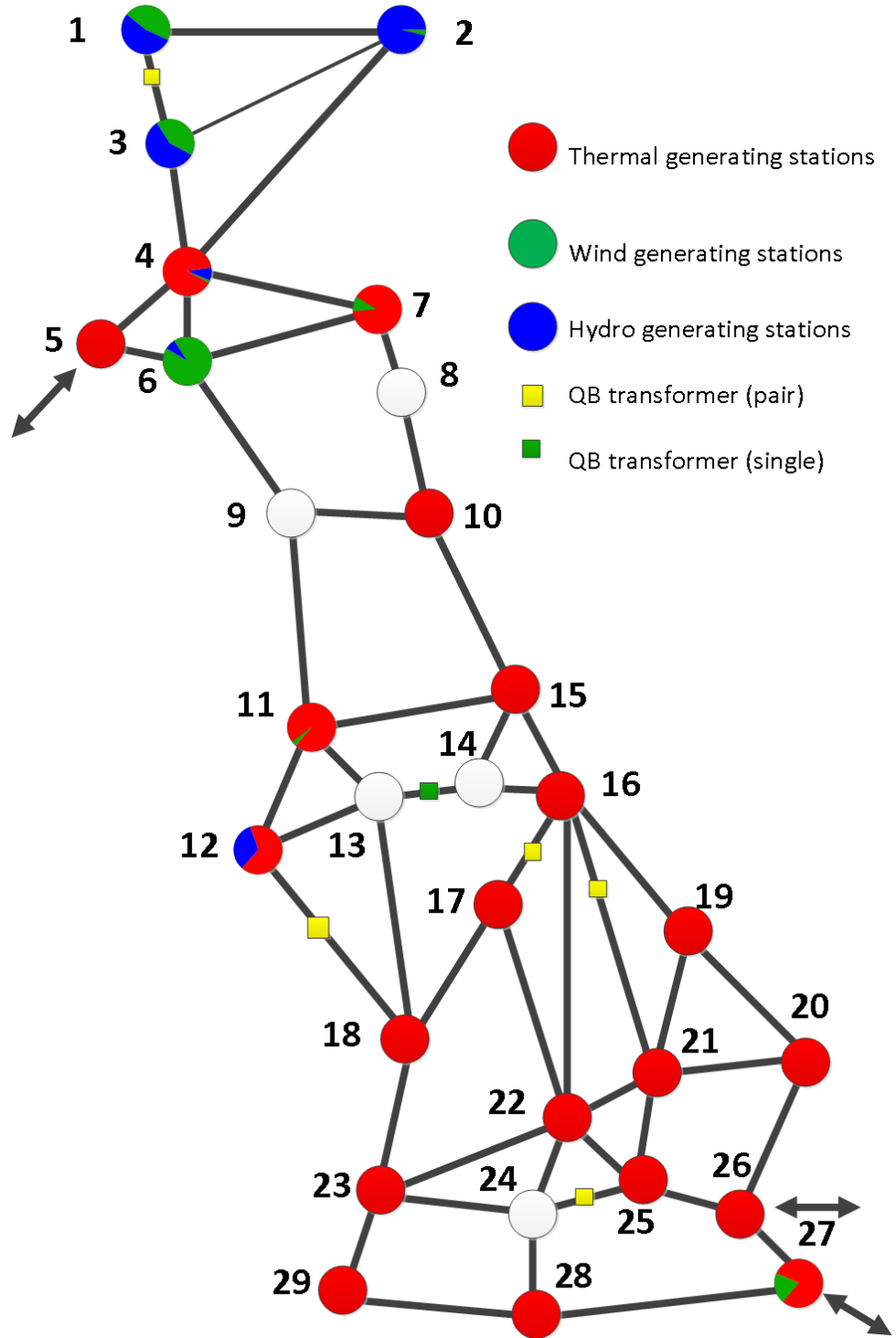


Figure 5.4: Representative GB system network

5.2.4 Dynamic modeling of representative GB network

The representative GB network model developed by UoS contains 65 generators of various types. In this work, the dynamic model is developed to imitate the Scotland-

England inter-area mode. Hence some of the generators connected to one node are grouped together and represented as single generator. They are grouped into three such as Thermal, Hydro and Wind. This will help to reduce the complexity of the model while giving representation to different types of generators in the network. The generators corresponding to individual groups are indicated in Table. 5.2. The total number of generators in the model is reduced to 34. Each generator is connected to one of the 29 high voltage nodes through a transformer. Altogether, the system used in this work has now 29 high voltage buses and 34 generator buses. This forms the 2010 operating condition for the representative GB system. The representative model provided by UoS does not contain dynamic data for the generators. The dynamic parameter data set for GB system is developed for this work. The recommended range of values for different parameters are obtained from [72]. The parameters are tuned to obtain the well observed Scotland-England inter-area mode close to 0.5Hz. The inertia of thermal generators vary from 7pu to 10 pu whereas hydro generators have an inertia of 3pu in machine base. The wind generators are represented using the generic Type-3 WTG model. No FACTS device is modeled separately. The power flow and dynamic data for 2010 operating scenario of the GB system is given in Appendix E.

5.2.5 Modal analysis

Table 5.4 and Fig. 5.5 show the electromechanical modes of the representative GB network for 2010 operating scenario. The generator number in the table represents the high voltage bus number where the synchronous machine is connected. The modes #11 and #17 are inter-area modes and others are local modes. Mode #11 is well damped. The mode #17 is closer to that of the Scotland-England inter-area model present in the actual network. The mode has participation from generators in the Scotland and in the England.

Table 5.5 shows the normalized participation factor and mode shape of the inter-area mode. The mode shape corresponding to δ and ω states of the generators in the buses #2, #4, #5, and #7 located in the Scotland are in opposite to the generators in buses #23 and #26 located in the England. This shows the the former group of generators oscillates with the later group. This inter-area mode is the limiting factor to the effective utilization of transmission line capacity in the network.

Fig. 5.6 shows the angle difference between the generators at buses #2 and #23 following a three phase fault. The inter-area mode with frequency around 0.57Hz is captured in the figure.

Table 5.4: Electromechanical modes of representative GB system for 2010 operating scenario

Serial No.	Eigenvalue	Frequency (Hz)	Damping ratio (%)	Dominant states (generator)
1	-0.08 + 9.43i	1.50	0.92	ω, δ (6)
2	-0.08 + 9.38i	1.49	0.92	ω, δ (4)
3	-0.09 + 9.34i	1.49	1.00	ω, δ (12)
4	-0.05 + 9.00i	1.43	0.63	ω, δ (3)
5	-0.18 + 8.50i	1.35	2.21	ω, δ (1)
6	-0.64 + 6.76i	1.07	9.50	ω, δ (1)
7	-0.70 + 6.72i	1.06	10.48	ω, δ (21)
8	-0.58 + 6.60i	1.05	8.77	ω, δ (28)
9	-0.65 + 6.60i	1.05	9.82	ω, δ (20)
10	-0.59 + 6.30i	1.00	9.33	ω, δ (17,18)
11	-0.43 + 4.79i	0.76	8.94	ω, δ (2,4,7,15,16)
12	-0.59 + 6.12i	0.97	9.64	ω, δ (11,15,16)
13	-1.23 + 5.60i	0.89	21.55	ω, δ (27)
14	-0.57 + 5.89i	0.93	9.75	ω, δ (11,12)
15	-0.65 + 5.99i	0.95	10.84	ω, δ (25)
16	-0.63 + 5.80i	0.92	10.82	ω, δ (19)
17	-0.09 + 3.58i	0.57	2.67	ω, δ (2,4,5,7,23,26)
18	-0.39 + 4.45i	0.71	8.82	ω, δ (2)
19	-0.49 + 5.06i	0.81	9.68	ω, δ (11)
20	-0.56 + 5.48i	0.87	10.24	ω, δ (4,5)
21	-0.54 + 5.57i	0.89	9.79	ω, δ (15)
22	-0.57 + 5.23i	0.83	10.91	ω, δ (9,23,26)
23	-0.57 + 5.24i	0.83	10.83	ω, δ (26,29)
24	-0.56 + 5.37i	0.86	10.41	ω, δ (7,10)
25	-0.63 + 5.38i	0.86	11.65	ω, δ (23,29)

Table 5.5: Mode shape of the GB system inter-area mode

Gen. Bus	Location	State	Normalized PF	Mode shape (deg)
2	Scotland	δ, ω	1.00	-91
4	Scotland	δ, ω	0.46	-86
5	Scotland	δ, ω	0.12	-85
7	Scotland	δ, ω	0.22	-79
23	England	δ, ω	0.13	101
26	England	δ, ω	0.11	102

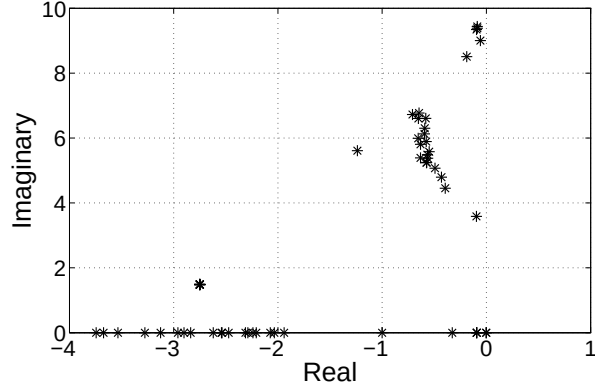


Figure 5.5: Electromechanical modes of representative GB system for 2010 operating scenario

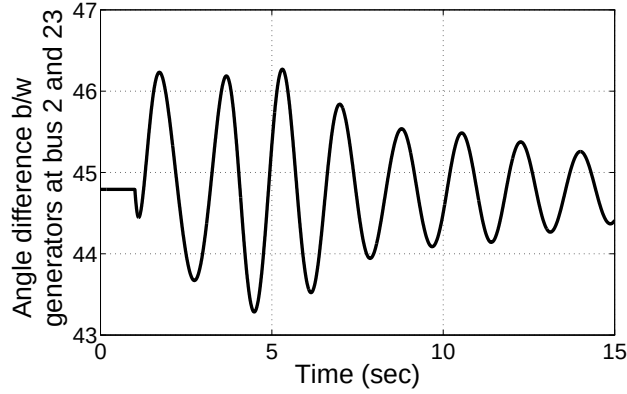


Figure 5.6: Response of GB system following a three phase bus fault for 100 msec

5.3 Representative GB system for 2020

The objective of this study is to analyze the effect of increased wind penetration and subsequent variable operating conditions in the inter-area mode of the GB system. The system will source 15% energy from renewable by year 2020. The wind is going to contribute large part of this target along with nuclear and CCGT plants. Table 5.2 shows the change in different types of generation expected in the future scenario. The Coal and Gas powered generation will decline whereas all other types of generating stations show an increase in generation. For the representative system these generators are grouped into three as given in Table 5.3. It shows the change in generation for different groups of generators in actual GB system. The same change is adopted for the representative GB system to obtain the generation and load scenario for 2020. In this study no generators are removed from the representative GB network. Instead, the generation capacity is modified in every bus according to the change in

Table 5.3. The dynamic parameters of synchronous machines are also altered to suit the changes in generation capacity. The data is given in Appendix F.

Shortcoming of this study

The representative model as developed by UoS resembles the power flow scenarios in the actual GB network in 2010. It has been validated with National Grid power flow data. But the network will undergo a lot of changes in 10 years time. A significant proportion of generation will be coming from renewable generation in the Scotland and several thermal generating stations will be closed and new stations will be added. In order to accommodate these changes, the National Grid is planning several reinforcement options including transmission line capacity increase, installation of new FACTS devices and two HVDC lines connecting Scotland and England etc. While the changes in generation are more or less accommodated in this work, the changes in transmission network are not considered. However, it will not impact the major objectives of this work; to analyze the impact of wind penetration and resulting network conditions in damping of inter-area mode. The model developed is good enough to qualitatively represent the Scotland-England inter-area mode variation. However it is to be noted that the proposed changes in transmission line capacity enhancement will improve the inter-area oscillation damping of the system.

Secondly, since no additional reactive power support devices are used, it is impossible to transmit more power from Scotland while maintaining voltage profile in the network. Hence 100% wind penetration is not considered for power flow scenarios presented in next section.

5.3.1 Operating scenarios in GB network

Similar to the analysis carried out for two-area system, ten possible scenarios in GB network are analyzed in this section. Table 5.6 lists the operating scenarios and the corresponding inter-area mode eigenvalue. The voltage levels of the generators are adjusted to accommodate various generation patterns in the network using existing reactive power support in the 2010 system. Since no additional reactive power support devices are considered, the wind penetration is limited below 100% in most cases. The reactive power output is maintained within the limits of synchronous and wind generators. More details of the operating conditions such as active and reactive power output of generators and voltage profile of network are given in Appendix G.

Case-1 is the base case where the generation pattern is similar to 2010 scenario

Table 5.6: Operating scenarios in representative GB network

Cases	Description	Inter-area mode		
		Eigenvalue	Frequency (Hz)	Damping ratio (%)
Case-1	Generation similar to 2010	$-0.12 \pm 3.75j$	0.59	3.11
Case-2	Reduced thermal across the grid	$-0.03 \pm 3.52j$	0.56	0.91
Case-3	Reduced thermal in the England	$0.01 \pm 3.50j$	0.56	-0.16
Case-4	Reduced thermal close to wind	$-0.35 \pm 3.31j$	0.52	10.38
Case-5	Removed all synchronous generators in the Scotland	No inter-area mode		
Case-6	Removed generator with higher PF at bus #26	$-0.00 \pm 3.57j$	0.568	0.006
Case-7	Removed generator with higher PF at bus #23	$0.002 \pm 3.58j$	0.57	-0.064
Case-8	Removed generator with no PF at bus #11	$0.004 \pm 3.53j$	0.56	-0.11
Case-9	Removed generators with no PF at buses #17, #21, #25, & #28	$0.002 \pm 3.55j$	0.57	-0.07
Case-10	Case-8 plus further increase in wind in the Scotland and remove thermal at bus #2	$-0.097 \pm 3.96j$	0.63	2.44

with relatively less wind generation. But the capacity of individual generators, such as thermal generators, are different from 2010 case and hence the dynamic parameters are different. The inter-area mode damping improved compared to 2010 case due to the changes in generation capacity. For **Case-2**, with increase in wind penetration the thermal generators across the grid reduce their outputs. With increased contribution of wind energy and reduction in synchronous generator output, the damping of inter-area mode improves. But in **Case-3** only the thermal generators in the England reduce their output with increase in wind generation. While the synchronous generator output on one side of the grid is relieved significantly, the inter-area power flow increases due to increased generation in the Scotland and reduced generation in the England. Hence, the damping becomes negative for this case. This case is similar to Case-5 of two-area system which has less damping than Case-4 of two-area system due to higher inter-area power flow. For **Case-4**, the increased wind penetration is balanced by reducing thermal generation close to wind farms. This will reduce the synchronous generator output at both ends of the grid while not affecting the inter-area power flow. This case differentiate two effect: effect of inter-area power flow and effect of change in generation. It is clear that, a reduction in generation can improve damping. This type of operation is best considering the stability of the system as the

damping ratio improves significantly. But in practice this may not be the case, as the decision to cut thermal generation is based on other considerations. In **Case-5**, all synchronous generators in the Scotland is removed to balance the load and generation with increase in wind output. As expected, with removal of synchronous generators in one area, inter-area mode disappears. In **Case-6** and **Case-7** generators with higher participation to inter-area mode located in England are removed whereas for **Case-8** and **Case-9** generators with no participation to inter-area mode located in England are removed. All the four cases result in increased inter-area power flow. But comparing these cases, damping of Case-6 and Case-7 are slightly better than that of Case-8 and Case-9. Though the difference is not as visible as in four machine case, the effect of removing synchronous generator with higher participation in the mode is felt. Also in these four cases the thermal generators in the England are removed which is the most likely scenario in future to match environmental considerations, and the damping is poor. For **Case-10** a further increase in wind for the scenario of Case-8 is considered. The generation is balanced with load by removing synchronous generator at bus #2 which has highest participation to inter-area mode. The inter-area power flow in this case is almost same as Case-8, but the damping improves significantly. This reiterates the earlier conclusion that change in output of generator participating in the mode affects damping ratio. A reduction frequency of inter-area mode with increased inter-area power flow can be observed by comparing Case-1 with other cases. It is also to be noted that with possible export of wind power from Scotland to France and Netherland, the inter-area power flow in GB system will increase, which will affect damping of the mode significantly.

5.4 Chapter summary

The chapter discusses the effect of wind penetration on inter-area mode damping of power system. The results are presented using two test systems: a two-area test system with a wind farm and a representative GB test system. The dynamic modeling of GB test system is carried out to simulate the well observed Scotland-England inter-area mode. Different possible operating scenarios of the networks with large scale wind penetration is analyzed. Three critical factors are analyzed; effect of change in output of generator participating in inter-area mode, effect of disconnecting synchronous generator, and effect of inter-area power flow. In a practical power system these factors will occur concurrently which may deteriorate the damping of inter-area oscillation for several operating conditions and in effect may constrain the effective

utilization of new generation and transmission capacity.

Damping controllers must be installed in the network to provide additional damping to inter-area modes. However, variability in operating conditions of future power system pose further challenge to controller design. The next chapter discusses a signal selection procedure, which will ensure robust performance for FACTS based damping controllers.

Chapter 6

Robust signal selection for damping controller design

The studies presented in the previous chapter show that with increase in penetration of weather dependent wind generators, operating scenarios of power system will vary significantly. It is shown that such changes cause large variations in the residue related to damping controller and hence affect controller performance. A feedback signal with less variation in residue is key to design a robust damping controller for future power system. This chapter focuses on selection of feedback signal for damping controller design in order to ensure robust performance for a wide range of operating conditions.

The chapter is organized as follows. A brief introduction about control objective is presented in Section-1. The Section-2 describes the residue followed by controller design concept in Section-3. Section-4 describes a probabilistic signal selection criteria. Simulation studies using 16 machine system and application of proposed signal selection criteria is explain in Section-5. Section-6 have some concluding remarks.

6.1 Control objectives

In general, the objective of a controller is to modify input signal(s) to achieve desired system performance. Power system damping controllers are designed to improve damping of oscillations in frequency range of 0 to 2Hz. Generally, damping requirements are set by grid operator which are specified in terms of settling time. For example, the National Grid defines poor damping as “where electromechanical oscillations of generating units are such that the resultant peak deviations in machine

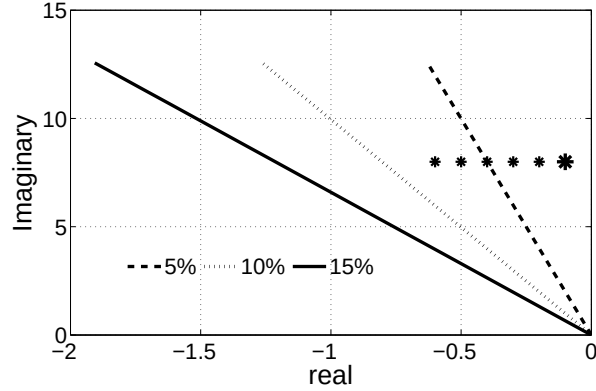


Figure 6.1: Damping line representing different damping ratios

rotor angle and/or speed at the end of a 20 second period remain in excess of 15% of the peak deviations at the outset (i.e. the time constant of the slowest mode of oscillation exceeds 12 seconds” [102]. This is approximately equivalent to a damping ratio of 0.03. Other Grid operators specify similar performance criteria. For example, in the Danish and Norwegian power systems, 10 to 20 sec settling time is considered adequate. In this thesis performance criteria is specified in terms of damping ratio. This is because, the use of damping ratio is more appropriate as oscillation frequency varies in a wide range. However damping ratio specification for different frequency and settling time is different. For a fixed settling time, required damping ratio increases as frequency reduces. Damping ratio of 0.1 or more is required for low frequency modes such as inter-area mode [10].

Fig. 6.1 shows damping line in s-plane for different damping ratio in 0 to 2Hz range. The function of a damping controller is to shift poorly damped eigenvalue(s) corresponding to electromechanical mode(s) towards left of eigen-plane to ensure required damping. The initial shift of the eigenvalue for a static gain controller can be explained using residue which is discussed in following the section.

6.2 Residue

If a disturbance is applied to a stable power system and then quickly removed, oscillations will set up which will eventually decay depending on the damping ratio of each mode. Given a disturbance point and observation point, residue represents amplitude of any mode caused by an impulse at the disturbance point [103]. It is the numerator of the term in the partial fraction expansion of the transfer function between the disturbance and the observation. For example, (3.14) can be represented

as [104],

$$\mathbf{G}(s) = \frac{R_1}{s - p_1} + \frac{R_2}{s - p_2} + \dots \frac{R_n}{s - p_n} \quad (6.1)$$

where R_i represents residue corresponding to p_i .

To find the residue R_2 of 2nd pole, set $s = p_2$ and ignore $(s - p_2)$ term in (3.14). That is,

$$R_2 = \frac{k(p_2 - z_1)(p_2 - z_2) \dots (p_2 - z_m)}{(p_2 - p_1) \dots (p_2 - p_n)} \quad (6.2)$$

Geometrically (6.3) can be interpreted as,

$$R_2 = \frac{\text{product of vectors from zeros to pole at } p_2}{\text{product of vectors from poles to pole at } p_2} \quad (6.3)$$

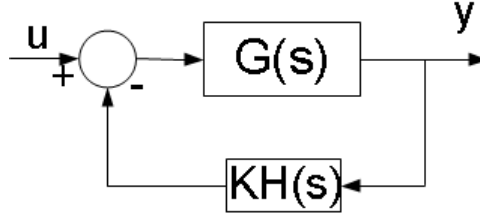


Figure 6.2: Schematic diagram of closed loop system

For a system $\mathbf{G}(s) = \sum_{i=1}^{i=n} \frac{R_i}{s - \lambda_i}$ in Fig. 6.2, residue R_i corresponding to a mode λ_i represents sensitivity of the mode to feedback gain given by,

$$\frac{\Delta \lambda_i}{\Delta K} = R_i H(\lambda_i) \quad (6.4)$$

Equation (6.4) indicates that an input output combination with maximum R_i will be most effective to control i^{th} mode.

For a static gain controller ($KH(s) = K$), shift in mode with gain is given by (6.5). This approximation is valid only for small value of K . For small values of controller gain mode shift is proportional to magnitude of residue and direction of

shift is equal to angle of residue ¹ $\angle R_i$.

$$\Delta\lambda_i = \Delta\sigma_i + j\Delta\omega_i = K[Re(R_i) + jIm(R_i)] \quad (6.5)$$

A controller with transfer function $\mathbf{H}(s)$ such that $\angle(H(\lambda_i)) = -\angle R_i$ can direct mode towards left to improve damping (6.6).

$$\Delta\lambda_i = \Delta\sigma_i + j\Delta\omega_i = K[Re(R_i H(\lambda_i)) + jIm(R_i H(\lambda_h))] \quad (6.6)$$

6.2.1 Controller design using residue

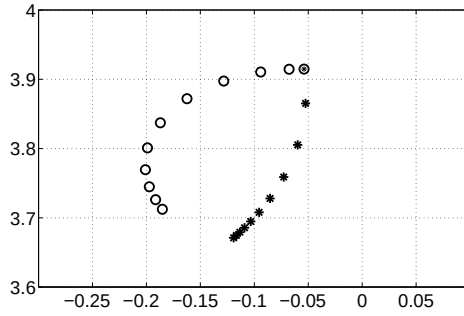
Let us recall the two-area test system with a SVC at bus #8 discussed in Chapter-3. Table 6.1 shows residue of transfer function between different feedback signals and the SVC reference input corresponding to electromechanical modes. Feedback signals P_{6-7} , P_{10-9} , ω_{G1} , and ω_{G3} represent active power flow between buses #6 & #7, active power flow between buses #10 & #9, speed of the generator at bus #1, and speed of the generator at bus #3, respectively. The signals provide different angles of residue for IAM. A transfer function $\mathbf{H}(s)$ is designed for each of the feedback signals to compensate for the phase difference such that $\angle(H(\lambda_i)) = -\angle R_i$. Fig. 6.3 shows inter-area mode shift for a static gain controller and the controller $\mathbf{H}(s)$ corresponding to the four feedback signals with incremental change in gain. For P_{6-7} , the residue angle of IAM is 95.54 and initial inter-area mode shift for constant gain controller exhibit same angle in Fig. 6.3(a). A controller $\mathbf{H}(s)$ with phase angle $\angle(H(\lambda_i)) = -95.97$ at IAM frequency is designed which changes the inter-area mode shift toward left. Similar observations can be made for other feedback signals.

However this direction of shift is true only for small value of controller gain. As the controller gain increases, the direction of movement of eigenvalue changes because the large gain behavior is influenced by location of zero. The controller transfer function $\mathbf{H}(s)$ can be re-tuned to obtain required damping as shown in Fig. 6.5. Modified controller transfer functions $\mathbf{H}'(s)$ are listed in Table. 6.2. The tuning can be performed by trial and error, or pole placement method [10]. For all the feedback signals the modified controller $\mathbf{H}'(s)$ provides required damping for IAM.

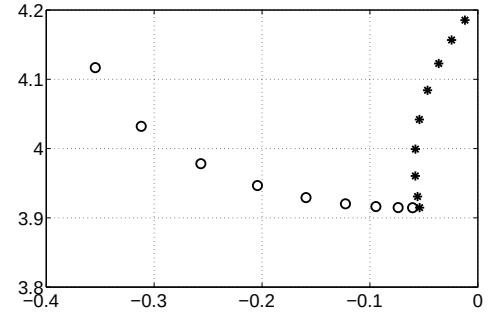
¹Angle of residue is measured with respect to negative real axis in anticlockwise direction

Table 6.1: Residue and controller transfer function corresponding to different feedback signals for two-area test system using SVC based damping controller.

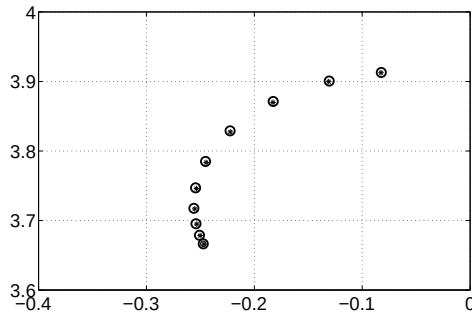
Signal	Residue			Controller TF $H(s)$	$\angle H(\text{IAM})$
	IAM	LM1	LM2		
P_{6-7}	1.19 $\angle 95.54$	0.5 $\angle -89.8$	1.5 $\angle 101.5$	$\frac{0.036s^3+1.2s^2+10s}{2.304s^3+9.83s^2+10.96s+1}$	-95.97
P_{10-9}	1.67 $\angle -82.24$	0.14 $\angle 78.8$	2.26 $\angle -87.6$	$\frac{2.304s^3+9.6s^2+10s}{0.1s^3+2.01s^2+10.2s+1}$	82.63
ω_{G1}	0.6 $\angle 0.22$	1.9 $\angle -40.8$	0.26 $\angle 149.3$	$\frac{0.9s^2+10s}{s^2+10.1s+1}$	-0.5
ω_{G3}	0.75 $\angle -171.6$	0.45 $\angle 28.2$	1.72 $\angle -94.35$	-1	180



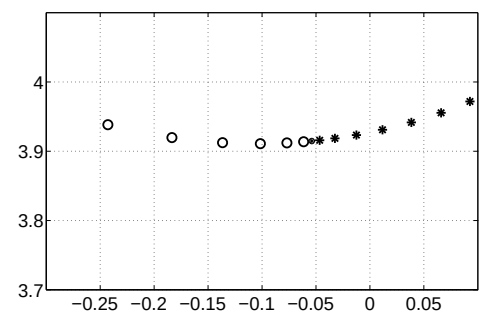
(a) Using feedback signal P_{6-7}



(b) Using feedback signal P_{10-9}



(c) Using feedback signal ω_{G1}



(d) Using feedback signal ω_{G3}

Figure 6.3: Inter-area mode shift in a two-area system using SVC based damping controller $H(s)$ for different feedback signals. (*) indicates shift using a static gain controller and (o) indicates shift using $H(s)$.

Signal	Modified Controller TF $\mathbf{H}'(s)$
P_{6-7}	$\frac{10s}{7.744s^3+18.37s^2+11.76s+1}$
P_{10-9}	$\frac{3.6s^3+12s^2+10s}{0.1s^3+2.01s^2+10.2s+1}$
ω_{G1}	$\frac{0.1s^2+10s}{4s^2+10.4s+1}$
ω_{G3}	$\frac{-0.004s^2-0.4s}{0.04s^2+0.5s+1}$

Table 6.2: Modified controller transfer function for two-area test system using SVC based damping controller

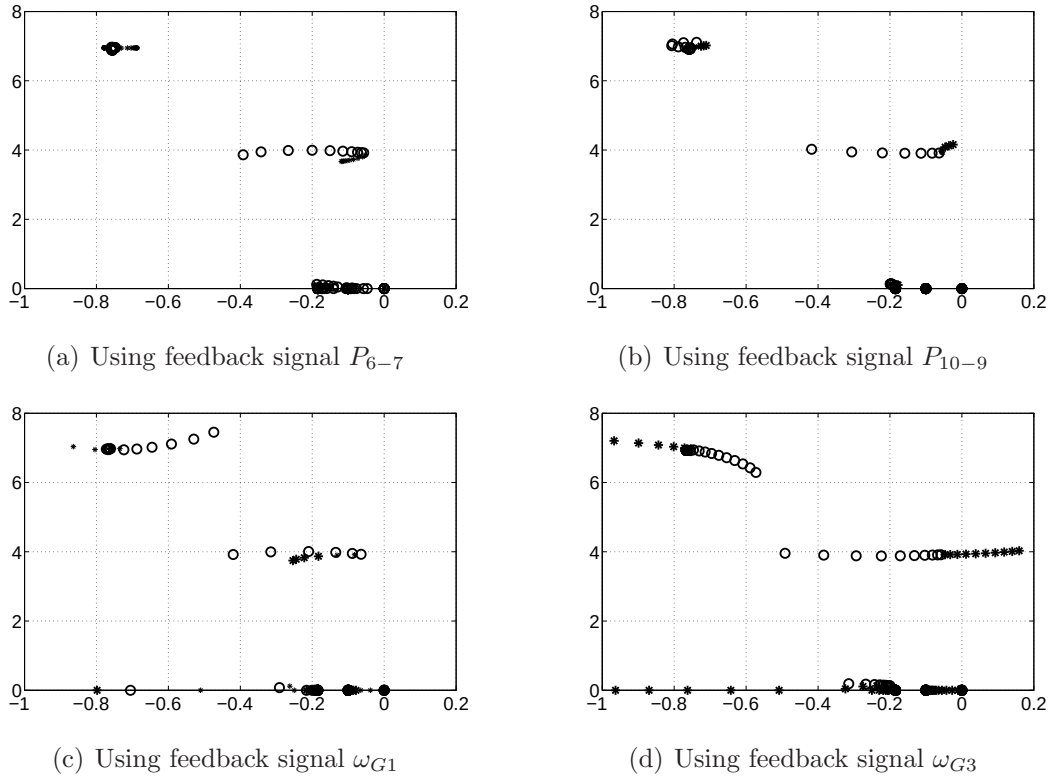


Figure 6.4: Inter-area mode shift in a two-area system using SVC based damping controller $H'(s)$ for different feedback signals. (*) indicates shift using a static gain controller and (o) indicates shift using $H(s)$.

Figure 6.5: Inter-area mode shift for a static gain controller (*) and modified controller, $H'(s)$ (o) for different feedback signals (a) P_{6-7} , (b) P_{10-9} , (c) ω_{G1} , and (d) ω_{G3}

6.3 Concept of damping controller and signal selection

A classical example of damping controller is PSS. It modulates generator excitation so as to produce a component of electrical torque in phase with rotor speed variation to reduce power swing. Similarly, supplementary control of FACTS devices can also enhance damping of the system. But their influence is rather indirect [20]. FACTS devices can modulate voltage, active power or reactive power in a transmission line or at a bus. This will modulate power flow in the transmission line. If the line is in favorable location such that it can cause corresponding variation in the generator torque, the damping can be improved. This implies that in order to enhance damping using a FACTS device, it should be placed in such a way that modulation of its output will indirectly cause modulation in torque of generators participating in inter-area mode oscillation. In other words, the FACTS device output should have a controllability towards the mode of interest.

Further in order to correctly modulate FACTS device output, the oscillations need to be sensed or observed accurately. A signal having good enough amplitude of the oscillation is required as feedback signal to the controller. In other words, the feedback signal should have good observability of the mode.

Equation for modal controllability and modal observability can be obtained from the transfer function representation of (3.13). Let (3.13) is represented as,

$$\mathbf{G}(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} \quad (6.7)$$

$$= \sum_{i=1}^{i=n} \frac{\mathbf{C}\phi_i\psi_i\mathbf{B}}{s - \lambda_i} \quad (6.8)$$

$$= \sum_{i=1}^{i=n} \frac{R_i}{s - \lambda_i} \quad (6.9)$$

From (6.8), residue corresponding to i th mode is expressed as $R_i = \mathbf{C}\phi_i\psi_i\mathbf{B}$. R_i can be conveniently split into modal controllability ($\psi_i\mathbf{B}$) and modal observability ($\mathbf{C}\phi_i$). The modal controllability describes effectiveness of a controller to an oscillatory mode from a specific location whereas the modal observability indicates whether an oscillatory mode is observable in chosen output signal (feedback signal). This follows that, a signal with good modal observability and an actuator with good modal controllability, hence higher magnitude of residue, to a mode are essential

requirement for good damping controller design. The residue which is the product of modal controllability and modal observability is a good indicator to assess suitability of a signal-actuator pair for damping controller design. For best performance FACTS device location and feedback signal should be selected to obtain best residue magnitude. But in practice, FACTS devices in a network are installed based on their primary objectives such as power flow and voltage control with little emphasis on the damping control requirements. Due to this, the modal controllability ($\psi_i \mathbf{B}$) cannot be influenced. Hence the possible option to improve $|R_i|$ is to find a feedback signal having good modal observability ($\mathbf{C}\phi_i$).

6.4 Signal selection criteria

Power system stabilisers are successful damping controllers in power system. They are installed at generators which provide maximum magnitude of residue to electromechanical mode of interest. Locally available signals such as generator speed, active power output etc are used as feedback signal. With proliferation of FACTS devices in power system, the possibility of using supplementary control of FACTS devices to improve damping becomes apparent. Damping controllers are designed using locally available signals for FACTS devices. However FACTS devices are used to provide fast voltage support and power flow control in the network. Their location depends on the primary objectives with little importance to stability improvement. It is shown that, the local signals for FACTS devices are not always the best feedback signals for damping controller design [9]. A better signal may be found elsewhere in power system having higher magnitude of residue compared to local signals. The wide spread use of WAMS technology provide access to feedback signals from remote locations in power system [29]. The choice of signal is grown exponentially which makes the signal selection process laborious. At the same time the operating characteristics of future power system will be unpredictable as discussed in the previous chapter. As the system undergoes wide changes in operating condition, the magnitude and angle of R_i vary accordingly. For a fixed parameter controller, the changes in R_i will influence the amount and direction of eigenvalue shift. In some operating cases, the variation may impact the stability of closed loop system. It is important to select a signal which is adequate for all operating conditions. The challenge is to select best signal from a large pool of signals for all possible operating conditions. Following section proposes a probability based signal selection criteria to obtain robust damping performance for large number of operating conditions.

Let us assume that a FACTS device is installed in a power system considering its primary objectives such as power flow and voltage control. The objective of signal selection is to find a feedback signal for the FACTS device for all operating conditions (N) to improve damping of one or more modes. Further assume that all N operating conditions of the system are known and modal analysis is performed to obtain system matrix for the operating conditions. Let $|R_i^{mk}|$ and θ_i^{mk} be the magnitude and angle of residue with respect to the m th operating scenario corresponding to the k th signal, respectively, of the i th mode. Following criteria are defined for signal selection.

6.4.1 Criteria-1: Effectiveness criteria

For a given operating scenario the effectiveness of a controller or the amount of damping achieved, greatly depends on the magnitude of the residue. From (6.4), a higher value of $|R_i|$ requires a lower controller gain. The choice of feedback signal with good $|R_i|$ is key to obtain a good damping performance [31, 32]. When controller is designed for many operating conditions with varying magnitude of residue, average magnitude of residue $\overline{|R_i^k|} = \frac{1}{N} \sum_{m=1}^N |R_i^{mk}|$ is a good indicator of effectiveness.

However, the use of average value over large number of operating conditions should be carried out with caution as a higher magnitude of the residue for some operating conditions cannot compensate for very low value of residue for other operating conditions. This can be ensured by selecting a signal with less variation in magnitude of residue. The Criteria-2 presented below automatically takes care of this factor.

6.4.2 Criteria 2: Robustness criteria

As the system undergoes wide changes in operating conditions, the magnitude and angle of R_i vary accordingly. For a fixed parameter controller, the changes in R_i will influence the magnitude and direction of eigenvalue shift. Hence for robust performance under different operating conditions, the residue R_i associated with feedback signal should have less variation in magnitude and angle.

A probabilistic method for finding such signals is described in the following subsections. At the core of this method is the residue error covariance matrix [105]. This matrix is computed for each signal over a large number of operating scenarios. For a given signal, the residue error covariance matrix can be represented by an ellipse in two dimensional plane [106]. We compute the area of this ellipse for each signal and the one with least area gives less uncertainty in the residue variation, and hence this signal can be accepted to give robust performance.

Error covariance matrix

Let $|R_i^{mk}|$ and θ_i^{mk} be the magnitude and angle of residue with respect to the m th operating scenario corresponding to the k th signal, respectively, of the i th mode. Let $|R_i^{0k}|$ and θ_i^{0k} be the average magnitude and angle of the residue corresponding to the k th signal, respectively. We define a vector of ‘error’ in residue as follows:

$$\mathbf{e}_i^{mk} = [|R_i^{mk}| - |R_i^{0k}|, \theta_i^{mk} - \theta_i^{0k}]^T \quad (6.10)$$

where $m = 1, \dots, N$. N is the number of operating scenarios. Given the residue error vectors corresponding to each operating scenario, the residue error covariance matrix $\mathbf{P}_i^k$ for the k th signal is given by

$$\mathbf{P}_i^k = E[(\mathbf{e}_i^{mk})(\mathbf{e}_i^{mk})^T] \quad (6.11)$$

Here $E[\cdot]$ is expectation operator. For N operating scenarios (6.11) can be approximated as

$$\mathbf{P}_i^k \approx \frac{1}{N} \sum_{m=1}^N (\mathbf{e}_i^{mk})(\mathbf{e}_i^{mk})^T \quad (6.12)$$

The diagonal elements of $\mathbf{P}_i^k$ represent the uncertainty associated with the magnitude and angle of the residue, respectively. Since these two quantities are very different from each other in terms of numerical values, we form the relative residue error covariance matrix by normalizing the elements of $\mathbf{P}_i^k$ with respect to the nominal values as:

$$\mathbf{P}_i^{rel,k} = \mathbf{K}_i^k \mathbf{P}_i^k \mathbf{K}_i^{kT} \quad (6.13)$$

where, $\mathbf{K}_i^k = \begin{bmatrix} |R_i^{0k}| & 0 \\ 0 & \theta_i^{0k} \end{bmatrix}^{-1}$

The relative residue error covariance matrix is computed for each signal and the best signal is selected as the one with the smallest relative residue error covariance matrix (in theoretical sense). A quantitative measure of the size of this matrix is discussed next.

Geometric interpretation of error covariance matrix

The relative error covariance matrix in (6.13) can be represented using an error ellipse. The axis of error ellipse is equal to square root of eigenvalues of $\mathbf{P}_i^{rel,k}$ and the larger eigenvalue corresponds to the axis with the larger uncertainty. Hence, the size of ellipse increases with increase in uncertainty. The objective of signal selection is to find a signal having least variation in magnitude and angle. This can be identified from the area of error ellipse which is obtained as shown below.

The equation of n -dimensional “zero mean” error ellipsoid is expressed as: $\mathbf{e}^T P^{-1} \mathbf{e} = c$, where $\mathbf{e}$ is error vector ($n \times 1$), P is the error covariance matrix ($n \times n$), and c is a constant [107].

Since, P^{-1} is a real symmetric matrix (property of the error covariance matrix), there exists an orthogonal matrix T such that $T^{-1} P^{-1} T = T^T P^{-1} T$ is a diagonal matrix, Λ without altering $\det P^{-1}$ [108]. The diagonal entries of Λ are the eigenvalues $(\lambda_1, \dots, \lambda_n)$ of P^{-1} .

Now let D be the diagonal matrix with entries $(\sqrt{\frac{c}{\lambda_1}}, \dots, \sqrt{\frac{c}{\lambda_n}})$ and consider the new vector variable $\mathbf{e}'$ defined by $\mathbf{e} = T D \mathbf{e}'$. Since T is an orthogonal matrix, the determinant of transformation $T D = c^{n/2} / (\lambda_1 \dots \lambda_n)^{1/2} = c^{n/2} / \det(P^{-1/2}) = c^{n/2} \sqrt{\det(P)}$.

In terms of transformed variables, the equation of error ellipse can be represented as, $e_1'^2 + \dots + e_n'^2 = 1$, which represents unit n -sphere whose volume is V . The volume of the ellipsoid is the volume V scaled by the determinant of the transformation and is expressed as $c^{n/2} V \sqrt{\det P}$.

In the, (2×2) case, where V represents the area of unit disk, and equals to π , the area of error ellipse is given by $c\pi\sqrt{\det P}$.

Based on this property, the size of the relative residue error covariance matrix is defined as the area of the ellipse represented by the determinant of the matrix:

$$Area(\mathbf{P}_i^{rel,k}) \propto \pi \sqrt{\det(\mathbf{P}_i^{rel,k})} \quad (6.14)$$

Thus, in principle, the robust signal is the one which has the lowest area of the error ellipse. Signal having least variation in residue i.e. least value for $\det(\mathbf{P}_i^{rel,k})$ can be selected for robust controller design.

6.4.3 Criteria 3: Criteria to reduce influence on other modes

Often large power systems have more than one electromechanical modes which are located very close to each other. Since electromechanical modes fall in a narrow frequency range, less than 2Hz, it is difficult to design controller for one mode while isolating the effect on another. This is the case when magnitude of residues corresponding to the modes are high. Recall Fig. 6.5 where a controller $\mathbf{H}'(s)$ shift inter-area mode towards left to improve its damping. The controller phase angle is selected considering the angle of residue corresponding to inter-area mode listed in Table 6.1. The controllers are able to improve damping of the inter-area mode using all four signals. However, for signals ω_{G1} and ω_{G3} in Fig. 6.4(c) and Fig. 6.4(d), respectively, the damping of one of the local modes decreases. This is due to large difference in angle of residue between the inter-area mode and one of the local modes. If all modes located in close proximity have angle of residue within a narrow range, they will shift almost in the same direction.

Feedback signal must be selected such that, a signal selected for one mode does not contribute to poor damping of another. This is particularly important when designing multi input controllers where each signal is selected to influence one or more mode and therefore, one signal's effort should not oppose the other's. This criteria is developed to reduce such interactions.

Recall from (6.5), the direction of shift in eigenvalue depends on the angle of residue. If two modes are located in a close frequency range and angle of residue between actuator reference input and a feedback signal for both the modes are equal, their shift will be in similar direction. However, if the angles of residue are 180 degree apart, they both will shift in opposite directions. In essence, it is advisable to have a signal where the angles of residue for closely located modes are same or within a narrow range. However, the amount of shift is proportional to magnitude of residue. Hence, if a signal gives opposite angles of residue but magnitude of one of the residues is close to zero, it will not significantly affect that mode. When considering multiple operating conditions, average angle of residue can be used along with variation in residue. The criteria is summarized in Table 6.3.

Consider a power system with two closely located electromechanical modes, mode-a & mode-b. Objective is to find a feedback signal to improve damping of mode-a. $\overline{|R_a^k|}$ and $\overline{|R_b^k|}$ represent average magnitude of residue corresponding to signal k for mode-a and mode-b, respectively. Similarly, $\overline{\angle R_a^k}$ and $\overline{\angle R_b^k}$ represent average angle of residue corresponding to signal k for mode-a and mode-b, respectively. Following four cases are possible. Cases are valid when variation in residue i.e. $\det(\mathbf{P}^{\text{rel},k})$ is

small.

Table 6.3: Criteria 3: influence of near by mode on signal selection

Cases	Angle criteria	Magnitude criteria	$det(\mathbf{P}^{rel,k})$	Comment
Case-1	$\overline{\angle R_a^k} - \overline{\angle R_b^k} < 90$	high $ \overline{R_a^k} $	small	good signal
Case-2	$\overline{\angle R_a^k} - \overline{\angle R_b^k} < 90$	high $ \overline{R_a^k} $ and $ \overline{R_b^k} $	small	good signal
Case-3	$\overline{\angle R_a^k} - \overline{\angle R_b^k} > 90$	$\frac{ \overline{R_b^k} }{ \overline{R_a^k} } > 0.33$	small	bad signal
Case-4	$\overline{\angle R_a^k} - \overline{\angle R_b^k} > 90$	$\frac{ \overline{R_b^k} }{ \overline{R_a^k} } < 0.33$	small	good signal

Case-1: $\overline{\angle R_a^k} - \overline{\angle R_b^k} < 90$ and high $|\overline{R_a^k}|$

This case ensures that the angle of residue for both the modes are in almost same direction and signal is effective to mode-a. A fixed parameter controller designed for mode-a will not cause poor damping to mode-b as direction of shift for mode-b also will be close to same direction. The signal can be selected to represent mode-a.

Case-2: $\overline{\angle R_a^k} - \overline{\angle R_b^k} < 90$ and high $|\overline{R_a^k}|$ and $|\overline{R_b^k}|$

This is special case of case-1, where the signal is effective for both modes. In this case one signal is enough to damp both the modes, if required. For better results, $\overline{\angle R_a^k}$ and $\overline{\angle R_b^k}$ must be within narrow range with less variation in angle of residue.

Case-3: $\overline{\angle R_a^k} - \overline{\angle R_b^k} > 90$ and $|\overline{R_b^k}|/|\overline{R_a^k}| > 0.33$

$\overline{\angle R_a^k} - \overline{\angle R_b^k} > 90$ means that the angle of residue for both modes are not in same direction. Also, $|\overline{R_b^k}|/|\overline{R_a^k}| > 0.33$ shows the signal is effective for both modes. A fixed parameter controller improving damping for mode-a may sometime reduce damping for mode-b. Hence such signals are not selected.

Case-4: $\overline{\angle R_a^k} - \overline{\angle R_b^k} > 90$ and $|\overline{R_b^k}|/|\overline{R_a^k}| < 0.33$

In this case, angle of residue for both modes are not in same direction. However, effectiveness of signal to mode-b is small compared to mode-a. A fixed parameter controller improving damping of mode-a cannot significantly reduce damping of mode-b. Hence this signal can be used to represent mode-a.

If all other conditions are satisfied and variation in residue is not small, designer's judgement based on magnitude and angle of residue is important. For example, a signal falls under case-1 of Criteria-3 but variation in residue for mode-b is high. The signal can be selected, if the effectiveness of that signal to mode-b is significantly small.

6.4.4 Algorithm for signal selection

The step by step procedure for signal selection is described below.

- Step 1** Obtain different operating conditions of the system
- Step 2** Perform modal analysis to ascertain the need for damping control
- Step 3** Select actuator, and list possible feedback signals
- Step 4** Perform residue analysis to compute residue with respect to various modes for transfer function between actuator reference input and feedback signals
- Step 5** Apply Criteria-1. Find average magnitude of residue for the mode of interest and normalize it with respect to maximum value. Shortlist signals fall above pre-defined limit and eliminate others. In this work, the limit is 0.33.
- Step 6** Apply Criteria-2. Find ECM for residue corresponding to short listed signals and list them in ascending order of determinant of ECM. Signal with least determinant of ECM can be the robust signal.
- Step 7** Apply Criteria-3. Compare residue of other modes for each signal based on Criteria-3. List all acceptable signals for damping control.

6.5 Simulation results

The proposed signal selection procedure is validated through simulation studies using a sixteen machine, five area test system. Two controllers, a PSS and a TCSC based supplementary damping controller, are designed to improve damping of critical electromechanical modes. The signal selection procedure is explained for both the controller.

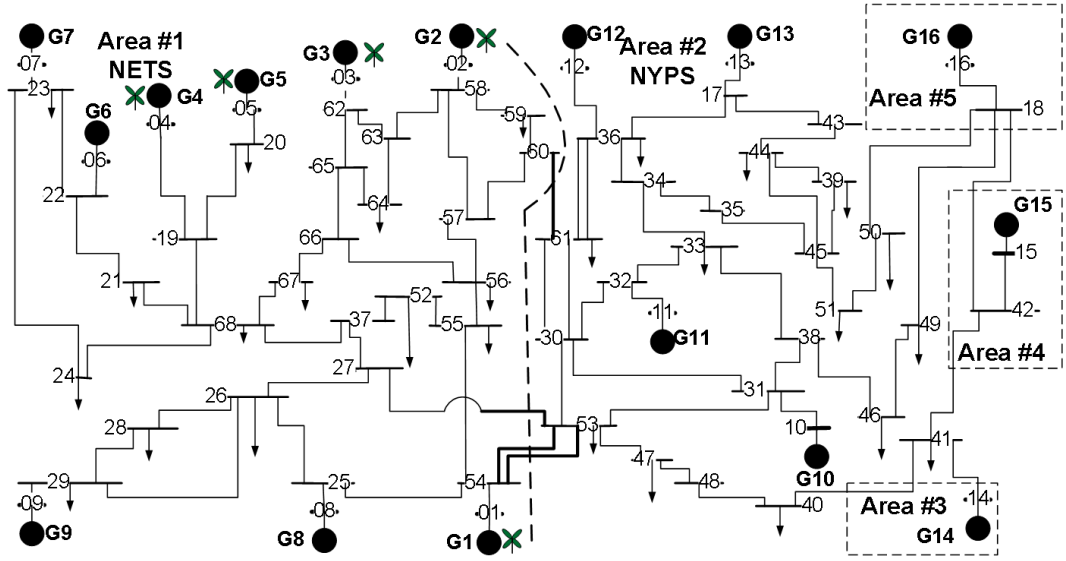


Figure 6.6: 16 machine five area test system

6.5.1 Test system

Fig. 6.6 shows the sixteen machine, five area test system used to validate the proposed signal selection method. It is a modified version of NETS-NYPS model [12]. The first five synchronous generators, machines G1 to G5, in the original system are replaced by wind generators of similar capacity. The synchronous machines G6, G7 and G8 have slow excitation control, and G9 has fast static excitation control. The remaining machines have constant excitation control. The machines #1 to #9 form part of Area-1. The machines G10 to G13 are part of Area-2. The other three generators represent equivalent model of the three connected areas, Area-3, Area-4, and Area-5. A TCSC is installed in the line connecting buses #18 and #50 with 50% compensation under nominal operating condition. The signal selection approach is validated using a damping controller design for the TCSC.

6.5.2 Generating operating conditions

This section details procedure to generate different feasible operating conditions of the power system. Scheduled voltage of generators and reactive power compensation at load buses are varied to control generator power factor and load bus voltages within its limit.

Output of synchronous generator and load

The uncertainty associated with both synchronous generator outputs and loads are modeled with the Gaussian distribution. The Gaussian distribution is preferred because the analysis based on this distribution is well developed and reported in the literature [109, 110]. Furthermore, based on the analysis of 211 contingencies reported by the United States power companies between years 1971 and 1976, [111] has suggested that the power system disturbance behavior can be modeled using the Gaussian approach. In this thesis, a further check using power flow analysis is carried out to verify the feasibility of the output obtained using Gaussian random variables.

The nominal operating condition (generation and load) is taken to be the mean (μ_i) of this distribution and the other operating scenarios are generated by considering a certain percentage of uncertainty around the mean. Such a choice of the variation covers large number of practical operating scenarios and the Gaussian modeling ensures that high probable cases are selected from the neighborhood of the mean and less probable cases are chosen from the extreme of the distribution. For example, in case of load variation the difference between maximum and minimum demand at a bus was captured by a $\pm 3\sigma$ variation which ensures that the 99.73% cases between minimum and maximum demands are covered. It is to be noted that a $\pm 3\sigma$ variation around the mean covers 99.73% area of the Gaussian curve. Thus the standard deviation of the distribution is computed as:

$$\sigma_i = \frac{\mu_i \times \%uncertainty}{3 \times 100} \quad (6.15)$$

The mean (μ_i) and variance (σ_i^2) are used to obtain an operating scenario z_i (i th load or generator) as:

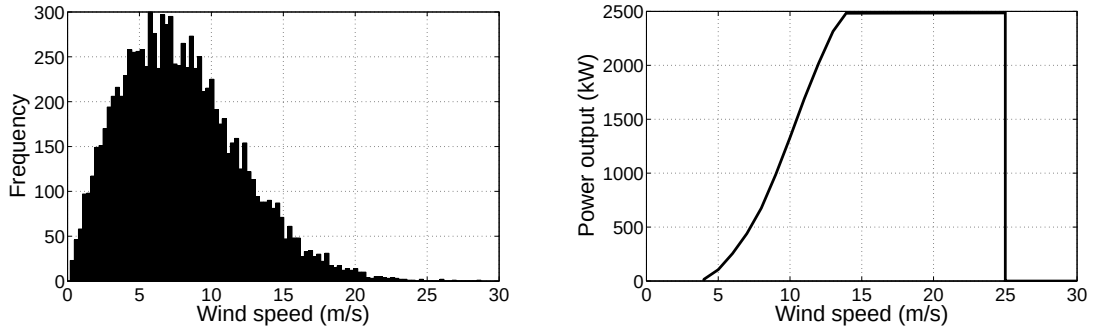
$$z_i = \mu_i + \sigma_i \mathcal{N}(0, 1) \quad (6.16)$$

where $\mathcal{N}(0, 1)$ is standard normal distribution with zero mean and unit variance.

Output of wind generator

Unlike synchronous generators, a wind farm output is sum of several wind turbine outputs. Output of wind farm is not demand driven but depends on the availability of wind. The characteristics of wind such as strength, direction, presence, variability etc. may vary from one wind farm to another. Also it has daily and seasonal

variation. The Weibull distribution has shown a closeness to annual wind speed distribution for many sites [112, 113, 114]. It is frequently used to characterize wind farm. The shape of Weibull distribution is described by *scale* and *shape* where the scale parameter relates to mean wind speed and shape parameter decides width of distribution. The MATLAB command *wblrnd* is used to obtain random numbers with Weibull distribution [76]. A typical Weibull distribution curve is shown in Fig. 6.7(a).



(a) Weibull distribution for scale = 9 and shape = 2 (b) Wind speed vs power output curve for a 2500kW turbine

Figure 6.7: An example Weibull distribution and Wind speed vs power output curve of WTG

Wind speed characteristics of different wind farms can be represented using the Weibull distribution with appropriate shape and scale parameters. Fig. 6.7(b) shows wind speed vs power output of a 2500kW wind turbine generator system. For a generic wind turbine model for wind farm, the curve is modified to suit output of wind farm. By combining both the curves, different possible outputs for wind farm over a period are obtained.

Operating limits

Following limits are imposed to obtain a realistic operating scenarios of the system

- Steady state voltage at all buses should be within 0.95pu and 1.05pu
- Power factor of all wind generators should be within 0.95 and unity
- Power factor of all synchronous generators should be within 0.9 lag and 0.85 lead.
- Slack bus generation should not exceed 1.2 times nominal generation

Algorithm for generating different operating scenarios

In order to study the variation in residue, feasible operating scenarios of the system are obtained through the following procedure:

- Step 1** Run the power flow program for nominal operating condition to obtain μ . The μ is a column vector in which an element μ_i represents the value of a generator output or a load under the nominal operating condition.
- Step 2** Using the methods described above, generate different operating scenarios for synchronous generators, wind generators and loads.
- Step 3** Select one of the operating conditions. Apply contingency if required. For generator contingency, corresponding generator is removed from the network along with the transformer.
- Step 3** Run power flow program.
- Step 4** Check operating limits for any violations. Adjust generator scheduled voltages and reactive power compensation to correct generator power factor and load bus voltages. Run load flow to check feasibility of operating condition.
- Step 5** Save the case if feasible operating condition is obtained, else discard it.
- Step 6** Repeat steps 3 to 5 until required number of feasible scenarios are obtained.

6.5.3 Operating scenarios of the test system

Using the method explained in previous section, 800 feasible operating scenarios of the system are generated. In this study, the uncertainty in synchronous generation and load (%uncertainty) is considered to be 40%. However this value is system dependent. For wind generators a Weibull distribution curve with scale = 9 and shape = 2 is used. This corresponds to an average wind speed of 7.97m/s. Wind generator contingency is not considered separately, as wind generator output will become zero during low wind speed periods. For synchronous generators #6 to #12 generator is removed from the network to simulate generator contingency. No contingency is considered for generator #13 which is a slack bus. For generators #14 to #16 which represent equivalent generation of Area #3, #4 and #5 respectively, nominal

generation is reduced to 50% to simulate contingency. Out of 800 cases, 300 cases are generated without contingencies and the remaining have a synchronous generator outage. Transmission line contingencies are not considered for this simulation, but they are important for robust controller design.

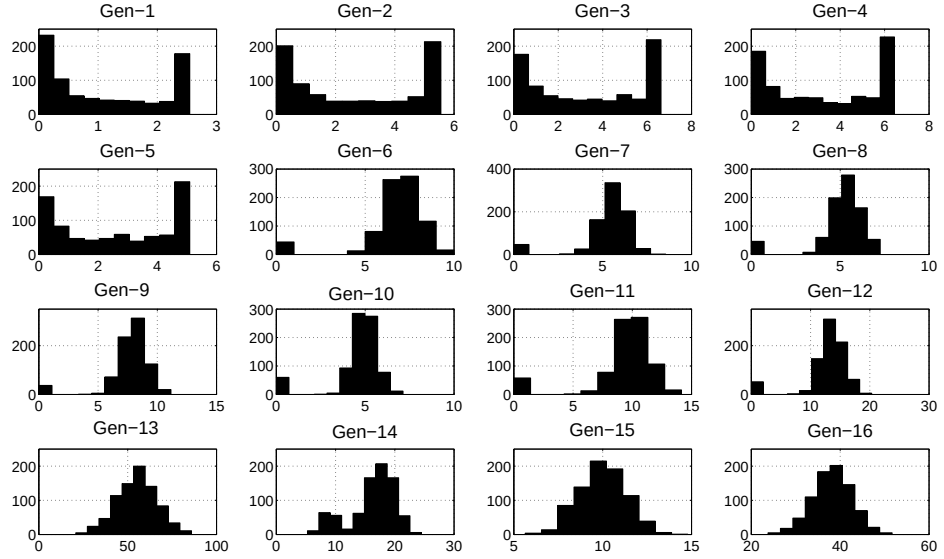


Figure 6.8: Histograms showing variation in generator output for different operating conditions of 16 machine test system. (Gen-1 represents generator at bus #1)

Fig. 6.8 shows variation in generation for all the operating conditions. Gen-1 to Gen-5 show output of wind generators which has two peaks, one representing wind speeds below cut in speed when wind farm output is zero and the other shows wind speed above rated wind speed when wind farm delivers rated output. Histogram Gen-6 to Gen-16 show normal distribution except a peak at zero which represents generator contingency. Fig. 6.9 shows variation in some of the loads for all the operating conditions. Fig. 6.10(a) and Fig. 6.10(b) shows histogram for total system load and inter-area power flow between Area #1 and Area #2, respectively. For some operating conditions the inter-area power flow reverses its direction. This is very likely scenario in future power systems with increased wind penetration and cross country inter-connection. Fig. 6.11(a) show average value of bus voltage for all the operating conditions. Dotted lines in the plot show minimum and maximum bus voltage present in the system. Similarly, Fig. 6.11(b) shows average power factor of generator for all the operating conditions. Power factors of wind generators and synchronous generators are within its respective limits. Also the closeness of maximum and average plot to unity shows that for majority of operating conditions

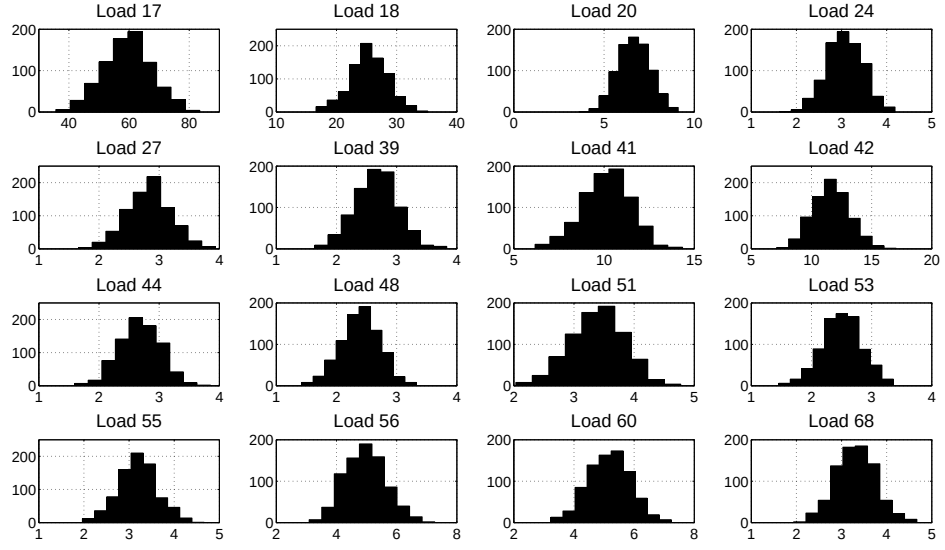


Figure 6.9: Histogram showing variation in load for different operating conditions of 16 machine test system. (Load 17 represents load at bus #17)

power factor of generator is close to unity. The approach presented to generate operating scenarios ensures that the generated operating conditions are the most likely feasible scenarios of actual power system.

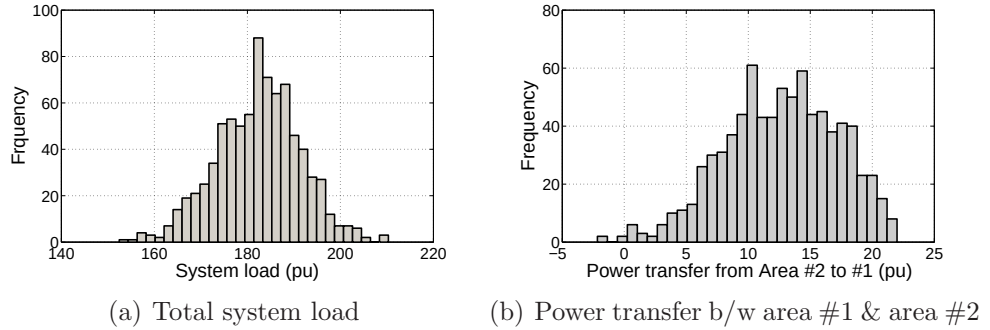


Figure 6.10: Histogram showing variation in (a) total system load and (b) power transfer b/w area #1 & area #2 for different operating conditions of 16 machine test system

6.5.4 Modal analysis of the system

State space representation of the system and eigenvalues of state matrix under each operating conditions are obtained from MATLAB simulation. The critical modes for all the operating conditions are plotted in Fig. 6.12. The system has four inter-area modes (IA1 to IA4) and six local modes (L1 to L6). The modes under nominal

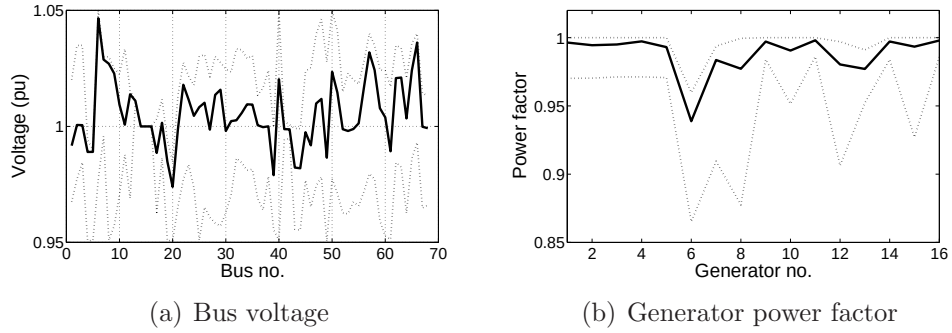


Figure 6.11: Plot showing average value of bus voltage and generator power factor for all operating conditions of sixteen machine test system. The dotted plots show minimum and maximum values.

operating condition are highlighted. As the operating condition changes with changes in generation, load and power flow pattern, the damping ratio of these critical modes undergo significant variation. Poor damping is observed for the inter-area modes and the local mode L2 which need damping improvement. A PSS at G9 is designed to improve damping of L2 whereas a supplementary damping control is added to the TCSC to improve damping of inter-area modes. The signal selection and controller design procedures are explained in remaining sections.

Table 6.4 shows critical eigenvalues and dominant states of the system. The local modes have participation from few closely coupled generators with significant participation from one of them. The modes may shift their participation between these generators or may be absent when some of the generators are removed from service. L5 is associated with G7 and/or G6, and shifts its participation depending on operating condition whereas L2 is absent when G9 is out of service. All the inter-area modes are present for all the operating conditions with little structural change. As seen from the figure, some of the modes are intermingled. For the purpose of residue computation these modes are tracked using participation factor analysis.

6.5.5 Residue analysis

The system has an unstable local mode and four poorly damped inter-area modes. Since L2 has higher participation to G9, a PSS at G9 can improve damping of this mode and supplementary damping controller using the TCSC is designed to improve damping of inter-area modes. The residue analysis is carried out for all the operating conditions with respect to both G9 excitation system reference input and the TCSC reference input. Feedback signals such as active power, reactive power, and current

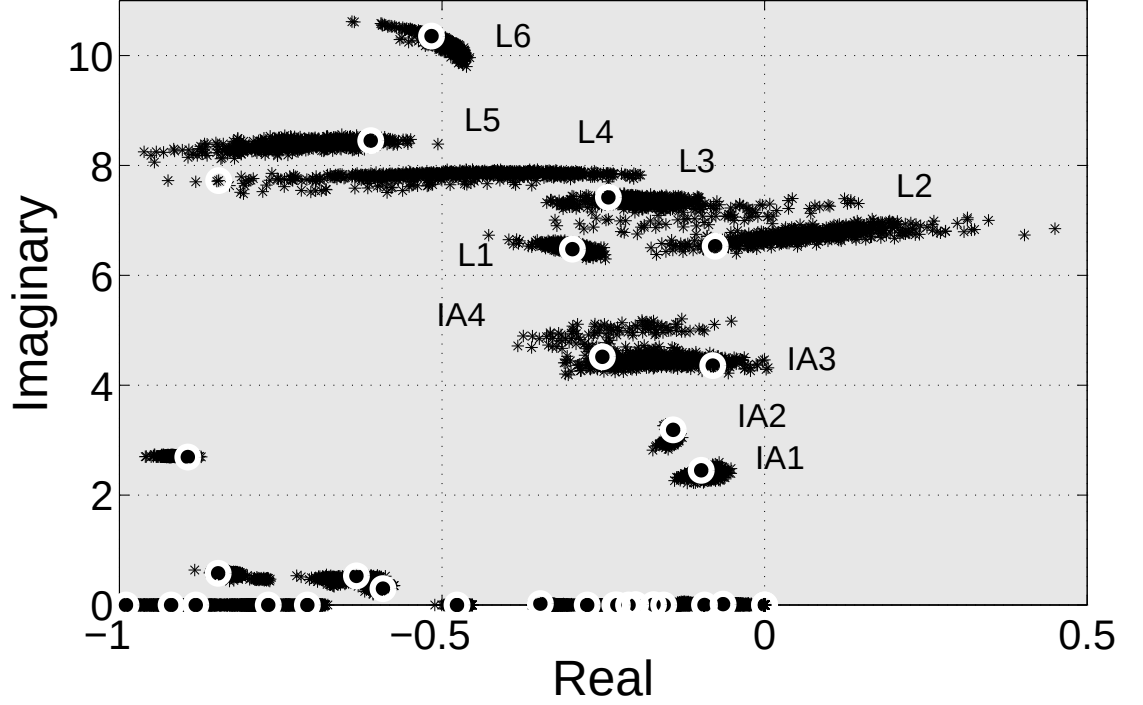


Figure 6.12: Electromechanical modes of the sixteen machine system for all the operating conditions

Table 6.4: Critical eigenvalue and dominant states of sixteen machine system

Mode	Eigenvalue	Dominant states (participation factor)
L6	$-0.5162 \pm 10.3557i$	ω, δ of G11(1)
L5	$-0.6103 \pm 8.4516i$	ω, δ of G7(0.99), G6 (0.7)
L4	$-0.8460 \pm 7.7239i$	ω, δ of G8(0.99), G9(0.12)
L3	$-0.2419 \pm 7.4192i$	ω, δ of G10(1)
L2	$-0.0764 \pm 6.5314i$	ω, δ of G9 (1), G6(0.23), G7(0.14), G8(0.12)
L1	$-0.2978 \pm 6.4777i$	ω, δ of G12(1), G13(0.2)
IA4	$-0.0803 \pm 4.3582i$	ω, δ of G6 (1), G7 (0.72), G8(0.17), G9(0.43), G13(0.46)
IA3	$-0.2513 \pm 4.5179i$	ω, δ of G14(0.42), G15(0.99), G16(0.16)
IA2	$-0.1417 \pm 3.1887i$	ω, δ of G14(0.46), G16(0.99)
IA1	$-0.0981 \pm 2.4517i$	ω, δ of G12(0.18), G13(0.99), G14(0.83), G15(0.65)

through various transmission lines, and generator speed are considered. For clarity of presentation, the signals are named as follows

P_{pq} Active power flow through transmission line connecting bus #p and bus #q

Q_{pq} Reactive power flow through transmission line connecting bus #p and bus #q

I_{pq} Current flow through transmission line connecting bus #p and bus #q

ω_p Speed of generator at bus #p

Fig. 6.13 presents the histograms showing the variation in the magnitude and the angle of the residue corresponding to IA1 of few signals for all operating conditions. It is evident from the histograms that both the magnitude and the angle of residues show large variation. The degree of variation is different for each signal. Similar variation is observed for other modes. A signal having good magnitude and least variation in the residue is an ideal choice for damping controller design.

6.5.6 PSS

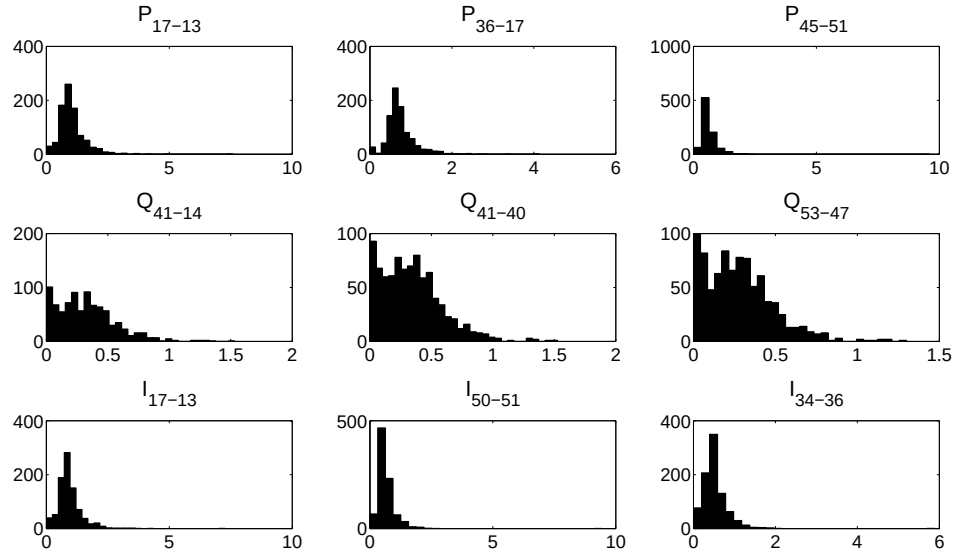
In Fig 6.12, the local mode L2 is unstable for many operating conditions which has a higher participation from G9. A PSS installed at G9 can improve damping of this mode. The signal selection procedure and controller design for the PSS is explained below.

Table 6.4 shows that, modes L4 and IA4 also have participation from ω and δ states of G9. A PSS at this generator can influence damping of both the modes. The Criteria-3 is important in this case to avoid possible negative effect to L4 and IA4.

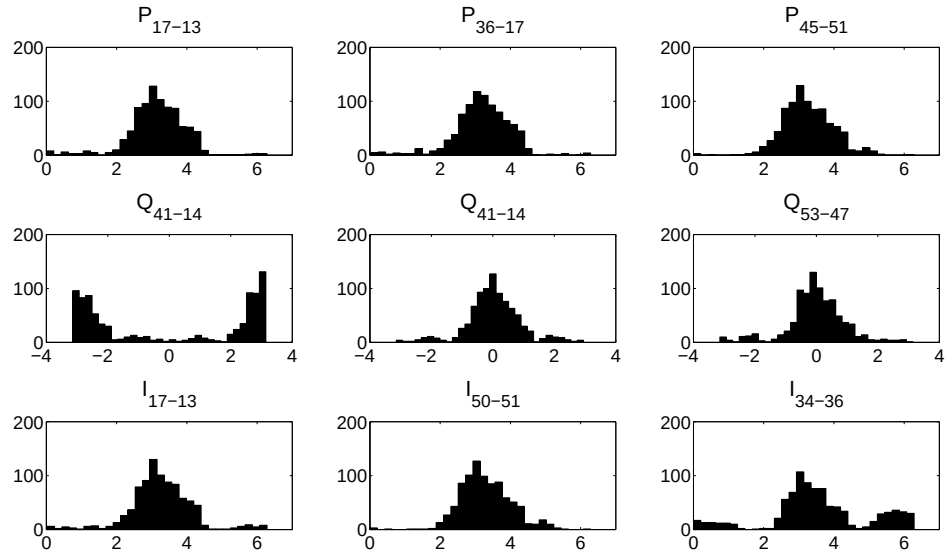
Feedback signal selection for PSS

The residues corresponding to L2, L4 and IA4 of the transfer function between excitation system reference input and various feedback signals are obtained. Average magnitude of residue, $\overline{|R_i^k|}$ and error covariance matrix, $\mathbf{P}_i^{rel,k}$ are computed for $i = L2, L4$, and $IA4$. Table 6.5 shows characteristics of different possible feedback signals for PSS. Six remote signals from 2 transmission lines and four local signals are considered. Since local modes are observable in the neighborhood of generator, only remote signals from two adjacent transmission lines from G9 are considered. 6.14 shows error ellipse corresponding to $\mathbf{P}_{L2}^{rel,k}$ for these signals.

The $\overline{|R_{L2}|}$ is high for I_{09-29} which satisfies the Criteria-1. However, the signal has high variation as evident from the error ellipse, hence fails in Criteria-2. Next best



(a) Magnitude of residue



(b) Angle of residue

Figure 6.13: Histogram showing variation in residue for nine feedback signals for TCSC corresponding to IA1. The title of histogram is the signal name

choice is ω_{G9} , which has high magnitude of residue and least variation. This satisfies Criteria-1 and Criteria-2. It has less variation for residue corresponding to IA4 and L4. The $\overline{\angle R_{L2}}$ and $\overline{\angle R_{IA4}}$ are very close to each other and $\overline{\angle R_{L4}}$ is in acceptable range which satisfies Criteria-3. Hence, the speed of generator G9, ω_{G9} is selected as feedback signal for PSS.

Table 6.5: Characteristics of possible PSS feedback signals

Signal Name	$\overline{ R_{L2} }$	$\det(\mathbf{P}_{L2}^{rel,k})$ *100	$\overline{\angle R_{L2}}$	$\overline{ R_{IA4} }$	$\det(\mathbf{P}_{IA4}^{rel,k})$ *100	$\overline{\angle R_{IA4}}$	$\overline{ R_{L4} }$	$\det(\mathbf{P}_{L4}^{rel,k})$ *100	$\overline{\angle R_{L4}}$
P_{28-29}	27.32	1.14	-69.09	4.05	10.53	81.18	7.36	0.03	2.3
Q_{28-29}	26.90	1.07	-67.55	4.07	10.23	80.14	7.24	0.03	0.7
I_{28-29}	7.63	3.36	-67.43	1.46	15.51	-64.42	2.36	8.7	-140.2
P_{26-29}	3.80	1.29	-46.32	0.93	18.40	-54.23	1.51	0.07	-119.02
Q_{26-29}	25.15	5.89	-89.60	3.45	11.43	-73.33	6.78	60.55	180.38
I_{26-29}	27.52	4.41	-88.18	4.05	11.83	-72.58	7.42	4.8	-21.17
P_{09-29}	7.86	4.37	35.20	9.00	8.89	-40.04	1.68	7.6	-82.96
Q_{09-29}	2.13	1.78	60.75	2.39	3.43	76.05	0.62	0.45	-93.87
I_{09-29}	54.75	4.40	-88.27	8.17	11.96	-72.61	14.76	4.84	-23.68
ω_{G9}	36.51	0.58	-8.62	8.22	0.96	-1.37	8.49	0.11	-82.06

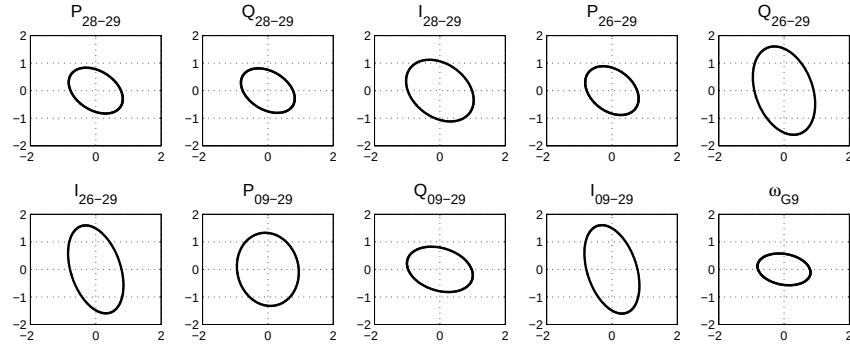


Figure 6.14: Error ellipse corresponding to various feedback signals of PSS

A speed input PSS (6.17) is designed for G9 in order to improve damping of this mode. 6.15 shows the movement of eigenvalues using the PSS for an operating condition. It is to be noted that the controller shifts L2, L4 and IA4 towards left while not influencing other modes. Fig. 6.16 shows the modes of the system with and without PSS for all operating conditions where the modes L2, L4 and IA4 have achieved a left shift from its position and obtained required damping.

$$\mathbf{K}_{\text{PSS}} = \frac{0.06s^2 + 0.2s}{2s^2 + 10.2s + 1} \quad (6.17)$$

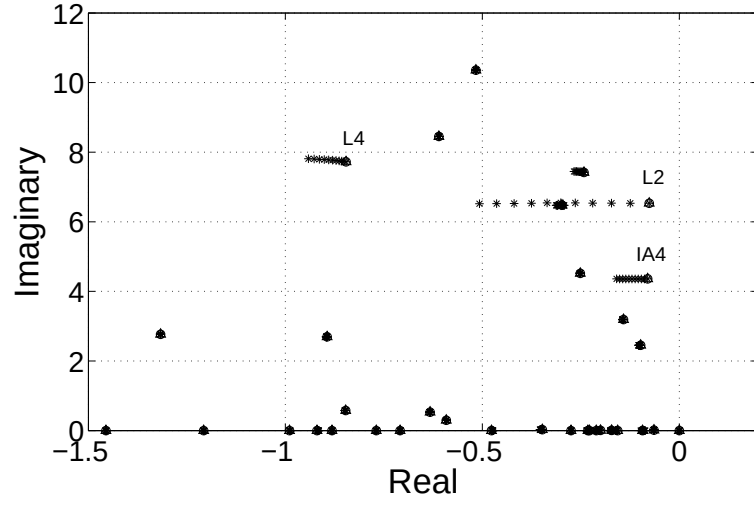


Figure 6.15: Eigenvalue shift with increase in PSS gain for an operating condition

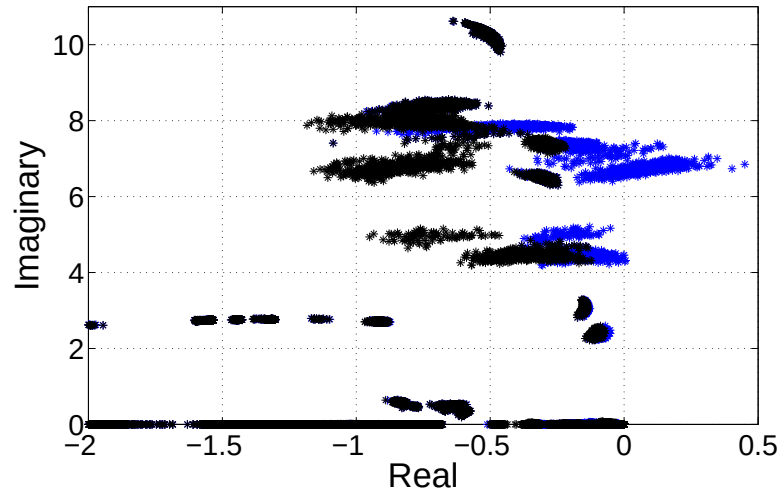


Figure 6.16: Eigenvalues of the sixteen machine system with and without PSS for all the operating conditions

6.5.7 TCSC based damping controller

A supplementary damping controller at the TCSC can improve damping of inter-area modes of the system [9]. A multiple input single output controller of structure shown in Fig. 6.17 is proposed for the damping controller. Maximum number of feedback signals is equal to the number of inter-area mode requiring damping. One feedback signal having high magnitude of residue is required for each mode. Any single or hybrid measurement from any part of the network can be used as feedback signal. In

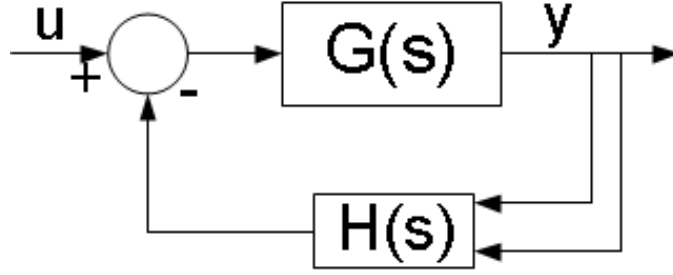


Figure 6.17: MISO controller structure

this work, active power, reactive power and current of 83 transmission lines along with generator speed from 11 synchronous generators are included in the initial signal set. Altogether 260 possible signals are selected. The residue corresponding to inter-area modes for the transfer function between the TCSC reference input and all the possible signals are obtained. The signal selection procedure for this controller is explained below.

Signal selection for IA1

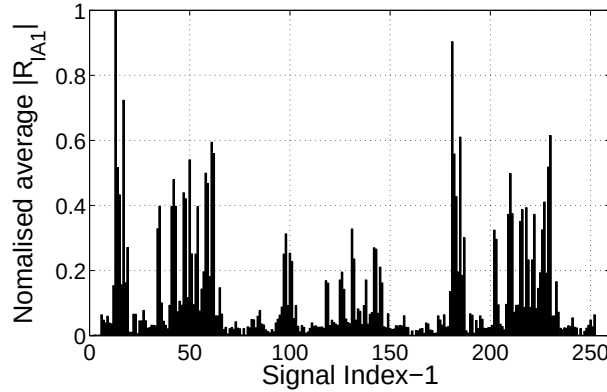


Figure 6.18: Normalized average magnitude of residue of feedback signals corresponding to IA1

Fig. 6.18 shows normalized average magnitude of residue corresponding to IA1 for all the signals. Signals having the magnitude of residue less than 0.33 are eliminated. Table 6.6 shows 30 potential feedback signals selected after Criteria-1, and other signals are eliminated. The table shows average magnitude of residue and determinant of ECM. The error ellipse corresponding to ECM is shown in Fig. 6.19 and determinant of ECM is plotted in Fig. 6.20. It is evident that most of the signals have less variation in residue and it is time to validate Criteria-3.

As mentioned before, the objective is not to find the best signal but to arrive at a suitable signal and eliminate any unsuitable one. There can be more than one good signal. Two example signals are discussed below.

Table 6.6: Potential feedback signals passed criteria-1 to represent IA1

Signal Index-1	Signal Index-2	Signal Name	Normalized average residue magnitude	Determinant of ECM
13	1	P_{17-13}	1	0.0189
14	2	P_{41-14}	0.5167	0.0299
15	3	P_{42-15}	0.4329	0.012
17	4	P_{36-17}	0.7232	0.0152
35	5	P_{61-30}	0.3975	0.0118
41	6	P_{35-34}	0.3967	0.0239
42	7	P_{34-36}	0.48	0.0232
43	8	P_{61-36}	0.3971	0.0118
47	9	P_{41-40}	0.439	0.012
48	10	P_{48-40}	0.4207	0.0127
50	11	P_{18-42}	0.5405	0.0229
54	12	P_{35-45}	0.3967	0.0239
58	13	P_{53-47}	0.4994	0.0109
59	14	P_{47-48}	0.4676	0.011
61	15	P_{45-51}	0.5941	0.0229
62	16	P_{50-51}	0.5597	0.0228
181	17	I_{17-13}	0.9036	0.0233
182	18	I_{41-14}	0.5582	0.0271
183	19	I_{42-15}	0.4271	0.0104
185	20	I_{36-17}	0.6102	0.0535
209	21	I_{35-34}	0.3727	0.3016
210	22	I_{34-36}	0.498	0.0649
211	23	I_{61-36}	0.3749	0.0216
215	24	I_{41-40}	0.3504	0.0122
216	25	I_{48-40}	0.3871	0.0226
218	26	I_{18-42}	0.3933	0.1235
222	27	I_{35-45}	0.3727	0.3016
227	28	I_{47-48}	0.4105	0.0518
229	29	I_{45-51}	0.518	0.0419
230	30	I_{50-51}	0.6147	0.0236

I_{42-15} is one of the signals passed criteria-1 and has least variation in residue corresponding to IA1. Table 6.7 summarizes the residue characteristics of I_{42-15} . $\overline{\angle R_{IA1}}$ is 11.51° whereas $\overline{\angle R_{IA2}}$ is 210.65° . Also $|\overline{R_{IA2}}|$ is more than $|\overline{R_{IA1}}|$. Similarly, for IA4, $\overline{\angle R_{IA4}}$ is 176.01° with higher $|\overline{R_{IA4}}|$ compared to $|\overline{R_{IA1}}|$. Also note the large $\det(\mathbf{P}_{IA2}^{rel, I_{42-15}})$ and $\det(\mathbf{P}_{IA4}^{rel, I_{42-15}})$ with high magnitude of residue which will result

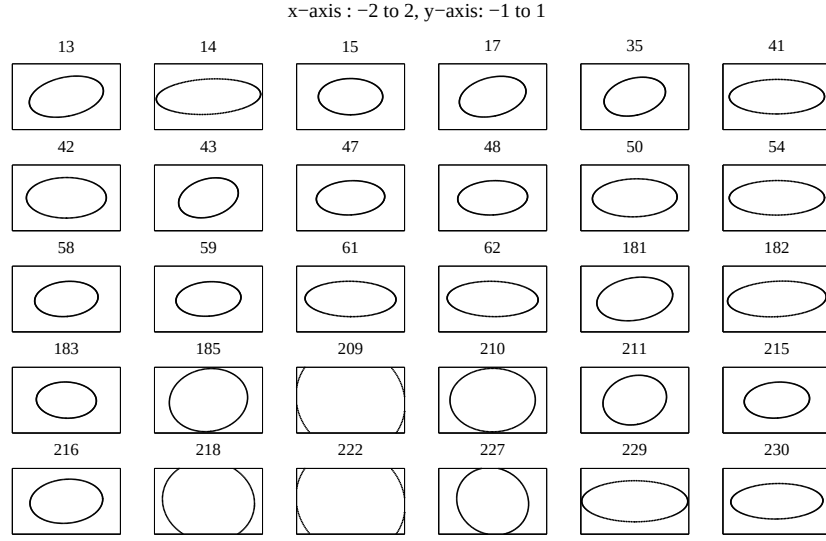


Figure 6.19: Error ellipse of potential feedback signals passed criteria-1 to represent IA1. Title show Signal Index-1

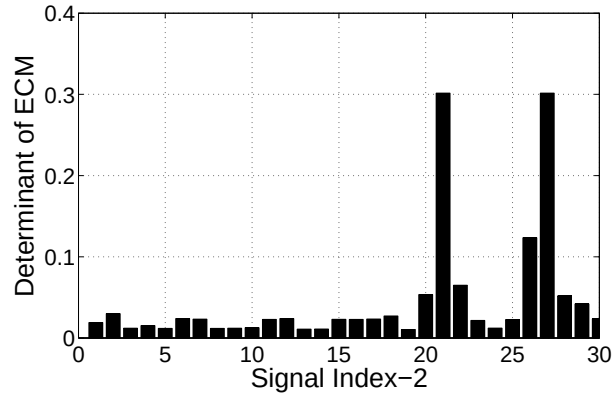


Figure 6.20: Determinant of ECM of potential feedback signals passed criteria-1 to represent IA1

Table 6.7: Residue characteristics of signal I_{42-15}

Signal : I_{42-15}			
Mode	$\overline{ R }$	$\overline{\angle R}$	$\det(\mathbf{P}^{rel, I_{42-15}})$
IA1	0.429	11.51	0.0104
IA2	0.548	210.65	3.67
IA3	8.290	81.09	0.019
IA4	1.369	176.01	1.218

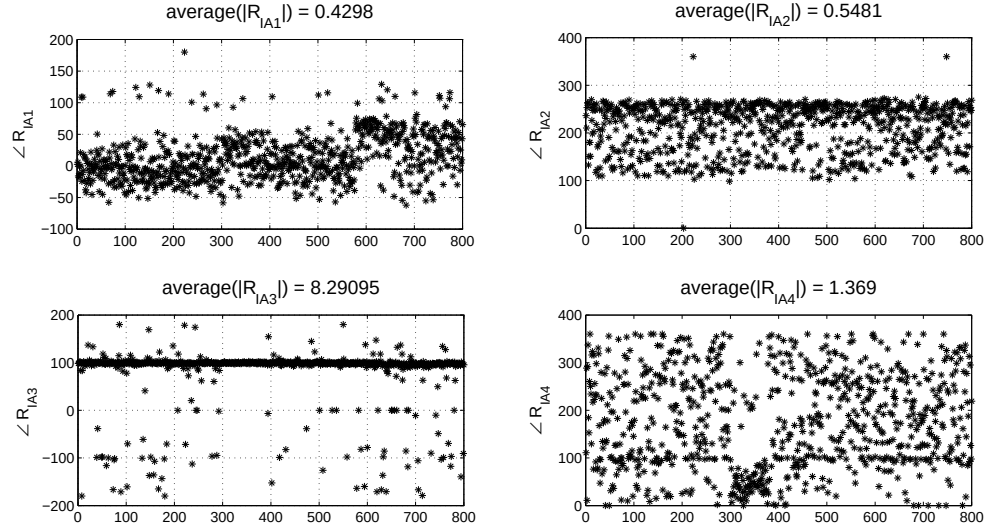


Figure 6.21: Angle of residues for the signal I_{42-15}

in ineffective eigenvalue movement. Hence this signal cannot be selected to represent IA1.

For further clarification, Fig. 6.21 shows the angle of residue corresponding to the inter-area modes for the signal I_{42-15} for all operating conditions. Each subplot shows average magnitude of residue. The $\angle R_{IA1}$ varies around 0° while $\angle R_{IA2}$ varies around 180° . The average magnitude of residue for IA2 is more than that of IA1. If this signal is selected to damp IA1 using a fixed parameter controller, it will decrease damping of IA2. IA4 will also exhibit similar behavior as the $\angle R_{IA4}$ varies from 0° to 360° .

P_{61-30} is another signal which has passed Criteria-1 and have less variation in residue corresponding to IA1. Table 6.8 summarizes the residue characteristics of P_{61-30} . $\overline{\angle R_{IA1}}$ and $\overline{\angle R_{IA4}}$ are same whereas angles of other two modes lie within 90° which satisfy the Criteria-3. Fig. 6.22 shows the angle of residue corresponding to the inter-area modes for the signal P_{61-30} for all operating conditions. Each subplot shows average magnitude of residue. The $\angle R_{IA1}$ varies around 180 degree while $\angle R_{IA2}$ and $\angle R_{IA3}$ are close to 90 degree and $\angle R_{IA4}$ varies around 180 degree. Variation in $\angle R_{IA2}$ and $\angle R_{IA3}$ are less and their average magnitude of residue is close to that of IA1. Hence this signal could be considered as a potential feedback signal. Other possible options can be investigated. The important point here is that $\overline{\angle R}$ for all the modes are in the same half plane and with less variation in residue. A fixed parameter controller shifting IA1 to left will not cause poor damping of other modes. Though better signals can be explored, this signal is selected as one of the feedback signals

for the proposed controller.

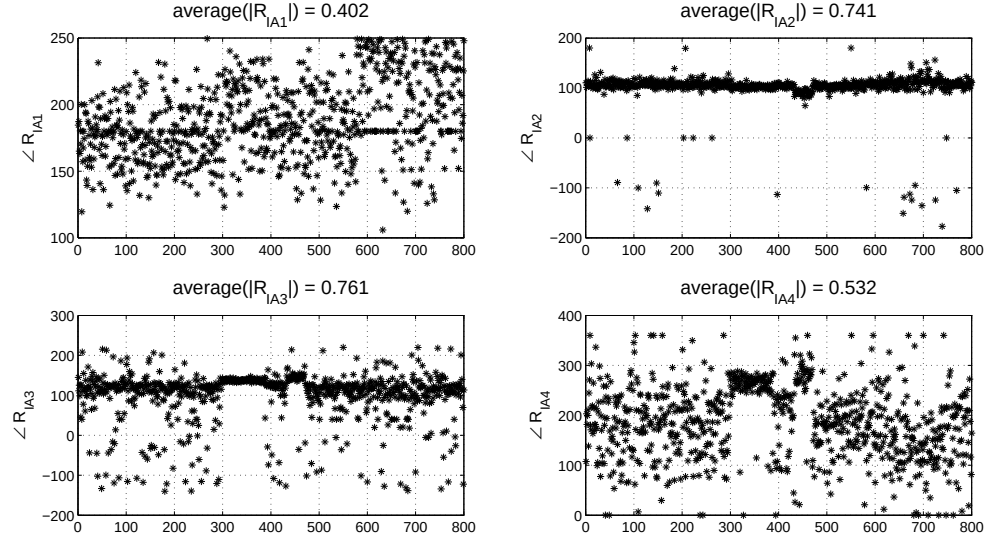


Figure 6.22: Angle of residues for the signal P_{61-30}

Table 6.8: Residue characteristics of signal P_{61-30}

Signal : P_{61-30}			
Mode	$\overline{ R }$	$\overline{\angle R}$	$\det(\mathbf{P}^{rel, P_{61-30}})$
IA1	0.402	187	0.0118
IA2	0.741	110.23	0.0360
IA3	0.761	117.87	0.0150
IA4	0.5321	187	0.0440

Signal selection for IA2

Fig. 6.23 shows the normalized average magnitude of residue corresponding to IA2. Table 6.9 lists the signals which have passed Criteria-1. All the selected signals have less variation as evident from the determinant of ECM. P_{18-16} is the signal with least variation in residue corresponding to IA2. Fig. 6.24 shows the angle of residue corresponding to the inter-area modes for the signal P_{18-16} for all operating conditions and Table 6.10 summarizes the residue characteristics of P_{18-16} . Each subplot shows average magnitude of residue. $\angle R_{IA2}$ and $\angle R_{IA3}$ have less variation and their values are around 90 degree. $\angle R_{IA1}$ and $\angle R_{IA4}$ have higher variation and their values are around 180 degree. However, values of $\overline{|R_{IA1}|}$ and $\overline{|R_{IA4}|}$ are significantly less

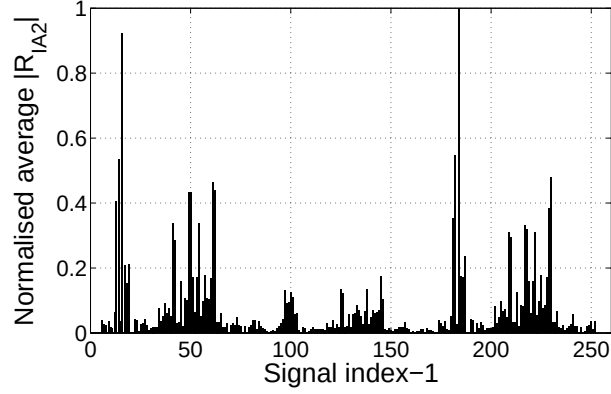


Figure 6.23: Normalized average magnitude of residue for feedback signals corresponding to inter-area mode, IA2

compared to $\overline{|R_{IA2}|}$. Hence a controller shifting IA2 to left will not influence IA1 or IA4. Since $\angle R_{IA2}$ and $\angle R_{IA3}$ are within a narrow range, the direction of shift of IA2 and IA3 will be almost in same direction.

Table 6.9: Potential feedback signals passed Criteria-1 to represent IA2

Signal Index-1	Signal Index-3	Signal Name	Normalized average residue magnitude	Determinant of ECM
13	1	P_{17-13}	0.4045	0.0029
14	2	P_{41-14}	0.5350	0.0009
16	3	P_{18-16}	0.9234	0.0009
41	4	P_{35-34}	0.3362	0.0013
49	5	P_{42-41}	0.4330	0.0010
50	6	P_{18-42}	0.4316	0.0013
54	7	P_{35-45}	0.3362	0.0013
61	8	P_{45-51}	0.4648	0.0013
62	9	P_{50-51}	0.4373	0.0012
181	10	I_{17-13}	0.3521	0.0077
182	11	I_{41-14}	0.5456	0.0009
184	12	I_{18-16}	1.0000	0.0011
217	13	I_{42-41}	0.3313	0.0340
229	14	I_{45-51}	0.3821	0.0314
230	15	I_{50-51}	0.4784	0.0024

Signal selection for IA3

Table 6.11 lists the signals which have passed Criteria-1 for IA3. All the selected signals have less variation as evident from the determinant of ECM. The signal P_{18-16}

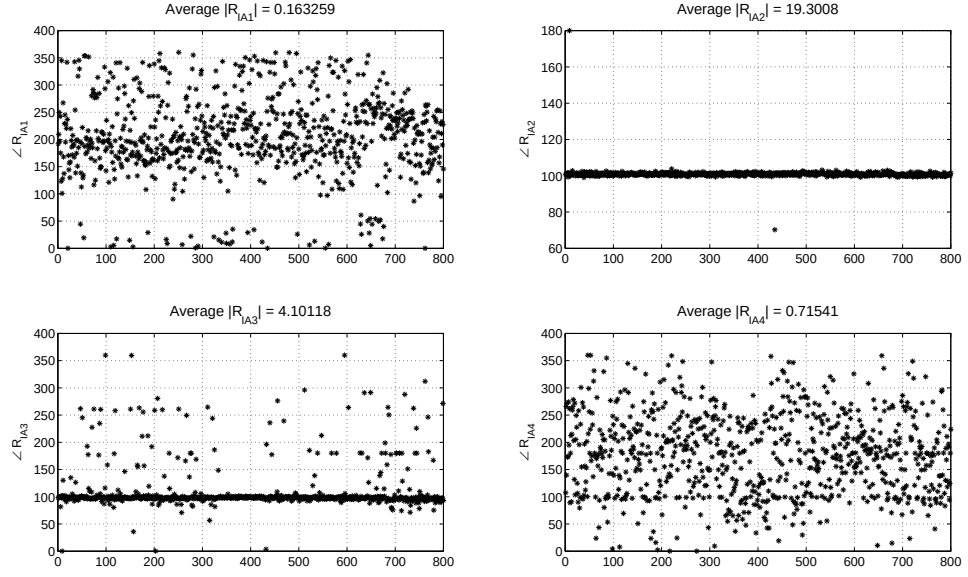


Figure 6.24: Angle of residues for the signal P_{18-16}

Table 6.10: Residue characteristics of signal P_{18-16}

Signal : P_{18-16}			
Mode	$\overline{ R }$	$\overline{\angle R}$	$\det(\mathbf{P}^{rel, P_{18-16}})$
IA1	0.1633	206.20	2.0122
IA2	19.300	97.479	0.0008
IA3	4.1011	83.46	0.0156
IA4	0.7154	177.81	0.8019

has least variation in residue as evident from determinant of ECM. This is also the signal selected to represent IA2 and it is suitable for IA3 as well.

Signal selection for IA4

From 260 initial signals, 40 signals passed criteria-1 for IA4. Few of those signals are listed in Table 6.12. However, the variation in residue corresponding to IA4 for transfer function between the signals and the TCSC reference input is found to vary a lot as evident from higher determinant of ECM. This is also verified using visual inspection of residue. If the TCSC is used to damp the IA4, it will result in unexpected eigenvalue movement. Hence it is not advisable to use the TCSC to improve damping of IA4. Moreover, the PSS has significantly improved the damping of IA4 which is sufficient for stable operation.

Table 6.11: Potential feedback signals passed Criteria-1 to represent IA3

Signal Index-1	Signal Index-4	Signal Name	Normalized average residue magnitude	Determinant of ECM
14	1	P_{41-14}	0.6370	0.0188
15	2	P_{42-15}	1.0000	0.0198
16	3	P_{18-16}	0.4794	0.0156
49	4	P_{42-41}	0.5644	0.0219
50	5	P_{18-42}	0.4304	0.0203
182	6	I_{41-14}	0.6487	0.0187
183	7	I_{42-15}	0.9697	0.0192
184	8	I_{18-16}	0.5050	0.0167
217	9	I_{42-41}	0.4303	0.0763

Table 6.12: Potential feedback signals passed criteria-1 to represent IA4

Signal Index-1	Signal Index-5	Signal Name	Normalized average residue magnitude	Determinant of ECM
17	1	P_{36-17}	1	0.0748
13	2	P_{17-13}	0.9582	0.0954
181	3	I_{17-13}	0.9565	0.0805
185	4	I_{36-17}	0.8776	0.1436
211	5	I_{61-36}	0.8768	0.0601
43	6	P_{61-36}	0.8695	0.0752
15	7	P_{42-15}	0.8667	1.2296
183	8	I_{42-15}	0.8373	1.2187
241	9	P_{60-61}	0.607	0.0576
233	10	P_{53-54}	0.5977	0.0506

Controller design

A two input single output controller for the TCSC is designed using the selected feedback signals. The controller should improve damping of IA1, IA2 and IA3 while preserving the damping of other modes. Residue approach mentioned earlier is used to design the controller. The proposed controller structure is given by,

$$\mathbf{K}(s) = \begin{bmatrix} \mathbf{K}_1(s) \\ \mathbf{K}_2(s) \end{bmatrix} = \frac{1}{D_k(s)} \begin{bmatrix} N_{k,1}(s) \\ N_{k,2}(s) \end{bmatrix}$$

Table 6.13: feedback signals for the TCSC damping controller

No.	Signal	Mode of interest	$\angle R$
1	P_{61-30}	IA1	$\angle R_{IA1} = 187^\circ$
2	P_{18-16}	IA2	$\angle R_{IA2} = 97.5^\circ$
		IA3	$\angle R_{IA1} = 83.46^\circ$

Table 6.13 lists the two feedback signals and its characteristics. The signal P_{61-30} is selected to improve damping of IA1 with $\overline{\angle R_{IA1}}$ equals to 187° . This angle will decide phase of $\mathbf{K}_1(s)$. Similarly, P_{18-16} is selected for IA2 and IA3 with $\overline{\angle R_{IA2}}$ and $\overline{\angle R_{IA3}}$ equal to 97.5° and 83.46° , respectively, which decides phase of $\mathbf{K}_2(s)$. However, some tuning is required to make robust performance which can be carried out using variety of techniques such as robust pole placement [12].

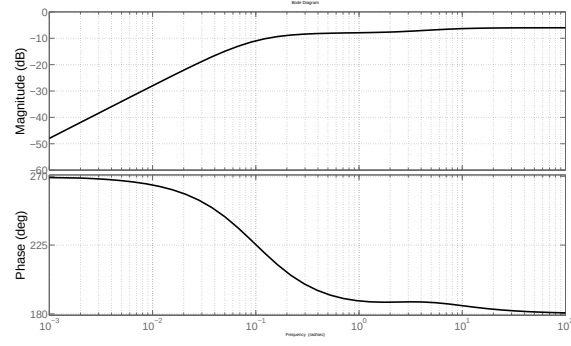
$$\mathbf{K}(s) = \frac{1}{2s^2 + 10.2s + 1} \begin{bmatrix} -s^2 - 4s \\ 0.0004s^2 + 0.4s \end{bmatrix} \quad (6.18)$$

(6.18) shows the transfer function of the TCSC based damping controller and Fig. 6.25 shows the bode diagram of the transfer function. The phase angle of the final controller compensates for the respective residue angle. Fig. 6.26 shows the closed loop and open loop eigenvalues of the 16 machine system with and without damping controllers, respectively. The blue shade indicates the open loop eigenvalues for all operating conditions and the red shade show closed loop eigenvalues obtained using the PSS and the TCSC damping controllers. It is clear from the figure that, all the modes show negative shift indicating improvement in damping ratio. The important point to note is that, the proposed signal selection approach helps to design a controller using simple methods and it inherently ensures robust controller performance for large number of operating conditions by selecting feedback signals with less variation in residue.

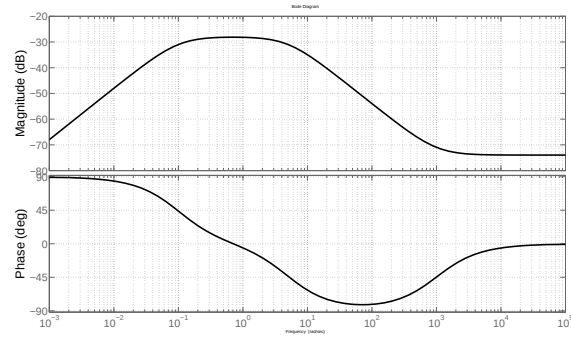
However, it should be noted that in the proposed signal selection method the performance of the controller is sometimes compromised by selecting the feedback signals with less magnitude of the residue. In the figure, though the controller is able to shift the inter area modes towards the left the amount of shift is not enough under some other operating cases. Such operating cases require further damping action from other sources. However, the selection of the feedback signals with least variation in the residue helps in designing the controller which is robust for many operating scenarios.

6.6 Art of signal selection

Availability of WAMS signal makes the feedback signal selection process laborious due to number of choices available. On the other hand operating conditions in future power system will show large variation which makes robust damping controller



(a) $K_1(s)$



(b) $K_2(s)$

Figure 6.25: Bode plot of the TCSC damping controller

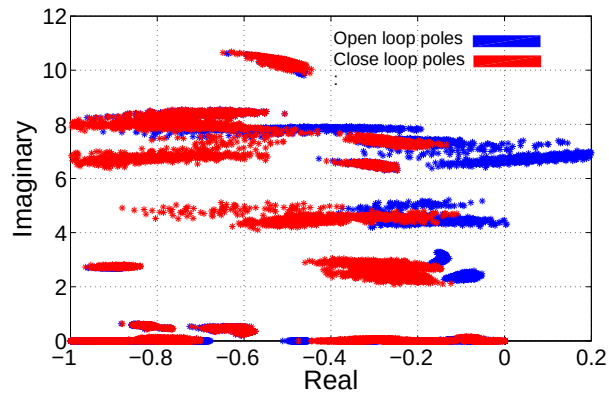


Figure 6.26: Closed loop eigenvalues of the 16 machine system with damping controllers. Blue shade show open loop eigenvalues and red shade show closed loop eigenvalues.

design difficult. The judicious selection of feedback signal using the criteria presented above can achieve robust damping controller for large number of operating conditions. However applying these criteria for all possible signals including hybrid signals is a lengthy task. In this chapter an elimination approach rather than selection is adopted, where signals are eliminated following each criteria.

From Tables 6.6, 6.9, 6.11, and 6.12, it is evident that signal with higher magnitude of residue lies in the corridor connecting generators participating in inter-area mode. A designer can focus on this corridor eliminating signals from all other locations. Any power system signals such as voltage, current, power or its combinations can be included in the initial signal set.

In a large power system, one can easily pick hundreds of possible feedback signals. Applying signal selection criteria for all possible signals is a lengthy task. The importance of the elimination concept is useful in this context, where signals are eliminated following each criterion. The objective of signal selection can be slightly changed to finding a suitable signals instead of the best signal. All unsuitable signals can be eliminated one by one culminating in a suitable signal.

However in this procedure, a signal having less magnitude of residue may be selected which will increase the control effort or reduce controller performance. However, the signal will be robust to all operating conditions and will ensure a shift in eigenvalues towards increased damping for large number of operating scenarios.

6.7 Chapter summary

The chapter presents a signal selection criteria for damping controller design for power systems with large variation in operating conditions. The variation in operating conditions will change modal controllability and modal observability, product of which is the residue. The magnitude and angle of the residue is an important factor for controller performance. The signal selection criteria presented in the chapter selects signal having least variation in residue and hence ensures robustness in controller performance for large number of operating conditions. Simulation results using a 16 machine test system is presented to validate the proposed method. 800 operating scenarios of the test system are generated considering variations in synchronous generator output and load, and wind farm output variation. A PSS and a TCSC based supplementary damping controller are designed to improved damping of local and inter-area modes.

Chapter 7

Damping improvement using wind generators

In this chapter, the possibility of using wind generator as an actuator for inter-area oscillation damping controller is discussed. The results are presented using the two-area test system and the representative GB network.

Because of the decoupling nature of the system both active and reactive power can be controlled independently. The torque reference input is modulated to change the active power output. Additional power required can be extracted from turbine through changing pitch angle under rated regime of operation, and slowing down of turbine during sub-rated regime of operation. For reactive power variation, either voltage reference input or reactive power reference input can be modulated, depending on the individual settings of the wind farm.

The chapter is organized as follows. Using a detailed WTG model, the concept of controller design using active and reactive power modulation is explained. The issue of interaction between torsional mode and methods of reducing such interaction is explored. The damping controller concept is validated using the two-area test system model. The choice of active or reactive power modulation for wind farm is explored using the reduced GB network model. The generic WTG model is used in the GB network and the concept of damping controller design using wind farm is extended to the GB system.

7.1 Damping improvement using active power control

The modulation of active power input to the system can directly influence the angular difference between synchronous generators and hence can be used to damp inter-area oscillations. If the location of wind farm provides sufficient controllability to inter-area mode, active power modulation might be viable option. Earlier literatures suggest that, in some cases active power control may be better than reactive power control [115, 116, 117].

Case for active power modulation

However, the choice of active power modulation for wind farm may be perceived as difficult due to two reasons. (1) Active power modulation will induce torsional mode oscillations between turbine and generator shafts and cause fatigue. The interaction of torsional mode is discussed in the next section. (2) Unavailability of headroom for active power modulation for damping control due to the urge to utilize 100% of the available wind power. But this may not be the case in future. In order to securely operate power system in the event of a generation loss, reserve capacity must be present in the network at all times. Synchronous generators automatically provide this service initially through inertial response and later by governor action. Since the modern WTGs do not offer any inertial response, other than synthetic inertia, synchronous generators are bound to stay in the network. However, some grid operators are encouraging wind farm operators to allocate certain percentage of available capacity for frequency response [118, 119, 120]. Fig. 7.1 shows the frequency controlled active power regulation requirement set by the Eirgrid, the Irish grid operator. During the frequency points B and C around 50Hz, the output of wind farm is reduced to a set point. With stable demand and increased wind generation in future, wind output may be constrained [121, 122]. This is particularly true for the systems having large nuclear generation during light loading conditions. Similarly, network conditions can force the wind to reduce its output [123]. It is inevitable that wind farm may operate at less than its available capacity. The unused capacity in future can be used to provide damping support through active power modulation.

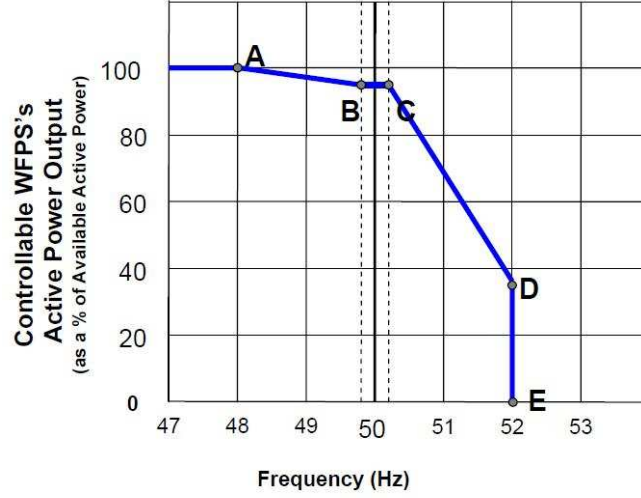


Figure WFPS1.2 – Example of Power-Frequency Response Curve.

Figure 7.1: Wind farm Power-Frequency Response Curve of Irish Grid, Source Eirgrid, [119]

7.1.1 Interaction with torsional mode due to active power modulation

One of the issues with the active power modulation is the possible interference with torsional oscillation mode of wind turbines [116]. The active power modulation may decrease the damping ratio of torsional mode while improving the inter-area mode damping.

Let us consider the two-area test system with three synchronous generators and a DFIG. The Table. 4.1 shows the modes of the system. The mode $(-2.14 \pm j11.2)$ having higher participation to ω_r and θ_{tw} states of the DFIG represents torsional mode oscillations of the machine and the mode $(-0.003 \pm j4.32)$ having participation to ω and δ of synchronous generators G1, G2 and G3 represent the inter-area modes in the system. The frequency of torsional mode and inter-area mode are 1.78Hz and 0.68Hz, respectively and the damping ratio of the modes are 18.82% and 0.001%, respectively. It is to be noted that, the inter-area mode is poorly damped while torsional mode has higher damping. However, due to critical and complex nature of WTG system, higher damping is necessary and a fall in damping of this mode is not acceptable.

Fig. 7.2 shows the root locus of the system with active power modulating input and various output signals. Signals such as active power, reactive power and current, between three different pairs of buses are considered. In all the root locus plots, a zero is located at the right hand side of the torsional mode. With increase in feedback gain, the torsional mode shifts towards right reducing the damping ratio which is

undesirable. Such interaction will question the use of active power modulation for damping controller design.

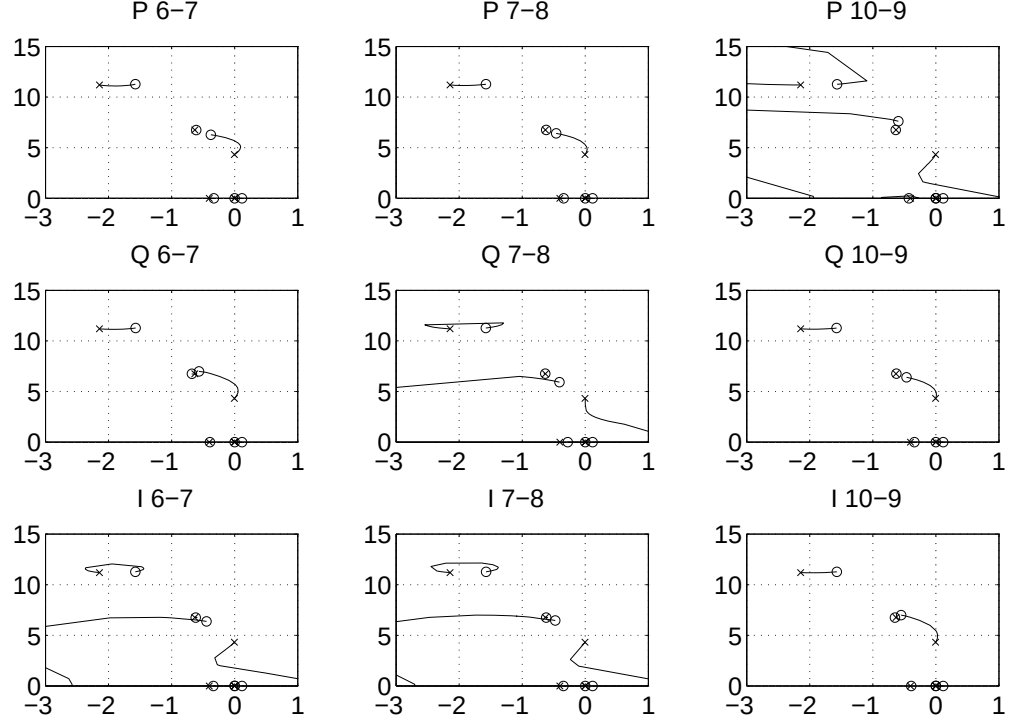


Figure 7.2: Root locus plots of the two-area system with DFIG showing effect of active power modulation on torsional mode. System input is torque reference and outputs are specified in title of subplots. $P6 - 7$ indicates active power flow between buses 6 and 7.

But, a judicious selection of feedback signal can solve this issue. Following two criteria are used as thumb rules to select feedback signals for inter-area mode damping controller so as to avoid any possible interaction with torsional mode. They are formed in line with Criteria-3 defined in Chapter-6

- $\angle R_{TM}$ and $\angle R_{IAM}$ for the feedback signal should be equal or within narrow range. This will give a similar direction of shift for a static gain controller, and with a phase compensation, both the modes will shift towards the left.
- The magnitude of residue corresponding to torsional mode (R_{TM}) should be as small as possible compared to the magnitude of residue corresponding to inter-area mode (R_{IAM}). This will ensure that, the shift of torsional mode is smaller than the shift of inter-area mode.

7.1.2 Damping controller design

From the root locus plots in Fig. 7.2, the plots corresponding to signals $P10 - 9$, $Q7 - 8$, $I6 - 7$, and $I7 - 8$ have initial shift of both the mode towards left. This satisfies first criteria and suggests an improved damping for small values of feedback gain. Fig. 7.3 shows the normalized (w.r.t IAM) magnitude of residue corresponding to torsional mode given by,

$$\overline{|R_{TM}^f|} = \frac{|R_{TM}^f|}{|R_{IAM}^f|} \quad \text{where, f indicates feedback signal} \quad (7.1)$$

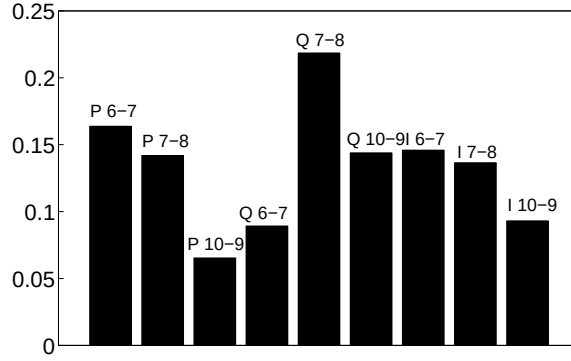


Figure 7.3: Normalized magnitude of residue corresponding to torsional mode for active power reference input in the two-area test system with DFIG

Out of the four signals found suitable based on angle criteria, the signal $P10 - 9$ has the least $\overline{|R_{TM}^f|}$, 5%, for the torsional mode compared to the inter-area mode. Which means, if $P10 - 9$ is used as feedback signal, for every one unit shift of inter-area mode, torsional mode will shift 0.05 unit. This estimate is true only for small values of controller gain constant and can change with controller transfer function.

A controller with transfer function in (7.2) is designed using the feedback signal $P10 - 9$ and active power modulation input. The eigenvalue shift with increase in controller gain constant is plotted in Fig. 7.4. The controller is able to provide sufficient damping without causing any deterioration to torsion mode damping.

$$\mathbf{K}(s) = \frac{0.1s^2 + 10s}{2s^2 + 10.2s + 1} \quad (7.2)$$

The controller performance is validated using a time domain simulation following a three phase fault at bus #7. The inter-area oscillation is captured between the

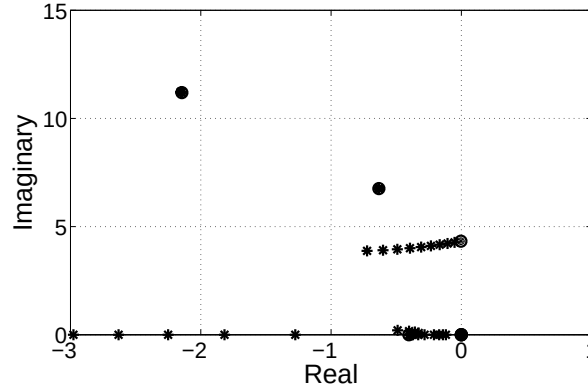


Figure 7.4: Plot showing eigenvalue shift for the two-area system with DFIG for damping controller using active power modulation

generators in both the areas and plotted in the Fig. 7.5. The oscillation is well damped with the designed controller. The modulated active power and the reactive power output of DFIG are shown in Fig. 7.6 and Fig. 7.7, respectively.

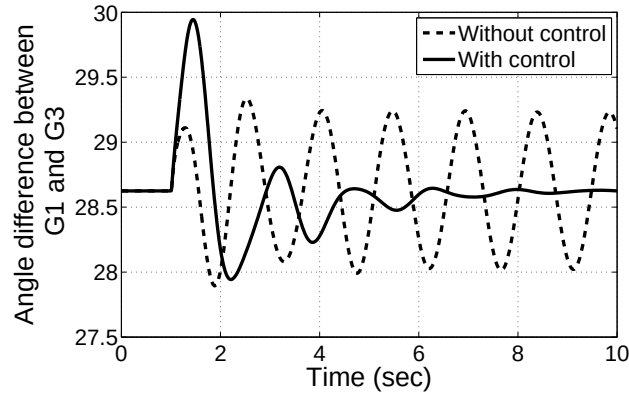


Figure 7.5: Closed loop response of two-area system with DFIG using damping controller modulating active power output: Plot shows angle difference between generators G1 and G3

7.2 Damping improvement using reactive power or voltage control

From the perspective of damping control, the reactive power control of wind farm is similar to SVC operation. The voltage or reactive power reference of wind farm can be modulated using a supplementary damping controller to achieve required stability margin for the power system. Like active power control, the controllability, hence the

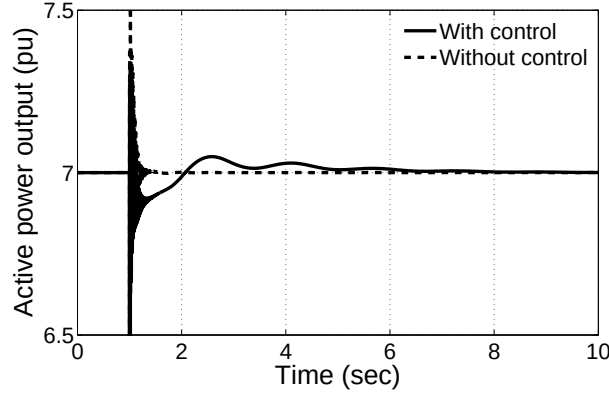


Figure 7.6: Closed loop response of two-area system with DFIG using damping controller modulating active power output: Plot shows active power output of DFIG

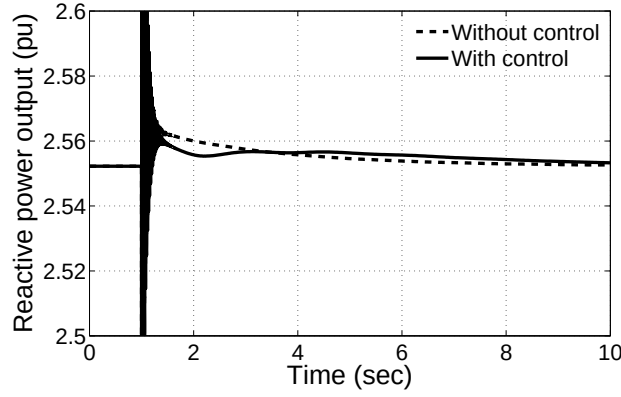


Figure 7.7: Closed loop response of two-area system with DFIG using damping controller modulating active power output: Plot shows reactive power output of DFIG

location of the wind farm, is an important selection criteria.

7.2.1 Interaction of torsional mode due to reactive power modulation

The Fig. 7.8 shows the root locus plots of the system with reactive power modulation input and different output signals for the two-area test system. Signals such as active power, reactive power and current, between three different pairs of buses are considered. It is clear from the figure that, for all the combinations of outputs and reactive power input, the torsional mode does not exhibit any change. This means that, reactive power modulation has no impact on torsional mode oscillation of the system.

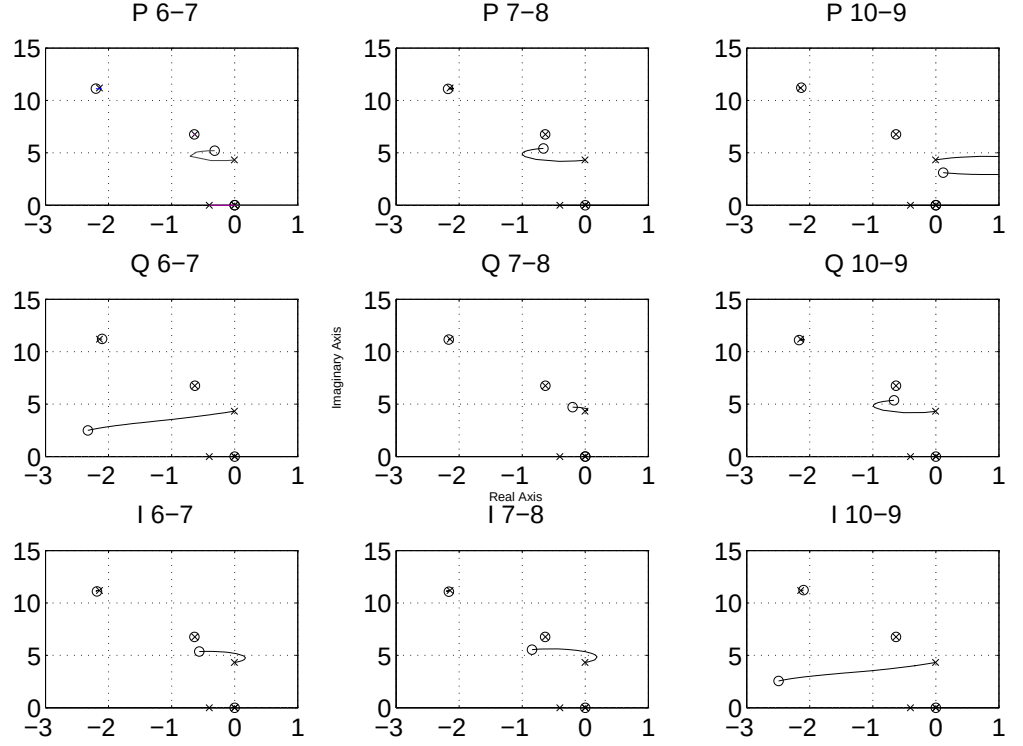


Figure 7.8: Root locus plots of the two-area system with DFIG showing effect of reactive power modulation on torsional mode. System input is voltage reference and outputs are specified in title of subplots. $P6 - 7$ indicates active power flow between buses 6 and 7.

7.2.2 Damping controller design

A controller of the transfer function in (7.3) is designed with reactive power reference input and active current between buses #9 and #10 as inputs to controller. The signal is selected based on the higher magnitude of residue. The robustness is not considered as controller design criteria as the objective of this study is to validate the potential of reactive power modulation for damping control. The scheduled voltage of all generators are altered (compared to system used in previous section) to lower the reactive power output of wind farm. This will provide sufficient reactive power margin for damping controller operation.

$$K(s) = \frac{0.002s^3 + 0.01s^2 + 0.8s}{0.0324s^3 + 0.3924s^2 + 1.36s + 1} \quad (7.3)$$

Fig. 7.9 shows the inter-area mode oscillation with and without damping controller which shows a good performance. The active and modulated reactive power output of

DFIG are plotted in Fig. 7.10 and 7.11, respectively. As expected from the decoupled control of DFIG, only the reactive power output is modulated leaving active power more or less same irrespective of the presence of damping controller.

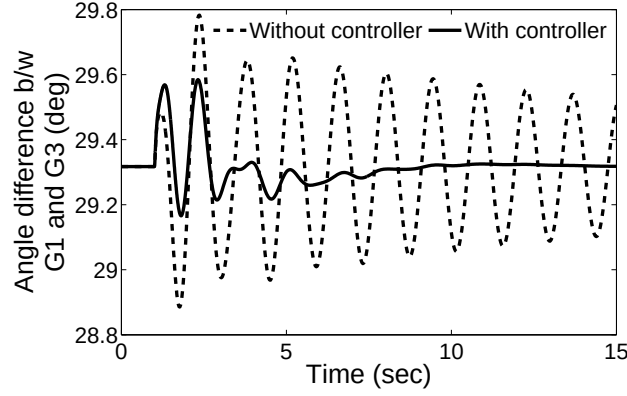


Figure 7.9: Closed loop response of two-area system with DFIG using damping controller modulating reactive power output: Plot shows angle difference between generators G1 and G3

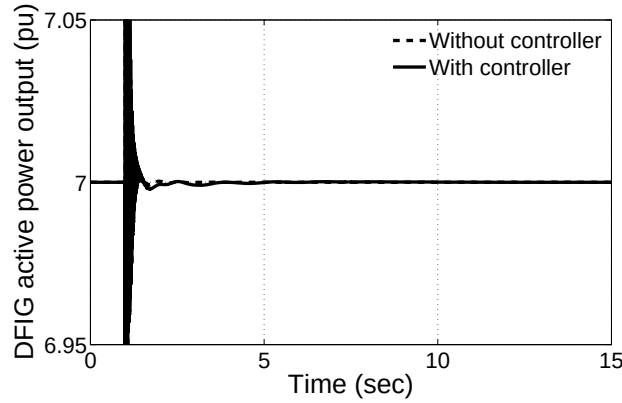


Figure 7.10: Closed loop response of two-area system with DFIG using damping controller modulating reactive power output: Plot shows active power output of DFIG

7.3 Damping improvement for GB system

Inter-area oscillation damping improvement using wind farm control for equivalent GB system is discussed in this section. The Type-4 generic WTG model is used to represent the wind farm. For controller using active power modulation, the output of controller is added to the active power reference input signal P_{ord} . For damping controller using reactive power modulation, two inputs are possible. If the wind farm

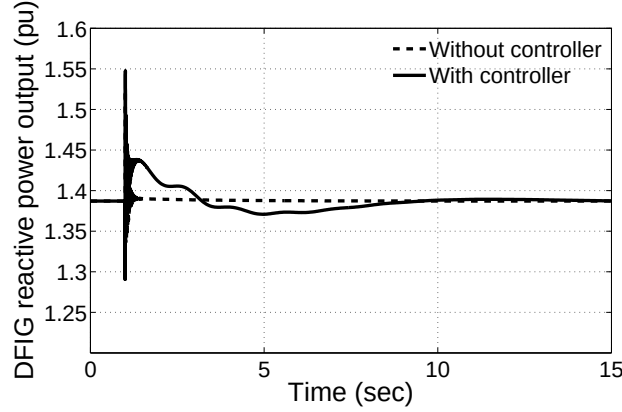


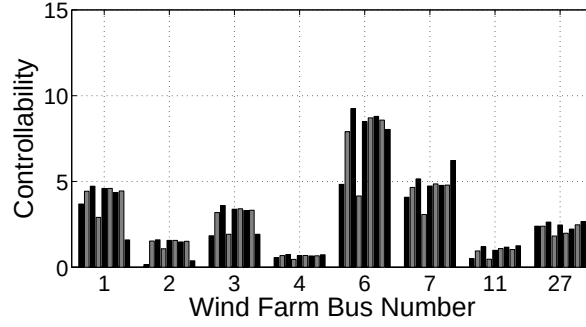
Figure 7.11: Closed loop response of two-area system with DFIG using damping controller modulating reactive power output: Plot shows reactive power output of DFIG

is operating in constant reactive power mode the controller output can be added with Q_{ord} . In case, it is operating in voltage control mode, the input V_{aux} in generator converter model can be used to connect controller output. The controller design considers all operating conditions discussed in previous chapter.

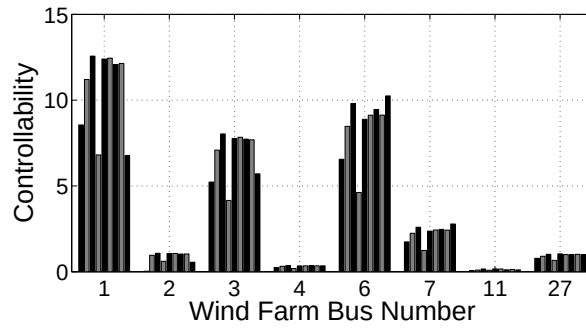
7.3.1 Choice between active and reactive power modulation

As described in previous section, wind farm can contribute to damping improvement using both active power and reactive power modulation. The choice of control input is very important for effective control action. In this section, the choice of actuator for the GB system is presented. As with any other type of damping controller, the controllability of interested mode through selected input is the best criterion for actuator selection. Fig. 7.12 shows the controllability of voltage reference input and active power reference input for different wind farms over the nine operating conditions discussed in the Chapter 5. The controllability indicates the influence of the input on the mode of interest. The x-axis shows high voltage bus number where the wind farm is located.

From the figure, the first wind farm has higher controllability for active power reference input compared to voltage reference input for all operating conditions. So it is better to use active power modulation for this wind farm. The third wind farm shows similar trend. The controllability of the inter-area mode using active power modulation is poor for wind farms in buses #2, #4, #11, and #27. It is not advisable to use those wind farms for damping control action using active power modulation. The wind farm at bus #6 shows similar controllability for both active and reactive power reference input. Hence, both types of controllers can be designed for this wind



(a) Voltage/reactive power reference input



(b) Active power reference input

Figure 7.12: Controllability of inter-area mode in representative GB system for different wind farms under the nine operating conditions.

farm. For wind farms in buses #2, #7 and #27 reactive power modulation is better than active power modulation.

Another important factor to consider while selecting wind farm is its capacity. Sufficient margin for active power output is required for damping control action. Hence if wind farm relatively small in capacity and/or is operating close to its available capacity it may not be able to support damping control action. Similarly, for the reactive power modulation, the wind farm power factor must be closer to unity or sufficiently far away from its limiting value, 0.95.

In this chapter, wind farm in bus #1 is used to design damping controller using active power modulation and wind farm at bus #6 is used to design controller modulating voltage reference input.

7.3.2 Damping controller

Using reactive power modulation

The damping controller modulates the voltage reference input of the wind farm located at #6. The residue analysis is carried out to find a suitable feedback signal for the damping controller design. Fig. 7.13 shows the residue corresponding to the inter-area mode for transfer function between various feedback signals and voltage reference input of the wind farm. Different feedback signals such as active power, reactive power and active current through all transmission lines are considered. Since most of the transmission lines lie between the Scotland-England corridor, the mode is observable in several signals and hence number of good signals are available with high magnitude of residue.

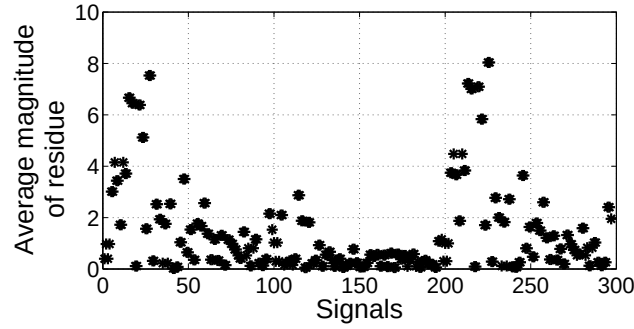


Figure 7.13: Average magnitude of residue for transfer function between different feedback signals and voltage reference input of wind farm at bus #6; GB test system

$$\mathbf{K}(s) = \frac{0.02s^2 + 0.8s}{2.4s^2 + 10.24s + 1} \quad (7.4)$$

Active power signal on a transmission line between buses #6 and #9 is used for the controller design. The transfer function given by (7.4) is designed. The open loop and closed loop eigenvalues of the system with the controller are plotted in Fig. 7.14. It is shown that the inter-area mode damping is improved for all the operating scenarios of the GB network.

The controller is validated using time domain simulation in which a three phase fault is applied for 100msec in bus #24. The angle difference between generators at buses #2 and #23 is plotted in Fig. 7.15 which shows the inter-area mode oscillation with and without controller. The controller is able to effectively damp out the oscillation. The reactive and active power output of DFIG used for damping control

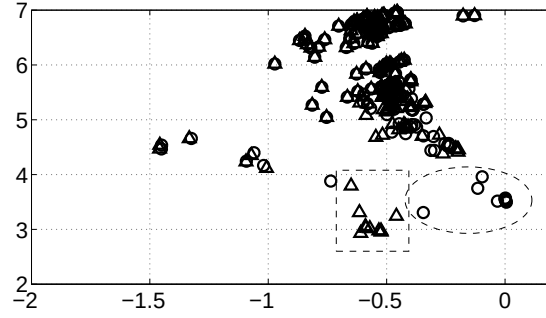


Figure 7.14: Eigenvalues of GB system with damping controller using reactive power modulation. 'o' show open loop eigenvalues and 'Δ' show closed loop eigenvalue. The dotted rectangle encloses closed loop inter-area modes and ellipse encloses open loop inter-area modes

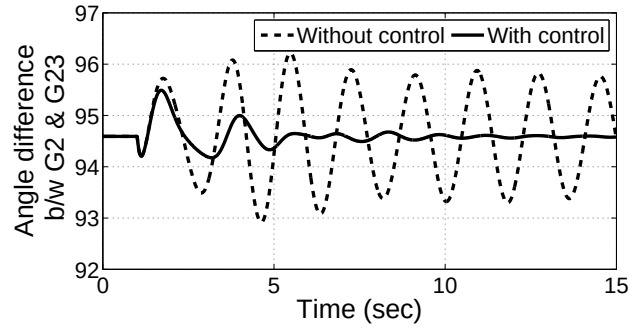


Figure 7.15: Closed loop response of GB system using damping controller modulating reactive power output: Plot shows angle difference between G1 and G23

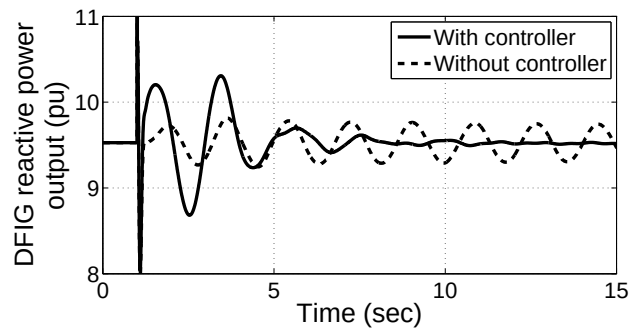


Figure 7.16: Closed loop response of GB system using damping controller modulating reactive power output: Plot shows reactive power output of DFIG used for damping control

is plotted in Fig. 7.17, and Fig. 7.16 respectively. With controller in operation, the reactive power output is high during first two cycles after the fault. The margin of reactive power available for damping control is very important as the wind farms cannot operate power factors less than 0.95. The active power does not vary owing to the decoupled control of the wind farm.

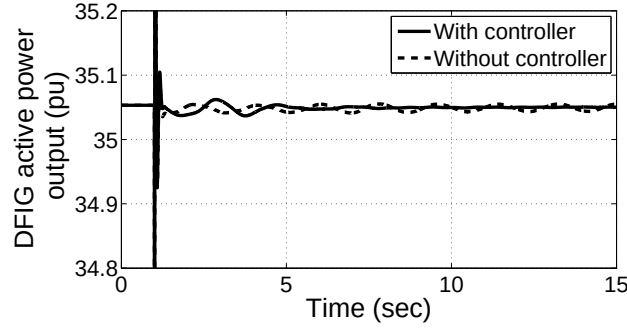


Figure 7.17: Closed loop response of GB system using damping controller modulating reactive power output: Plot shows active power output of DFIG used for damping control

Using active power modulation

The wind farm located at bus #1 is selected to install a damping controller modulating active power output. Using residue analysis, the active power signal through a transmission line connecting buses #6 and #9 is selected as feedback signal. A controller of transfer function given in (7.5) is designed.

$$\mathbf{K}(s) = \frac{0.165s^2 + 0.3s}{0.4s^2 + 10.04s + 1} \quad (7.5)$$

The open and closed loop poles of the system for all the operating conditions using the controller are plotted in Fig. 7.18. The controller shifts the inter-area modes towards left to improve the damping for all the operating conditions.

Similar to the previous case, time domain simulation is run with a three phase fault of 100msec at bus #24. The response is plotted in Fig. 7.19, Fig. 7.21, and Fig. 7.20 where it is shown that the controller effectively damps the oscillation. The active power output is modulated to improve the damping, whereas the change in reactive power is due to the voltage controller.

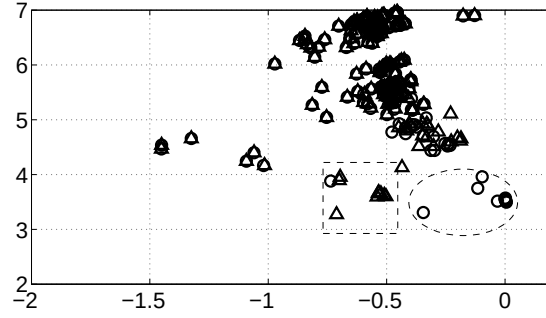


Figure 7.18: Eigenvalues of GB system with damping controller using active power modulation. 'o' show open loop eigenvalues and 'Δ' show closed loop eigenvalue. The dotted rectangle encloses closed loop inter-area modes and ellipse encloses open loop inter-area modes

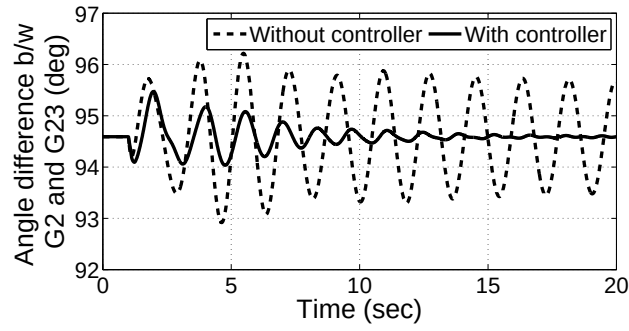


Figure 7.19: Closed loop response of GB system using damping controller modulating active power output: Plot shows angle difference between G1 and G23

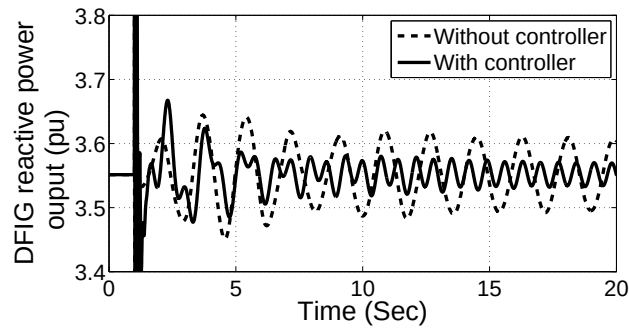


Figure 7.20: Closed loop response of GB system using damping controller modulating active power output: Plot shows reactive power output of DFIG used for damping control

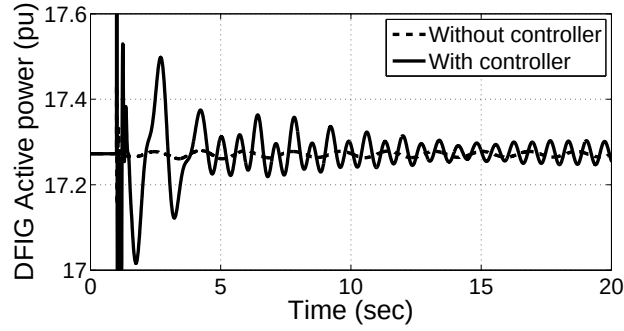


Figure 7.21: Closed loop response of GB system using damping controller modulating active power output: Plot shows active power output of DFIG used for damping control

7.4 Chapter summary

The chapter discusses the possibility of using WTG system as an actuator for damping controller design. The decoupling control of DFIG system, allow the use of active or reactive power modulation for damping control. However, the active power modulation will interfere with torsional mode oscillation of the WTG. It is shown that, through careful selection of feedback signal the negative effect of damping controller on torsional mode can be minimized. Further, the location dependency of WTG on selection of active or reactive power modulation is discussed using the GB test system model. The chapter shows that, WTGs can be used for damping control depending on the location of wind farm.

Chapter 8

Conclusions and Future work

The thesis deals with stability of inter-area oscillations in future power systems. The oscillations are the transmission line bottleneck in many systems. The future power systems will be characterized by higher variability in operating conditions due to large contribution of weather dependent renewable generation, large scale interconnection involving several grids, free electricity market where price takes precedence over economic despatch or technical boundaries, etc. A combined effect of them will create different power flow patterns in transmission network. The stability of inherent oscillatory modes in the ac system is important for providing flexibility required under these operating conditions. The major contribution of the thesis is discussed below.

The first achievement of the thesis is development of a dynamic test system model for GB transmission network. The model contains 34 generators (21-thermal, 5-hydro and 8-wind farm) and 63 buses (29-high voltage buses and 34-generator buses). The model is suitable for analyzing the well observed 0.5Hz Scotland-England inter-area mode with different generation scenarios. The share of wind penetration in GB network will increase by approximately eight folds by year 2020 compared to year 2010. Similarly, several thermal power stations which are close to its working life will be closed. Further, large amount of power will be exchanged between UK and mainland Europe through new and existing inter-connections creating large variation in operating conditions in the network. The dynamic model of GB network is useful to analyze the effect of these operating scenarios of future GB system on the inter-area mode. The generation mix in the dynamic test system model can be varied to simulate different operating scenarios.

The Chapter 5 presents a qualitative behavior of inter-area mode damping with increased wind generation. The study is conducted using two test systems; a two-area test system with a WTG and the GB test system model. Different possible operating

scenarios of two test systems are generated with increased wind penetration. Effect of three factors are considered in the chapter: the effect of change in output of generator participating in inter-area mode, the effect of disconnecting synchronous generator, and the effect of change in inter-area power flow. With increased wind penetration, conventional generating station output, especially thermal generators will be reduced. Some times, the generators will be disconnected from the network. The results show that, change in damping ratio is higher, if change in generation occur in generators participating in inter-area mode, for similar power flow. Similar behavior is observed when generators are disconnected from the network. If the generator have high participation to inter-area mode, the damping will improve. It is also shown that, the change in inter-area mode with change in output of generator participating in the mode is in horizontal direction in the eigenplane. However, a vertical shift of the mode in the eigenplane is observed when synchronous generators are connected/disconnected from the network. This is due to change in effective inertia of the system. The change in inter-area power flow causes the eigenvalue movement in vertical direction in the eigenplane with a frequency increase as inter-area power flow reduces.

In practical power systems, these factors occur in tandem and in different proportions from time to time. This will cause large variation in damping of inter-area mode. In GB test system model, when thermal generators close to wind farm reduced their output, the damping improved. However, when thermal generators in England reduced their output or removed from the network which represents most likely scenario in future, the damping decreased and some times become negative. With higher export of wind power from Scotland to main land Europe through England, the inter-area power flow will increase resulting in poor damping of the inter-area mode.

Power system damping controllers must be installed in the network to improve damping of the mode for all possible operating conditions to achieve future operational objectives. However, it is shown that with increased wind penetration and variation in operating condition, the modal controllability and modal observability, product of which is residue, varies in wide range. Variation in magnitude and angle of residue will affect the performance of damping controllers.

In the Chapter 6, a signal selection approach for power system damping controller design is presented. The method is suitable for selecting signal for FACTS based damping controllers used in power systems with large variation in operating conditions. The underlying idea behind the method is to select a signal with least

variation in magnitude and angle of residue. This will simplify controller design and ensure robust controller performance for large number of operating conditions. The method is based on error covariance matrix. This matrix is computed for each signal over a large number of operating scenarios. For a given signal, the residue error covariance matrix can be represented by an ellipse in two dimensional plane. We compute the area of this ellipse for each signal and the one with least area gives less uncertainty in the residue variation and hence this signal can be accepted to give robust performance. The criteria presented in the chapter is used to design damping controller for a 16 machine test system. Using the proposed signal selection approach a simple low order controller is designed which give robust performance for large number of operating conditions. However in this procedure, a signal having less magnitude of residue may be selected which will increase the control effort or reduce controller performance. Nevertheless, the signal will ensure robust damping controller performance for large number of operating scenarios.

The possibility of using wind farm as actuator for damping controller design is discussed in Chapter 7. Because of its decoupled control, active and reactive power modulation can be used for damping control action. However, the potential negative effect of active power modulation on torsional mode of WTG will deter the manufacturers from installing this control. The thesis shows that, the problem can be minimized by selecting appropriate feedback signal which minimizes the impact on torsional mode. Further, the location dependence of wind farm on choice of active or reactive power modulation is explored using GB test system. It is shown that, when the wind farm is located at one of the areas participating in the mode, the active power modulation is more appropriate. Similarly when the wind farm is located along the tie line connecting two areas participating in the mode, the reactive power modulation can be used. Using GB test system simulation results, the active and reactive power modulation based damping controller is validated.

8.0.1 Future work

The inter-area mode oscillations are complex phenomena which depends on several factors. Some of the further research directions are listed below.

- One of the factors overlooked in this research is the effect of wind farm control parameters on damping. Since wind farms are required to control the voltage at the point of common coupling with grid, its performance may affect damping similar to a SVC operation. The voltage control requirement of wind farm widely differs between grid operators [122, 124], and it is important to analyze

the effect of the controller parameters on inter-area oscillation damping.

- Also of interest for future power system is the interaction between different devices such as wind farms, FACTS devices, HVDC controllers and synchronous machines. In order to make power systems more flexible, several such devices will be brought into the system. They may get placed in close electrical proximity to one another whose interactions can cause instability. Further research using detailed electromagnetic transient based simulation will be essential.
- In this work, it is assumed that the feedback signals are readily available from remote locations. However in practice, issues such as signal delay, difference in delay between multiple feedback signals, loss of one or more signals etc are important factors to be considered. Further work is required to improve the performance of WAMS based damping controller.
- The research has demonstrated that it is possible to improve damping of inter-area mode through active or reactive power modulation. However, the wind farms are different from conventional generating stations as it consists of many WTGs connected through a collector system. For large wind farms, the active power output of individual WTGs is different depending on factors such as wind speed, wind direction, wake effect, collector system configuration etc. Further work is required to find the best division of active power contribution required from each WTG. This is also important in case of reactive power modulation due to the fact that, the WTG closer to the grid may contribute more effectively compared to the one away from the grid. Communication and control issues inside wind farm will also play a major role in damping effectiveness.
- Also, the complex and critical nature of WTG system require more detailed analysis on the effect of active power modulation on torsional mode damping. The wind farm operator may not be willing to take risk on the torsional mode oscillations in the system. A higher order model of the system is required for detailed analysis and controller design validation.
- Further work is underway to improve the dynamic GB system model by introducing FACTS devices, HVDC lines, and interconnections. A more realistic power flow scenario for the GB system for year 2020 is sought considering correlation of wind and load, correlation of wind across the grid, and power flow through inter-connections.

Appendix A

Simulink realization of simple transfer function blocks in Simulink

Assume a first order transfer function of the form,

$$TF = \frac{y}{x} = \frac{1}{1 + sT_a} \quad (\text{A.1})$$

It can be written as

$$y + T_a s y = x \quad (\text{A.2})$$

$$\dot{y} = \frac{1}{T_a} (x - y) \quad (\text{A.3})$$

$$y = \int \dot{y} \quad (\text{A.4})$$

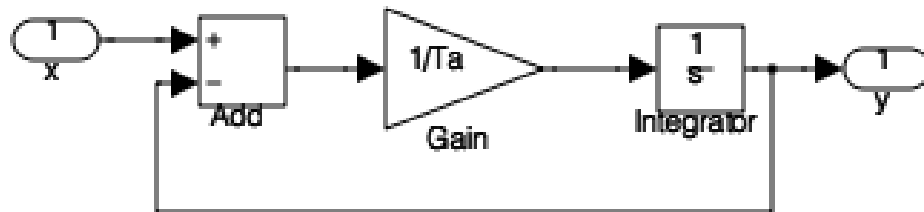


Figure A.1: Simulink representation of a first order transfer function

A pictorial representation of these equation in given in Fig. A.1. The value of x

or y is found by setting $\dot{y} = 0$. The value of y at time $t=0$ needs to be specified in the integrator block.

Lead-lag block

A lead-lag block is split into two branches in order to avoid a differentiation block in simulation.

$$TF = \frac{y}{x} = \frac{1 + sT_a}{1 + sT_b} \quad (\text{A.5})$$

$$= \frac{T_a}{T_b} + \frac{1 - \frac{T_a}{T_b}}{1 + sT_b} \quad (\text{A.6})$$

$$= K1 + \frac{K2}{1 + sT_a} \quad (\text{A.7})$$

Alternatively a big transfer function can be converted to state space form to include in the Simulink model. Simulink implementation of synchronous machine's torque-angle loop and rotor electrical block are shown in Fig. A.2 and Fig. A.3, respectively.

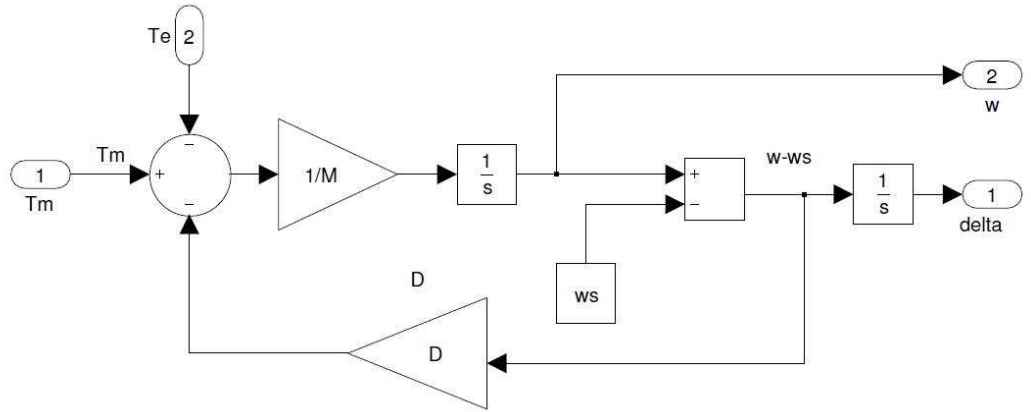


Figure A.2: Implementation of Torque-Angle loop

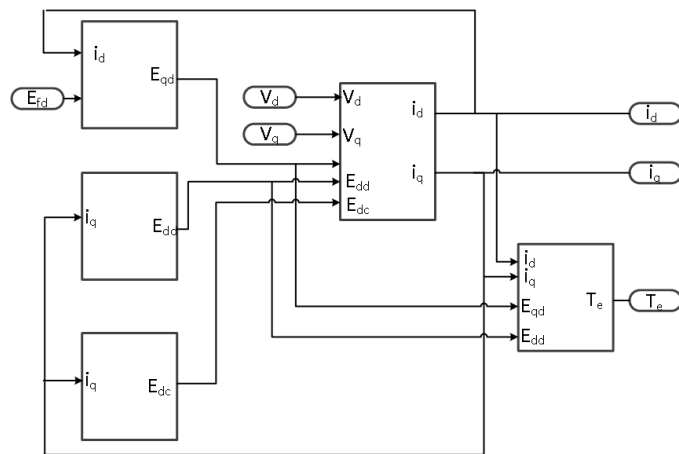


Figure A.3: Implementation of rotor electrical block shown in Fig. 3.2

Appendix B

Two area test system data

Wind generators use standard parameters specified in Appendix . When a generator is removed from the network, corresponding buses and transformer are also removed. All the data is specified in system base MVA = 100 MVA. The data is adopted from [72, 73]. The WTG data is given in Appendix D.

Table B.1: Two area system: Bus data

Bus no	V_b	θ_b	P_g	Q_g	P_L	Q_L	G	B
1	1.03	-0.69	7.00	1.08	0.00	0.00	0.00	0.00
2	1.01	-13.55	3.50	0.18	0.00	0.00	0.00	0.00
3	1.03	0.00	7.00	1.32	0.00	0.00	0.00	0.00
4	1.01	-12.94	3.50	0.76	0.00	0.00	0.00	0.00
5	1.02	-7.07	0.00	0.00	0.00	0.00	0.00	0.00
6	1.01	-16.83	0.00	0.00	0.00	0.00	0.00	0.00
7	1.01	-22.72	0.00	0.00	9.67	1.00	0.00	2.00
8	1.05	-24.72	0.00	0.00	0.00	0.00	0.00	0.00
9	1.00	-26.28	0.00	0.00	17.67	1.00	0.00	3.50
10	1.00	-16.26	0.00	0.00	0.00	0.00	0.00	0.00
11	1.02	-6.40	0.00	0.00	0.00	0.00	0.00	0.00
12	1.00	-9.54	7.00	0.46	0.00	0.00	0.00	0.00

Table B.2: Two area system: Line data

From bus	To bus	Resistance	Reactance	Line charging
----------	--------	------------	-----------	---------------

1	5	0.0000	0.0167	0.00
2	6	0.0000	0.0167	0.00
3	11	0.0000	0.0167	0.00
4	10	0.0000	0.0167	0.00
5	6	0.0025	0.0250	0.0437
10	11	0.0025	0.0250	0.0437
6	7	0.0010	0.0100	0.0175
9	10	0.0010	0.0100	0.0175
7	8	0.011	0.1100	0.1925
7	8	0.011	0.1100	0.1925
8	9	0.011	0.1100	0.1925
8	9	0.011	0.1100	0.1925
10	12	0.001	0.02	0.00

Table B.3: Two area system: Synchronous machine parameters

Mac No.	Bus No.	Base MVA	X_l	R_a	x_d	x'_d	T'_{d0}	x_q	x'_q	T'_{q0}	H
1	1	100	0.022	0.0003	0.2	0.033	8	0.19	0.06	0.4	63
2	2	100	0.022	0.0003	0.2	0.033	8	0.19	0.06	0.4	63
3	3	100	0.022	0.0003	0.2	0.033	8	0.19	0.06	0.4	54
4	4	100	0.022	0.0003	0.2	0.033	8	0.19	0.06	0.4	54

Table B.4: Two area system: Excitation system data

K_A	T_A	T_C	T_B	K_E	T_E	K_F	K_F
40	0.02	0	0	1	0.785	1	0.03

Appendix C

Sixteen Machine five area test system data

All the data is specified in system base MVA = 100 MVA, except WTG data which is in machine base. The WTG data is given in Appendix D. The data is adopted from [12].

Table C.1: 16 machine system: Bus data

Bus no	V_b	θ_b	P_g	Q_g	P_L	Q_L	G	B
1.00	1.00	12.24	2.50	0.15	0.00	0.00	0.00	0.00
2.00	0.99	15.15	5.45	1.76	0.00	0.00	0.00	0.00
3.00	1.00	17.38	6.50	2.14	0.00	0.00	0.00	0.00
4.00	1.00	18.97	6.32	0.77	0.00	0.00	0.00	0.00
5.00	1.01	17.44	5.00	1.37	0.00	0.00	0.00	0.00
6.00	1.05	21.99	7.00	3.01	0.00	0.00	0.00	0.00
7.00	1.03	24.70	5.60	1.20	0.00	0.00	0.00	0.00
8.00	1.03	17.57	5.40	0.87	0.00	0.00	0.00	0.00
9.00	1.03	22.13	8.00	0.52	0.00	0.00	0.00	0.00
10.00	1.01	17.12	5.00	0.23	0.00	0.00	0.00	0.00
11.00	1.00	19.85	10.00	0.15	0.00	0.00	0.00	0.00
12.00	1.02	5.31	13.50	2.91	0.00	0.00	0.00	0.00
13.00	1.01	0.00	36.04	9.10	0.00	0.00	0.00	0.00
14.00	1.00	48.09	17.85	1.06	0.00	0.00	0.00	0.00
15.00	1.00	41.60	10.00	0.71	0.00	0.00	0.00	0.00
16.00	1.00	47.11	40.00	5.06	0.00	0.00	0.00	0.00
17.00	0.99	-6.84	0.00	0.00	60.00	3.00	0.00	0.00
18.00	0.99	40.16	0.00	0.00	24.70	1.23	0.00	0.00

19.00	0.99	13.80	0.00	0.00	0.00	0.00	0.00	0.00
20.00	0.99	12.32	0.00	0.00	6.80	1.03	0.00	0.00
21.00	0.99	11.54	0.00	0.00	2.74	1.15	0.00	0.00
22.00	1.01	16.59	0.00	0.00	0.00	0.00	0.00	0.00
23.00	1.01	16.29	0.00	0.00	2.48	0.85	0.00	0.00
24.00	0.99	8.85	0.00	0.00	3.09	-0.92	0.00	0.00
25.00	1.01	10.71	0.00	0.00	2.24	0.47	0.00	0.00
26.00	1.01	9.14	0.00	0.00	1.39	0.17	0.00	0.00
27.00	1.00	7.13	0.00	0.00	2.81	0.76	0.00	0.00
28.00	1.02	12.49	0.00	0.00	2.06	0.28	0.00	0.00
29.00	1.02	15.29	0.00	0.00	2.84	0.27	0.00	0.00
30.00	1.01	7.05	0.00	0.00	0.00	0.00	0.00	0.00
31.00	1.01	9.82	0.00	0.00	0.00	0.00	0.00	0.00
32.00	1.01	12.43	0.00	0.00	0.00	0.00	0.00	0.00
33.00	1.01	8.65	0.00	0.00	1.12	0.00	0.00	0.00
34.00	1.02	3.33	0.00	0.00	0.00	0.00	0.00	0.00
35.00	1.02	3.32	0.00	0.00	0.00	0.00	0.00	0.00
36.00	1.00	-0.41	0.00	0.00	1.02	-0.19	0.00	0.00
37.00	0.99	7.47	0.00	0.00	0.00	0.00	0.00	0.00
38.00	1.01	9.85	0.00	0.00	0.00	0.00	0.00	0.00
39.00	0.98	-8.22	0.00	0.00	2.67	0.13	0.00	0.00
40.00	1.03	16.66	0.00	0.00	0.66	0.24	0.00	0.00
41.00	1.00	46.55	0.00	0.00	10.00	2.50	0.00	0.00
42.00	1.00	40.74	0.00	0.00	11.50	2.50	0.00	0.00
43.00	0.99	-7.48	0.00	0.00	0.00	0.00	0.00	0.00
44.00	0.99	-7.51	0.00	0.00	2.68	0.05	0.00	0.00
45.00	1.01	3.32	0.00	0.00	2.08	0.21	0.00	0.00
46.00	0.99	10.77	0.00	0.00	1.51	0.28	0.00	0.00
47.00	1.03	8.36	0.00	0.00	2.03	0.33	0.00	0.00
48.00	1.03	10.38	0.00	0.00	2.41	0.02	0.00	0.00
49.00	0.98	14.11	0.00	0.00	1.64	0.29	0.00	0.00
50.00	1.01	20.55	0.00	0.00	1.00	-1.47	0.00	0.00
51.00	1.02	7.43	0.00	0.00	3.37	-1.22	0.00	0.00
52.00	0.98	6.54	0.00	0.00	1.58	0.30	0.00	0.00
53.00	1.01	7.62	0.00	0.00	2.53	1.19	0.00	0.00
54.00	1.00	9.64	0.00	0.00	0.00	0.00	0.00	0.00

55.00	0.98	6.27	0.00	0.00	3.22	0.02	0.00	0.00
56.00	0.95	5.03	0.00	0.00	5.00	1.84	0.00	0.00
57.00	0.95	6.11	0.00	0.00	0.00	0.00	0.00	0.00
58.00	0.96	6.87	0.00	0.00	0.00	0.00	0.00	0.00
59.00	0.96	4.35	0.00	0.00	2.34	0.84	0.00	0.00
60.00	0.96	3.75	0.00	0.00	5.22	1.77	0.00	0.00
61.00	0.99	3.27	0.00	0.00	1.04	1.25	0.00	0.00
62.00	0.97	9.65	0.00	0.00	0.00	0.00	0.00	0.00
63.00	0.96	8.70	0.00	0.00	0.00	0.00	0.00	0.00
64.00	0.95	8.72	0.00	0.00	0.09	0.88	0.00	0.00
65.00	0.96	8.90	0.00	0.00	0.00	0.00	0.00	0.00
66.00	0.96	7.16	0.00	0.00	0.00	0.00	0.00	0.00
67.00	0.96	6.99	0.00	0.00	3.20	1.53	0.00	0.00
68.00	0.98	8.67	0.00	0.00	3.29	0.32	0.00	0.00

Table C.2: 16 machine system: Line data

From bus	To bus	Resistance	Reactance	Line charging
54.00	1.00	0.00000	0.0181	0.0000
58.00	2.00	0.00000	0.0250	0.0000
62.00	3.00	0.00000	0.0200	0.0000
19.00	4.00	0.00070	0.0142	0.0000
20.00	5.00	0.00090	0.0180	0.0000
22.00	6.00	0.00000	0.0143	0.0000
23.00	7.00	0.00050	0.0272	0.0000
25.00	8.00	0.00060	0.0232	0.0000
29.00	9.00	0.00080	0.0156	0.0000
31.00	10.00	0.00000	0.0260	0.0000
32.00	11.00	0.00000	0.0130	0.0000
36.00	12.00	0.00000	0.0075	0.0000
17.00	13.00	0.00000	0.0033	0.0000
41.00	14.00	0.00000	0.0015	0.0000
42.00	15.00	0.00000	0.0015	0.0000
18.00	16.00	0.00000	0.0030	0.0000
36.00	17.00	0.00050	0.0045	0.3200

49.00	18.00	0.00760	0.1141	1.1600
50.00	18.00	0.00120	0.0288	2.0600
68.00	19.00	0.00160	0.0195	0.3040
19.00	20.00	0.00070	0.0138	0.0000
68.00	21.00	0.00080	0.0135	0.2548
21.00	22.00	0.00080	0.0140	0.2565
22.00	23.00	0.00060	0.0096	0.1846
23.00	24.00	0.00220	0.0350	0.3610
68.00	24.00	0.00030	0.0059	0.0680
54.00	25.00	0.00700	0.0086	0.1460
25.00	26.00	0.00320	0.0323	0.5310
37.00	27.00	0.00130	0.0173	0.3216
26.00	27.00	0.00140	0.0147	0.2396
26.00	28.00	0.00430	0.0474	0.7802
26.00	29.00	0.00570	0.0625	1.0290
28.00	29.00	0.00140	0.0151	0.2490
53.00	30.00	0.00080	0.0074	0.4800
61.00	30.00	0.00095	0.0092	0.5800
30.00	31.00	0.00130	0.0187	0.3330
53.00	31.00	0.00160	0.0163	0.2500
30.00	32.00	0.00240	0.0288	0.4880
32.00	33.00	0.00080	0.0099	0.1680
33.00	34.00	0.00110	0.0157	0.2020
35.00	34.00	0.00010	0.0074	0.0000
34.00	36.00	0.00330	0.0111	1.4500
61.00	36.00	0.00110	0.0098	0.6800
68.00	37.00	0.00070	0.0089	0.1342
31.00	38.00	0.00110	0.0147	0.2470
33.00	38.00	0.00360	0.0444	0.6930
41.00	40.00	0.00600	0.0840	3.1500
48.00	40.00	0.00200	0.0220	1.2800
42.00	41.00	0.00400	0.0600	2.2500
18.00	42.00	0.00400	0.0600	2.2500
17.00	43.00	0.00050	0.0276	0.0000
39.00	44.00	0.00000	0.0411	0.0000
43.00	44.00	0.00010	0.0011	0.0000

35.00	45.00	0.00070	0.0175	1.3900
39.00	45.00	0.00000	0.0839	0.0000
44.00	45.00	0.00250	0.0730	0.0000
38.00	46.00	0.00220	0.0284	0.4300
53.00	47.00	0.00130	0.0188	1.3100
47.00	48.00	0.00125	0.0134	0.8000
46.00	49.00	0.00180	0.0274	0.2700
45.00	51.00	0.00040	0.0105	0.7200
50.00	51.00	0.00090	0.0221	1.6200
37.00	52.00	0.00070	0.0082	0.1319
55.00	52.00	0.00110	0.0133	0.2138
53.00	54.00	0.00350	0.0411	0.6987
54.00	55.00	0.00130	0.0151	0.2572
55.00	56.00	0.00130	0.0213	0.2214
56.00	57.00	0.00080	0.0128	0.1342
57.00	58.00	0.00020	0.0026	0.0434
58.00	59.00	0.00060	0.0092	0.1130
57.00	60.00	0.00080	0.0112	0.1476
59.00	60.00	0.00040	0.0046	0.0780
60.00	61.00	0.00230	0.0363	0.3804
58.00	63.00	0.00070	0.0082	0.1389
62.00	63.00	0.00040	0.0043	0.0729
64.00	63.00	0.00160	0.0435	0.0000
62.00	65.00	0.00040	0.0043	0.0729
64.00	65.00	0.00160	0.0435	0.0000
56.00	66.00	0.00080	0.0129	0.1382
65.00	66.00	0.00090	0.0101	0.1723
66.00	67.00	0.00180	0.0217	0.3660
67.00	68.00	0.00090	0.0094	0.1710
53.00	27.00	0.03200	0.3200	0.4100

Table C.3: 16 machine system: Synchronous machine parameters

Mac No.	Bus No.	Base MVA	X_l	R_a	x_d	x'_d	T'_{d0}	x_q	x'_q	T'_{q0}	H
------------	------------	-------------	-------	-------	-------	--------	-----------	-------	--------	-----------	-----

1.00	1.00	100.00	0.01	0.00	0.10	0.03	10.20	0.07	0.03	1.50	42.00
2.00	2.00	100.00	0.04	0.00	0.30	0.07	6.56	0.28	0.06	1.50	30.20
3.00	3.00	100.00	0.03	0.00	0.25	0.05	5.70	0.24	0.05	1.50	35.80
4.00	4.00	100.00	0.03	0.00	0.26	0.04	5.69	0.26	0.04	1.50	28.60
5.00	5.00	100.00	0.03	0.00	0.33	0.07	5.40	0.31	0.06	0.44	26.00
6.00	6.00	100.00	0.02	0.00	0.25	0.05	7.30	0.24	0.05	0.40	34.80
7.00	7.00	100.00	0.03	0.00	0.30	0.05	5.66	0.29	0.05	1.50	26.40
8.00	8.00	100.00	0.03	0.00	0.29	0.06	6.70	0.28	0.05	0.41	24.30
9.00	9.00	100.00	0.03	0.00	0.21	0.06	4.79	0.21	0.05	1.96	34.50
10.00	10.00	100.00	0.02	0.00	0.17	0.05	9.37	0.12	0.05	1.50	31.00
11.00	11.00	100.00	0.01	0.00	0.13	0.02	4.10	0.12	0.02	1.50	28.20
12.00	12.00	100.00	0.02	0.00	0.10	0.03	7.40	0.10	0.03	1.50	92.30
13.00	13.00	200.00	0.00	0.00	0.01	0.00	5.90	0.01	0.00	1.50	496.00
14.00	14.00	100.00	0.00	0.00	0.02	0.00	4.10	0.02	0.00	1.50	300.00
15.00	15.00	100.00	0.00	0.00	0.02	0.00	4.10	0.02	0.00	1.50	300.00
16.00	16.00	200.00	0.00	0.00	0.02	0.00	7.80	0.02	0.00	1.50	450.00

Table C.4: 16 machine system: Excitation system data

Bus no.	Type	K_A	T_A	T_C	T_B	K_E	T_E	K_F	T_F
1	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
2	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
3	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
4	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
5	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
6	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
7	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
8	DC	40.00	0.02	0.00	0.00	1.00	0.79	0.03	1.00
9	ST	200.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00

Appendix D

Wind turbine generator data

D.0.2 Detailed WTG data

The data is adopted from [85].

Lm	Rs	Rr	Lss	Lrr	Kopt	k	c	Ht	Hg
4	0.005	0.0055	4.04	4.0602	1	0.3	0.01	4	0.4

where

Lm mutual inductance

Rs stator resistance

Rr rotor resistance

Lss stator inductance

Lrr rotor inductance

K drive train shaft stiffness

c drive train damping coefficient

Ht turbine inertia

Hg generator inertia

Cp curve parameters c1 to c10 = {0.5 116 0.4 0 0 5 21 0.08 0.035 0}

D.0.3 Generic Type-3 WTG data

The data is adopted from [86].

Generator converter parameters:

Lpp = 0.8; Lvplsw = 1; Rrpwr = 5; Brkpt = 0.9;

Zerox = 0.5;

Converter control parameters

tr = 0.05; fn = 1; kiv = 5; kpv = 18;

```

tv = 0.05;      tc = 0.15;      kqi = 0.1;      kqv = 40;
Qmax = 0.436; Qmin = -0.436;    Vmax = 1.1;    Vmin = 0.9;
tsp = 5;      kpqrq = 3;      kitrq = 0.6;    tpc = 0.05;
Ipmax = 1.1;  xiqmax = 1.45;    xiqmin = 0.5;
pmax = 1.12;  pmin = 0.04;      prat = 0.45;

Turbine model
D = 0;      H = 4.94;  Kaero = 0.007;

Pitch control model
Kpp = 150;   Kip = 25;      Kpc = 3.0;      Kic = 30.0;
Tpi = 0.3;   PImax = 27.0;  PImin = 0.0;   pirat = 10;

```

D.0.4 Generic Type-4 WTG data

The data is adopted from [86].

Generator converter parameters

```

Lvplsw = 1;      Rrpwr = 5;      Brkpt = 0.7;      Zerox = 0.0;

```

Coverter control parameters

```

kqi = 0.1;      kvi = 120;      Vmax = 1.1;  Vmin = 0.9;
Qmax = 0.4;      Qmin = -0.4;    tr = 0.05;   tc = 0.15;
kiv = 5;      kpv = 18;      fn = 1;      Iphl = 1.11;
Iqhl = 1.25;    tv = 0.05;

```

Turbine model

```

tpw = 0.05;      kpp = 0.08;      kip = 0.1;      tf = 0.08;
kf = 0;          dpmax = 0.1;      dpmin = -0.1;

```

Appendix E

GB system data 2010

All the data is specified in system base MVA = 100 MVA, except WTG data which is in machine base. The WTG data is given in Appendix D. The network structure and generation profile are obtained from the University of Strathclyde, [100, 101]. The bus, line, and dynamic parameters are developed as part of this work.

Table E.1: GB system 2010: Bus data

Bus no	V_b	θ_b	P_g	Q_g	P_L	Q_L	G	B
1	1.01	45.8[W]	3.95	0.44	0.00	0.00	0.00	0.00
2	1.01	45.8[H]	4.55	0.51	0.00	0.00	0.00	0.00
3	1.01	44.7[W]	0.29	0.05	0.00	0.00	0.00	0.00
4	1.01	44.7	12.29	2.20	0.00	0.00	0.00	0.00
5	1.01	37.4[W]	3.21	0.79	0.00	0.00	0.00	0.00
6	1.01	37.4[H]	4.54	1.11	0.00	0.00	0.00	0.00
7	1.01	31.0[W]	0.20	0.03	0.00	0.00	0.00	0.00
8	1.01	31.0	20.34	3.34	0.00	0.00	0.00	0.00
9	1.01	31.0[H]	2.72	0.45	0.00	0.00	0.00	0.00
10	1.01	27.4	8.78	1.32	0.00	0.00	0.00	0.00
11	1.01	24.2[W]	8.01	1.18	0.00	0.00	0.00	0.00
12	1.01	24.2[H]	0.66	0.10	0.00	0.00	0.00	0.00
13	1.01	28.4[W]	1.81	0.12	0.00	0.00	0.00	0.00
14	1.01	28.4	18.56	1.22	0.00	0.00	0.00	0.00
15	1.03	19.8	28.02	4.10	0.00	0.00	0.00	0.00
16	1.03	13.5[W]	1.04	0.12	0.00	0.00	0.00	0.00
17	1.03	13.5	44.49	5.26	0.00	0.00	0.00	0.00
18	1.03	12.1	24.60	2.48	0.00	0.00	0.00	0.00

19	1.03	12.1[H]	8.77	0.89	0.00	0.00	0.00	0.00
20	1.01	16.4	62.40	3.19	0.00	0.00	0.00	0.00
21	1.01	15.4	97.85	6.86	0.00	0.00	0.00	0.00
22	1.02	7.5	16.00	-0.36	0.00	0.00	0.00	0.00
23	1.03	6.6	17.50	0.84	0.00	0.00	0.00	0.00
24	1.03	7.4	26.01	6.93	0.00	0.00	0.00	0.00
25	1.02	4.4	12.48	2.32	0.00	0.00	0.00	0.00
26	1.03	4.4	5.32	1.49	0.00	0.00	0.00	0.00
27	1.02	3.3	3.21	0.43	0.00	0.00	0.00	0.00
28	1.03	2.4	61.49	14.27	0.00	0.00	0.00	0.00
29	1.01	-0.3	16.98	5.08	0.00	0.00	0.00	0.00
30	1.01	4.0	44.07	5.47	0.00	0.00	0.00	0.00
31	1.01	0.0	4.00	-0.05	0.00	0.00	0.00	0.00
32	1.01	2.4 [W]	1.73	0.04	0.00	0.00	0.00	0.00
33	1.01	0.0	12.22	0.30	0.00	0.00	0.00	0.00
34	1.03	-0.9	17.33	1.42	0.00	0.00	0.00	0.00
35	1.00	41.2	0.00	0.00	4.91	1.02	0.00	0.27
36	1.00	40.2	0.00	0.00	5.39	1.13	0.00	0.05
37	0.99	32.8	0.00	0.00	5.83	1.05	0.00	0.00
38	1.00	26.5	0.00	0.00	13.73	3.17	0.00	0.00
39	1.00	22.8	0.00	0.00	5.27	1.28	0.00	0.00
40	1.00	19.6	0.00	0.00	12.35	3.15	0.00	0.00
41	1.01	23.9	0.00	0.00	7.82	1.71	0.00	0.09
42	1.00	23.8	0.00	0.00	1.23	0.37	0.00	0.00
43	1.01	15.7	0.00	0.00	1.36	0.53	0.00	2.33
44	1.02	15.4	0.00	0.00	26.89	4.65	0.00	5.64
45	1.02	9.1	0.00	0.00	35.28	7.60	0.00	7.25
46	1.02	7.7	0.00	0.00	12.48	3.38	0.00	-0.52
47	1.02	6.1	0.00	0.00	26.50	7.66	0.00	5.97
48	1.00	10.0	0.00	0.00	19.23	5.67	0.00	-2.37
49	1.01	11.8	0.00	0.00	27.65	6.95	0.00	4.50
50	1.01	10.9	0.00	0.00	16.87	6.55	0.00	0.13
51	1.02	3.1	0.00	0.00	11.35	3.71	0.00	5.15
52	1.03	2.3	0.00	0.00	56.30	19.35	0.00	37.55
53	1.01	3.0	0.00	0.00	21.20	6.48	0.00	2.92
54	1.01	0.0	0.00	0.00	10.79	3.06	0.00	2.87

55	1.01	0.0	0.00	0.00	7.37	2.02	0.00	5.44
56	1.01	-1.1	0.00	0.00	19.11	6.65	0.00	19.62
57	1.01	-2.0	0.00	0.00	49.71	13.37	0.00	2.04
58	1.01	-2.8	0.00	0.00	14.89	5.28	0.00	4.87
59	0.99	-4.9	0.00	0.00	102.21	29.02	0.00	8.16
60	1.00	-0.6	0.00	0.00	14.95	4.34	0.00	1.72
61	1.01	-2.1	0.00	0.00	4.80	1.38	0.00	1.10
62	1.01	-4.5	0.00	0.00	28.89	8.41	0.00	8.04
63	1.03	-5.3	0.00	0.00	27.06	3.56	0.00	8.35

Table E.2: GB system 2010: Line data

From bus	To bus	Resistance	Reactance	Line charging
1	35	0.0000	0.0203	0.0000
2	35	0.0000	0.0176	0.0000
3	36	0.0000	0.2745	0.0000
4	36	0.0000	0.0065	0.0000
5	37	0.0000	0.0249	0.0000
6	37	0.0000	0.0176	0.0000
7	38	0.0000	0.3968	0.0000
8	38	0.0000	0.0039	0.0000
9	38	0.0000	0.0294	0.0000
10	39	0.0000	0.0091	0.0000
11	40	0.0000	0.0100	0.0000
12	40	0.0000	0.1214	0.0000
13	41	0.0000	0.0441	0.0000
14	41	0.0000	0.0043	0.0000
15	44	0.0000	0.0029	0.0000
16	45	0.0000	0.0767	0.0000
17	45	0.0000	0.0018	0.0000
18	46	0.0000	0.0033	0.0000
19	46	0.0000	0.0091	0.0000
20	49	0.0000	0.0013	0.0000
21	50	0.0000	0.0008	0.0000
22	51	0.0000	0.0050	0.0000

23	52	0.0000	0.0046	0.0000
24	53	0.0000	0.0031	0.0000
25	54	0.0000	0.0064	0.0000
26	55	0.0000	0.0150	0.0000
27	56	0.0000	0.0249	0.0000
28	57	0.0000	0.0013	0.0000
29	59	0.0000	0.0047	0.0000
30	60	0.0000	0.0018	0.0000
31	61	0.0000	0.0092	0.0000
32	61	0.0000	0.0463	0.0000
33	62	0.0000	0.0065	0.0000
34	63	0.0000	0.0046	0.0000
35	36	0.0122	0.0200	0.0856
35	37	0.0070	0.1500	0.0520
35	36	0.0122	0.0200	0.2844
35	37	0.0070	0.1500	0.0520
36	38	0.0004	0.0650	0.4454
36	38	0.0004	0.0650	0.5545
38	41	0.0021	0.0135	0.1174
38	40	0.0013	0.0230	0.1496
38	40	0.0013	0.0230	0.1758
38	39	0.0010	0.0240	0.1250
38	39	0.0010	0.0240	0.1250
38	41	0.0021	0.0135	0.1538
39	40	0.0009	0.0105	0.3825
39	40	0.0015	0.0161	0.5930
40	43	0.0008	0.0085	0.0737
40	43	0.0008	0.0085	0.4635
41	42	0.0004	0.0001	0.7280
41	42	0.0004	0.0001	1.2872
41	40	0.0030	0.2000	0.2939
41	40	0.0030	0.2000	0.2939
42	44	0.0008	0.0175	0.6624
42	44	0.0008	0.0175	0.6624
43	45	0.0016	0.0163	0.4868
43	45	0.0016	0.0163	0.4868

43	44	0.0035	0.0245	0.1898
43	44	0.0049	0.0343	0.2502
44	49	0.0005	0.0084	5.3730
44	49	0.0005	0.0063	1.0636
45	49	0.0007	0.0420	0.3907
45	49	0.0010	0.0420	0.5738
45	47	0.0004	0.0052	0.2498
45	47	0.0004	0.0052	0.2664
45	46	0.0001	0.0085	0.0798
45	46	0.0001	0.0085	0.0798
46	47	0.0010	0.0108	0.3850
46	52	0.0007	0.0090	0.2911
46	52	0.0010	0.0090	0.3835
46	47	0.0010	0.0108	0.3850
47	52	0.0005	0.0070	0.1943
47	52	0.0008	0.0070	0.7759
47	49	0.0014	0.0230	0.6643
47	49	0.0016	0.0230	0.1104
47	48	0.0011	0.0116	1.1745
47	48	0.0008	0.0120	1.2125
48	50	0.0005	0.0160	0.2795
48	50	0.0050	0.0180	0.1466
49	50	0.0003	0.0052	0.3534
49	50	0.0002	0.0017	0.3992
49	48	0.0002	0.0022	0.7592
49	48	0.0002	0.0022	0.5573
50	53	0.0006	0.0141	0.4496
50	53	0.0006	0.0141	0.4496
51	50	0.0010	0.0107	0.2651
51	50	0.0010	0.0107	0.4573
51	56	0.0007	0.0097	0.4566
51	56	0.0007	0.0097	0.4574
52	51	0.0004	0.0018	0.2349
52	51	0.0004	0.0018	0.2349
52	57	0.0014	0.0096	0.4829
52	57	0.0012	0.0096	0.4122

54	60	0.0004	0.0023	0.2249
54	60	0.0004	0.0023	0.2249
54	53	0.0018	0.0213	0.6682
54	53	0.0013	0.0143	0.3656
55	50	0.0015	0.0182	0.9169
55	50	0.0015	0.0182	0.9169
55	59	0.0003	0.0100	0.1586
55	59	0.0003	0.0100	0.1586
55	54	0.0012	0.0048	0.4446
55	54	0.0012	0.0048	0.7000
55	53	0.0004	0.0059	0.2940
55	53	0.0004	0.0059	0.2955
56	50	0.0018	0.0172	0.8403
56	50	0.0018	0.0172	0.6270
56	59	0.0004	0.0041	0.4098
56	59	0.0003	0.0041	0.4290
56	55	0.0002	0.0011	0.1232
56	55	0.0005	0.0061	0.3041
57	63	0.0015	0.0182	0.5300
57	58	0.0009	0.0008	0.9622
57	58	0.0002	0.0007	2.8447
57	56	0.0006	0.0030	0.3468
57	56	0.0004	0.0030	0.2466
57	63	0.0015	0.0182	0.5300
58	62	0.0007	0.0070	0.2388
58	59	0.0010	0.0091	0.2918
58	59	0.0010	0.0091	0.2918
58	62	0.0007	0.0070	0.2388
59	60	0.0002	0.0057	0.5320
59	60	0.0002	0.0057	0.5320
61	60	0.0002	0.0050	0.1797
61	60	0.0002	0.0050	0.1797
62	61	0.0004	0.0071	0.2998
62	61	0.0004	0.0071	0.2998
63	62	0.0005	0.0080	0.3400
63	62	0.0005	0.0080	0.3400

37	38	0.0030	0.0410	0.0044
37	38	0.0030	0.0410	0.0440
37	36	0.0300	0.0770	0.0124

Table E.3: GB system 2010: Synchronous machine parameters

Mac No.	Bus No.	Base MVA	X_l	R_a	x_d	x'_d	T'_{d0}	x_q	x'_q	T'_{q0}	H
2	2	568.3	0.00264	0.0	0.1584	0.0616	5	0.1056	0.1056	1	17.1
4	4	1536	0.00098	0.0	0.1172	0.0195	8	0.1107	0.0358	0.4	147.5
6	6	568.12	0.00264	0.0	0.1584	0.0616	5	0.1056	0.1056	1	17.0
8	8	2543	0.00059	0.0	0.0708	0.0118	8	0.0669	0.0216	0.4	254.3
9	9	340	0.00441	0.0	0.2647	0.1029	5	0.1765	0.1764	1	10.2
10	10	1097.2	0.00137	0.0	0.1640	0.0273	8	0.1549	0.0501	0.4	105.3
12	12	82.4	0.01820	0.0	1.0922	0.4248	5	0.7282	0.7281	1	2.5
14	14	2320	0.00065	0.0	0.0776	0.0129	8	0.0733	0.0237	0.4	232
15	15	3503	0.00043	0.0	0.0514	0.0086	8	0.0485	0.0157	0.4	350.3
17	17	5561	0.00027	0.0	0.0323	0.0054	8	0.0306	0.0099	0.4	533.9
18	18	3075	0.00049	0.0	0.0585	0.0098	8	0.0553	0.0179	0.4	258.3
19	19	1096	0.00137	0.0	0.0821	0.0319	5	0.0547	0.0547	1	32.9
20	20	7800	0.00019	0.0	0.0230	0.0038	8	0.0218	0.0070	0.4	748.8
21	21	12231	0.00012	0.0	0.0147	0.0025	8	0.0139	0.0045	0.4	1223.1
22	22	2000	0.00075	0.0	0.09	0.0150	8	0.0850	0.0275	0.4	168
23	23	2188	0.00068	0.0	0.0822	0.0137	8	0.0777	0.0251	0.4	183.8
24	24	3251.8	0.00046	0.0	0.0553	0.0092	8	0.0523	0.0169	0.4	273.2
25	25	1560	0.00096	0.0	0.1154	0.0192	8	0.1090	0.0352	0.4	112.3
26	26	665	0.00225	0.0	0.2706	0.0451	8	0.2556	0.0827	0.4	47.9
27	27	401.1	0.00374	0.0	0.4487	0.0748	8	0.4238	0.1371	0.4	28.9
28	28	7686.01	0.00019	0.0	0.0234	0.0039	8	0.0221	0.0071	0.4	768.6
29	29	2123	0.00071	0.0	0.0848	0.0141	8	0.0801	0.0259	0.4	178.3
30	30	5509	0.00027	0.0	0.0326	0.0054	8	0.0309	0.0099	0.4	550.9
31	31	1082	0.00138	0.0	0.1663	0.0277	8	0.1571	0.0508	0.4	77.9
33	33	1528	0.00098	0.0	0.1178	0.0196	8	0.1113	0.0359	0.4	110.0
34	34	2166	0.00069	0.0	0.0831	0.0139	8	0.0785	0.0254	0.4	216.6

Table E.4: GB system 2010: Excitation system data

Bus no.	Type	K_A	T_A	T_C	T_B	K_E	T_E	K_F	T_F
2	ST	120	0.02	0	0	1	0.785	0.03	1
4	ST	120	0.02	0	0	1	0.785	0.03	1
6	ST	120	0.02	0	0	1	0.785	0.03	1
8	ST	120	0.02	0	0	1	0.785	0.03	1
9	ST	120	0.02	0	0	1	0.785	0.03	1
10	ST	120	0.02	0	0	1	0.785	0.03	1
12	ST	120	0.02	0	0	1	0.785	0.03	1
14	ST	120	0.02	0	0	1	0.785	0.03	1
15	ST	120	0.02	0	0	1	0.785	0.03	1
17	ST	120	0.02	0	0	1	0.785	0.03	1
18	ST	120	0.02	0	0	1	0.785	0.03	1
19	ST	120	0.02	0	0	1	0.785	0.03	1
20	ST	120	0.02	0	0	1	0.785	0.03	1
21	ST	120	0.02	0	0	1	0.785	0.03	1
22	ST	120	0.02	0	0	1	0.785	0.03	1
23	ST	120	0.02	0	0	1	0.785	0.03	1
24	ST	120	0.02	0	0	1	0.785	0.03	1
25	ST	120	0.02	0	0	1	0.785	0.03	1
26	ST	120	0.02	0	0	1	0.785	0.03	1
27	ST	120	0.02	0	0	1	0.785	0.03	1
28	ST	120	0.02	0	0	1	0.785	0.03	1
29	ST	120	0.02	0	0	1	0.785	0.03	1
30	ST	120	0.02	0	0	1	0.785	0.03	1
31	ST	120	0.02	0	0	1	0.785	0.03	1
33	ST	120	0.02	0	0	1	0.785	0.03	1
34	ST	120	0.02	0	0	1	0.785	0.03	1

Appendix F

GB system data 2020

All the data is specified in system base MVA = 100 MVA, except WTG data which is in machine base. The WTG data is given in Appendix D. The network structure and generation profile are obtained from the University of Strathclyde, [100, 101]. The bus, line, and dynamic parameters are developed as part of this work.

Table F.1: GB system 2020: Bus data

Bus no	V_b	θ_b	P_g	Q_g	P_L	Q_L	G	B
1	1.01	36.99	3.95	-0.55	0.00	0.00	0	0.00
2	1.01	39.63	4.55	0.00	0.00	0.00	0	0.00
3	1.02	5.04	0.29	0.00	0.00	0.00	0	0.00
4	1.04	39.86	12.29	3.68	0.00	0.00	0	0.00
5	1.00	28.93	3.21	-0.27	0.00	0.00	0	0.00
6	1.02	31.57	4.54	1.31	0.00	0.00	0	0.00
7	1.02	22.92	0.20	0.02	0.00	0.00	0	0.00
8	1.03	27.27	20.34	4.62	0.00	0.00	0	0.00
9	1.03	25.49	2.72	0.85	0.00	0.00	0	0.00
10	1.02	23.86	8.78	1.03	0.00	0.00	0	0.00
11	1.02	16.38	8.01	2.24	0.00	0.00	0	0.00
12	1.01	19.02	0.66	-0.04	0.00	0.00	0	0.00
13	1.01	20.63	1.81	-0.32	0.00	0.00	0	0.00
14	1.01	25.08	18.56	0.40	0.00	0.00	0	0.00
15	1.03	16.86	28.02	3.65	0.00	0.00	0	0.00
16	1.02	6.37	1.04	-0.33	0.00	0.00	0	0.00
17	1.03	10.72	44.49	5.14	0.00	0.00	0	0.00
18	1.03	9.39	24.60	2.50	0.00	0.00	0	0.00

19	1.03	7.61	8.77	1.03	0.00	0.00	0	0.00
20	1.01	13.66	62.40	3.73	0.00	0.00	0	0.00
21	1.01	12.87	97.85	7.72	0.00	0.00	0	0.00
22	1.02	4.92	16.00	-0.05	0.00	0.00	0	0.00
23	1.03	4.01	17.50	1.04	0.00	0.00	0	0.00
24	1.03	5.08	26.01	6.88	0.00	0.00	0	0.00
25	1.02	2.41	12.48	2.37	0.00	0.00	0	0.00
26	1.03	2.11	5.32	1.47	0.00	0.00	0	0.00
27	1.02	1.04	3.21	0.47	0.00	0.00	0	0.00
28	1.03	0.10	61.49	14.40	0.00	0.00	0	0.00
29	1.01	-2.53	16.98	5.01	0.00	0.00	0	0.00
30	1.01	2.14	44.07	5.92	0.00	0.00	0	0.00
31	1.01	0.00	12.41	0.40	0.00	0.00	0	0.00
32	1.01	-3.19	1.73	-0.01	0.00	0.00	0	0.00
33	1.01	-1.78	12.22	0.55	0.00	0.00	0	0.00
34	1.03	-2.96	17.33	1.66	0.00	0.00	0	0.00
35	1.01	36.35	0.00	0.00	4.99	1.02	0	0.27
36	1.02	34.94	0.00	0.00	5.46	1.13	0	0.05
37	1.00	28.27	0.00	0.00	5.91	1.05	0	0.00
38	1.01	22.28	0.00	0.00	13.93	3.17	0	0.00
39	1.01	18.82	0.00	0.00	5.35	1.28	0	0.00
40	1.01	15.75	0.00	0.00	12.53	3.15	0	0.00
41	1.01	19.99	0.00	0.00	7.94	1.71	0	0.09
42	1.01	19.91	0.00	0.00	1.25	0.37	0	0.00
43	1.02	12.03	0.00	0.00	1.38	0.53	0	2.33
44	1.02	11.91	0.00	0.00	27.28	4.65	0	5.64
45	1.02	5.74	0.00	0.00	35.79	7.60	0	7.25
46	1.02	4.41	0.00	0.00	12.67	3.38	0	-0.52
47	1.02	2.82	0.00	0.00	26.89	7.66	0	5.97
48	1.00	6.74	0.00	0.00	19.51	5.67	0	-2.37
49	1.01	8.55	0.00	0.00	28.05	6.95	0	4.50
50	1.01	7.74	0.00	0.00	17.12	6.55	0	0.13
51	1.02	-0.07	0.00	0.00	11.52	3.71	0	5.15
52	1.03	-0.91	0.00	0.00	57.12	19.35	0	37.55
53	1.01	0.08	0.00	0.00	21.51	6.48	0	2.92
54	1.01	-2.66	0.00	0.00	10.94	3.06	0	2.87

55	1.01	-2.90	0.00	0.00	7.48	2.02	0	5.44
56	1.01	-4.02	0.00	0.00	19.39	6.65	0	19.62
57	1.01	-4.89	0.00	0.00	50.43	13.37	0	2.04
58	1.01	-5.59	0.00	0.00	15.11	5.28	0	4.87
59	0.99	-7.75	0.00	0.00	103.70	29.02	0	8.16
60	1.00	-3.01	0.00	0.00	15.17	4.34	0	1.72
61	1.01	-3.84	0.00	0.00	4.87	1.38	0	1.10
62	1.01	-6.88	0.00	0.00	29.31	8.41	0	8.04
63	1.03	-7.89	0.00	0.00	27.45	3.56	0	8.35

Table F.2: GB system 2020: Line data

From bus	To bus	Resistance	Reactance	Line charging
1	35	0.00000	0.00289	0.00000
2	35	0.00000	0.01286	0.00000
3	46	0.00000	0.03921	0.00000
4	36	0.00000	0.00739	0.00000
5	37	0.00000	0.00356	0.00000
6	37	0.00000	0.01287	0.00000
7	38	0.00000	0.05669	0.00000
8	38	0.00000	0.00446	0.00000
9	38	0.00000	0.02150	0.00000
10	39	0.00000	0.01035	0.00000
11	40	0.00000	0.00143	0.00000
12	40	0.00000	0.08871	0.00000
13	41	0.00000	0.00630	0.00000
14	41	0.00000	0.00489	0.00000
15	44	0.00000	0.00324	0.00000
16	45	0.00000	0.01096	0.00000
17	45	0.00000	0.00204	0.00000
18	46	0.00000	0.00369	0.00000
19	46	0.00000	0.00667	0.00000
20	49	0.00000	0.00146	0.00000
21	50	0.00000	0.00093	0.00000
22	51	0.00000	0.00568	0.00000

23	52	0.00000	0.00519	0.00000
24	53	0.00000	0.00349	0.00000
25	54	0.00000	0.00728	0.00000
26	55	0.00000	0.01707	0.00000
27	56	0.00000	0.02830	0.00000
28	57	0.00000	0.00148	0.00000
29	59	0.00000	0.00535	0.00000
30	60	0.00000	0.00206	0.00000
31	61	0.00000	0.00545	0.00000
32	61	0.00000	0.00661	0.00000
33	62	0.00000	0.00743	0.00000
34	63	0.00000	0.00524	0.00000
35	36	0.01220	0.02000	0.08560
35	37	0.00700	0.15000	0.05200
35	36	0.01220	0.02000	0.28440
35	37	0.00700	0.15000	0.05200
36	38	0.00040	0.06500	0.44540
36	38	0.00040	0.06500	0.55450
38	41	0.00211	0.01350	0.11740
38	40	0.00130	0.02300	0.14960
38	40	0.00130	0.02300	0.17580
38	39	0.00100	0.02400	0.12500
38	39	0.00100	0.02400	0.12500
38	41	0.00210	0.01350	0.15380
39	40	0.00085	0.01051	0.38254
39	40	0.00151	0.01613	0.59296
40	43	0.00078	0.00852	0.07370
40	43	0.00078	0.00852	0.46350
41	42	0.00040	0.00010	0.72800
41	42	0.00040	0.00010	1.28720
41	40	0.00300	0.20000	0.29390
41	40	0.00300	0.20000	0.29390
42	44	0.00083	0.01750	0.66240
42	44	0.00083	0.01750	0.66240
43	45	0.00164	0.01630	0.48680
43	45	0.00164	0.01630	0.48680

43	44	0.00352	0.02453	0.18980
43	44	0.00492	0.03430	0.25020
44	49	0.00053	0.00835	5.37300
44	49	0.00052	0.00630	1.06360
45	49	0.00070	0.04200	0.39070
45	49	0.00099	0.04200	0.57380
45	47	0.00040	0.00520	0.24980
45	47	0.00040	0.00520	0.26640
45	46	0.00010	0.00850	0.07980
45	46	0.00010	0.00850	0.07980
46	47	0.00096	0.01078	0.38500
46	52	0.00074	0.00900	0.29110
46	52	0.00097	0.00900	0.38350
46	47	0.00096	0.01078	0.38500
47	52	0.00049	0.00700	0.19430
47	52	0.00084	0.00700	0.77590
47	49	0.00137	0.02300	0.66430
47	49	0.00164	0.02300	0.11040
47	48	0.00107	0.01163	1.17450
47	48	0.00082	0.01201	1.21250
48	50	0.00050	0.01600	0.27950
48	50	0.00500	0.01800	0.14660
49	50	0.00033	0.00520	0.35340
49	50	0.00016	0.00172	0.39920
49	48	0.00019	0.00222	0.75920
49	48	0.00018	0.00222	0.55730
50	53	0.00056	0.01410	0.44960
50	53	0.00056	0.01410	0.44960
51	50	0.00100	0.01072	0.26510
51	50	0.00100	0.01072	0.45730
51	56	0.00068	0.00970	0.45660
51	56	0.00069	0.00970	0.45740
52	51	0.00042	0.00180	0.23490
52	51	0.00042	0.00180	0.23490
52	57	0.00138	0.00960	0.48290
52	57	0.00117	0.00960	0.41220

54	60	0.00035	0.00230	0.22490
54	60	0.00035	0.00230	0.22490
54	53	0.00178	0.02130	0.66820
54	53	0.00132	0.01430	0.36560
55	50	0.00145	0.01824	0.91690
55	50	0.00145	0.01824	0.91690
55	59	0.00025	0.01000	0.15860
55	59	0.00025	0.01000	0.15860
55	54	0.00120	0.00480	0.44460
55	54	0.00120	0.00480	0.70000
55	53	0.00037	0.00590	0.29400
55	53	0.00037	0.00590	0.29550
56	50	0.00178	0.01720	0.84030
56	50	0.00178	0.01720	0.62700
56	59	0.00037	0.00410	0.40980
56	59	0.00034	0.00410	0.42900
56	55	0.00019	0.00111	0.12320
56	55	0.00048	0.00610	0.30410
57	63	0.00151	0.01820	0.53000
57	58	0.00086	0.00080	0.96220
57	58	0.00023	0.00070	2.84470
57	56	0.00055	0.00300	0.34680
57	56	0.00039	0.00300	0.24660
57	63	0.00151	0.01820	0.53000
58	62	0.00068	0.00700	0.23880
58	59	0.00104	0.00910	0.29180
58	59	0.00104	0.00910	0.29180
58	62	0.00068	0.00700	0.23880
59	60	0.00020	0.00570	0.53200
59	60	0.00020	0.00570	0.53200
61	60	0.00020	0.00503	0.17970
61	60	0.00020	0.00503	0.17970
62	61	0.00038	0.00711	0.29980
62	61	0.00038	0.00711	0.29980
63	62	0.00051	0.00796	0.34000
63	62	0.00051	0.00796	0.34000

37	38	0.00300	0.04100	0.00440
37	38	0.00300	0.04100	0.04400
37	36	0.03004	0.07700	0.01240

Table F.3: GB system 2020: Synchronous machine parameters

Mac No.	Bus No.	Base MVA	X_l	R_a	x_d	x'_d	T'_{d0}	x_q	x'_q	T'_{q0}	H
2	2	777.4344	0.0019	0.0	0.1158	0.0450	5.0	0.0772	0.0772	1.0	23.3230
4	4	1353.2160	0.0011	0.0	0.1330	0.0222	8.0	0.1256	0.0406	0.4	129.9087
6	6	777.1882	0.0019	0.0	0.1158	0.0450	5.0	0.0772	0.0772	1.0	23.3156
8	8	2240.3830	0.0007	0.0	0.0803	0.0134	8.0	0.0759	0.0245	0.4	224.0383
9	9	465.1200	0.0032	0.0	0.1935	0.0752	5.0	0.1290	0.1290	1.0	13.9536
10	10	966.6332	0.0016	0.0	0.1862	0.0310	8.0	0.1759	0.0569	0.4	92.7968
12	12	112.7232	0.0133	0.0	0.7984	0.3105	5.0	0.5323	0.5323	1.0	3.3817
14	14	2043.9200	0.0007	0.0	0.0881	0.0147	8.0	0.0832	0.0269	0.4	204.3920
15	15	3086.1430	0.0005	0.0	0.0583	0.0097	8.0	0.0551	0.0178	0.4	308.6143
17	17	4899.2410	0.0003	0.0	0.0367	0.0061	8.0	0.0347	0.0112	0.4	470.3271
18	18	2709.0750	0.0006	0.0	0.0664	0.0111	8.0	0.0628	0.0203	0.4	227.5623
19	19	1499.3280	0.0010	0.0	0.0600	0.0233	5.0	0.0400	0.0400	1.0	44.9798
20	20	6871.8000	0.0002	0.0	0.0262	0.0044	8.0	0.0247	0.0080	0.4	659.6928
21	21	10775.5110	0.0001	0.0	0.0167	0.0028	8.0	0.0158	0.0051	0.4	1077.5511
22	22	1762.0000	0.0009	0.0	0.1022	0.0170	8.0	0.0965	0.0312	0.4	126.8640
23	23	1927.6280	0.0008	0.0	0.0934	0.0156	8.0	0.0882	0.0285	0.4	138.7892
24	24	2864.8358	0.0005	0.0	0.0628	0.0105	8.0	0.0593	0.0192	0.4	240.6462
25	25	1374.3600	0.0011	0.0	0.1310	0.0218	8.0	0.1237	0.0400	0.4	98.9539
26	26	585.8650	0.0026	0.0	0.3072	0.0512	8.0	0.2902	0.0939	0.4	42.1823
27	27	353.3691	0.0042	0.0	0.5094	0.0849	8.0	0.4811	0.1556	0.4	25.4426
28	28	6771.3748	0.0002	0.0	0.0266	0.0044	8.0	0.0251	0.0081	0.4	677.1375
29	29	1870.3630	0.0008	0.0	0.0962	0.0160	8.0	0.0909	0.0294	0.4	134.6661
30	30	4853.4290	0.0003	0.0	0.0371	0.0062	8.0	0.0350	0.0113	0.4	485.3429
31	31	1834.2420	0.0008	0.0	0.0981	0.0164	8.0	0.0927	0.0300	0.4	132.0654
33	33	1346.1680	0.0011	0.0	0.1337	0.0223	8.0	0.1263	0.0409	0.4	96.9241
34	34	1908.2460	0.0008	0.0	0.0943	0.0157	8.0	0.0891	0.0288	0.4	183.1916

Table F.4: GB system 2020: Excitation system data

Bus no.	Type	K_A	T_A	T_C	T_B	K_E	T_E	K_F	T_F
2	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
4	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
6	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
8	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
9	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
10	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
12	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
14	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
15	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
17	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
18	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
19	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
20	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
21	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
22	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
23	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
24	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
25	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
26	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
27	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
28	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
29	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
30	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
31	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
33	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00
34	ST	120	0.02	0	0	1.00	0.7850	0.03	1.00

Appendix G

GB system operating conditions

The details of 10 operating conditions of representative GB system is given below. The output of generators are changed to make these operating conditions as discussed in 5.6. Table G.1 show the output of individual generators for the operating conditions. The reactive power output of generators and voltage profile of the network are shown in Fig. G.1 and Fig. G.2, respectively. The dotted lines in the figure show upper and lower limits of the variables.

Table G.1: Installed capacity and active power output of generators and generator groups for different operating conditions. Wind and hydro generators are indicated with w and h respectively

Generators	Capacity	Generation (pu) for different cases									
		1	2	3	4	5	6	7	8	9	10
G1(w)	34.5	3.9	17.0	17.0	17.0	20.8	17.0	17.0	17.0	17.0	19.5
G2(h)	7.8	4.5	4.5	4.5	4.5	0.0	4.5	4.5	4.5	4.5	4.5
G3(w)	2.6	0.3	1.3	1.3	1.3	2.3	1.3	1.3	1.3	1.3	1.4
G4	13.5	12.3	11.1	12.3	4.3	0.0	12.3	12.3	12.3	12.3	0.0
G5(w)	28.1	3.2	13.8	13.8	13.8	17.4	13.8	13.8	13.8	13.8	15.9
G6(h)	7.8	4.5	4.5	4.5	4.5	0.0	4.5	4.5	4.5	4.5	4.5
G7(w)	1.8	0.2	0.9	0.9	0.9	1.6	0.9	0.9	0.9	0.9	1.0
G8	22.4	20.3	18.3	20.3	7.1	0.0	20.3	20.3	20.3	20.3	20.3
G9(h)	4.7	2.7	2.7	2.7	2.7	0.0	2.7	2.7	2.7	2.7	2.7
G10	9.7	8.8	7.9	8.8	3.1	0.0	8.8	8.8	8.8	8.8	8.8
G11(w)	70.1	8.0	34.5	34.5	34.5	32.9	34.5	34.5	34.5	34.5	39.6
G12(h)	1.1	0.7	0.7	0.7	0.7	0.0	0.7	0.7	0.7	0.7	0.7
G13(w)	15.9	1.8	7.8	7.8	7.8	14.5	7.8	7.8	7.8	7.8	9.0
G14	20.4	18.6	16.7	18.6	6.5	0.0	18.6	18.6	18.6	18.6	18.6
G15	30.9	28.0	25.2	28.0	9.8	28.0	28.0	28.0	28.0	28.0	28.0
G16(w)	9.1	1.0	4.5	4.5	4.5	8.3	4.5	4.5	4.5	4.5	5.2
G17	49.0	44.5	40.0	44.5	44.5	37.2	44.5	44.5	0.0	44.5	0.0
G18	27.1	24.6	22.1	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
G19(h)	15.0	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
G20	68.7	62.4	56.2	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4
G21	107.8	97.8	88.1	97.8	97.8	97.8	97.8	97.8	97.8	97.8	97.8
G22	17.6	16.0	14.4	12.0	16.0	16.0	16.0	16.0	16.0	0.0	16.0
G23	19.3	17.5	15.8	13.1	17.5	17.5	17.5	17.5	17.5	17.5	17.5
G24	28.6	26.0	23.4	19.5	26.0	26.0	26.0	26.0	26.0	26.0	26.0
G25	13.7	12.5	11.2	9.4	12.5	12.5	12.5	12.5	12.5	12.5	12.5
G26	5.9	5.3	4.8	4.0	5.3	5.3	5.3	5.3	5.3	0.0	5.3
G27	3.5	3.2	2.9	2.4	3.2	3.2	3.2	3.2	3.2	3.2	3.2
G28	67.7	61.5	55.3	46.1	61.5	61.5	0.0	0.0	61.5	61.5	61.5
G29	18.7	17.0	15.3	12.7	17.0	17.0	17.0	17.0	17.0	0.0	17.0
G30	48.5	44.1	39.7	33.1	44.1	44.1	44.1	44.1	44.1	44.1	44.1
G31	9.5	12.4	7.8	6.5	10.9	0.0	11.2	11.2	0.6	5.0	0.9
G32(w)	15.1	1.7	6.2	12.9	7.4	15.7	12.1	12.1	3.5	6.9	3.5
G33	13.5	12.2	11.0	9.2	9.8	12.2	12.2	12.2	12.2	0.0	12.2
G34	19.1	17.3	15.6	13.0	13.9	17.3	17.3	17.3	17.3	17.3	17.3
Wind	177	20.2	85.8	92.5	87.1	113.5	91.7	91.7	83.1	86.6	95.0
Hydro	36	21.2	21.2	21.2	21.2	8.8	21.2	21.2	21.2	21.2	21.2
Therm	615	562	502	498	497	482	499	499	506	504	494

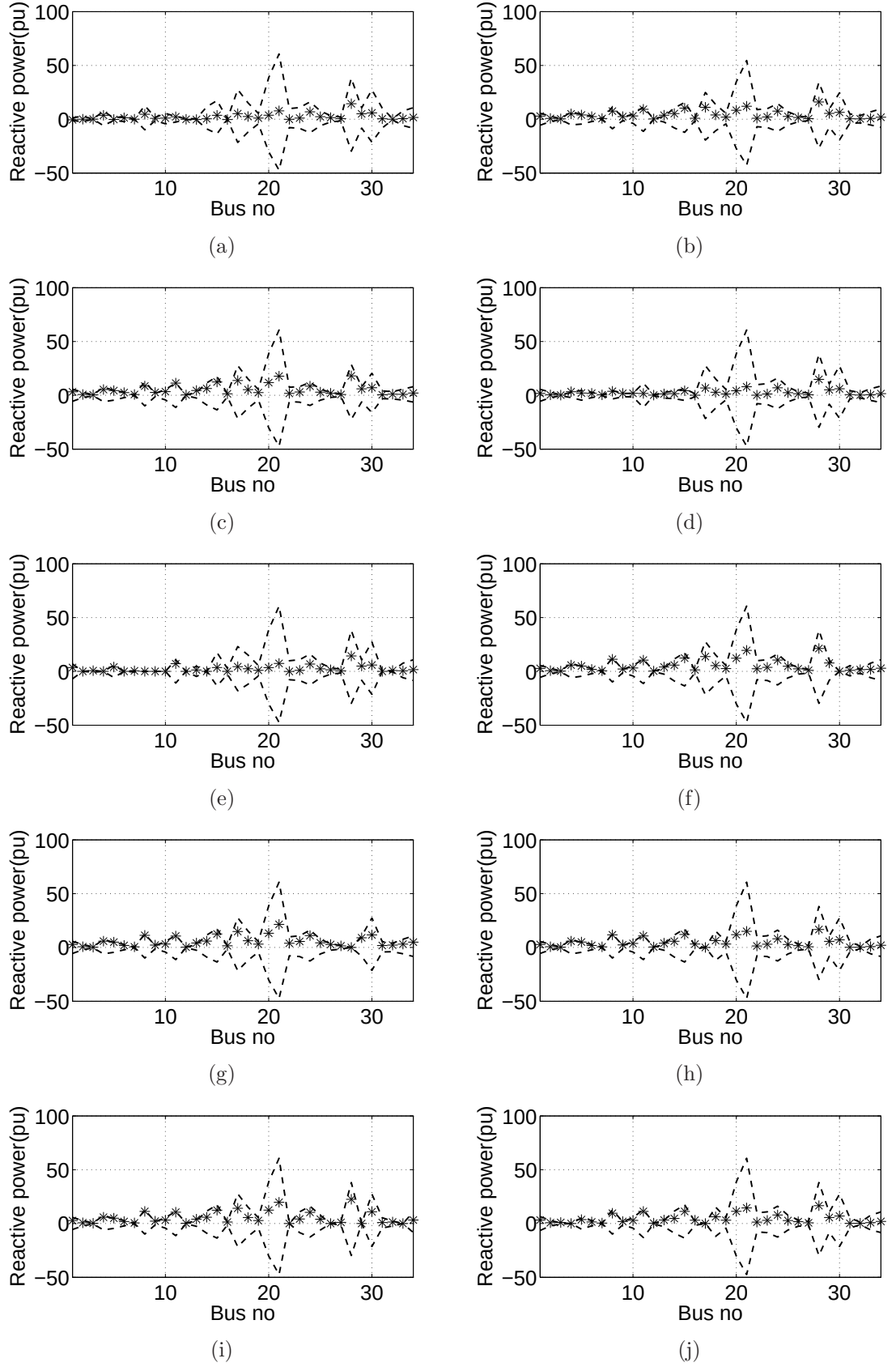


Figure G.1: Reactive power generation of different generators for the 2020 operating conditions of representative GB system. The dotted lines shows the upper and lower limits considering allowable power factor. Plot **a** corresponds to Case-1 and so on.

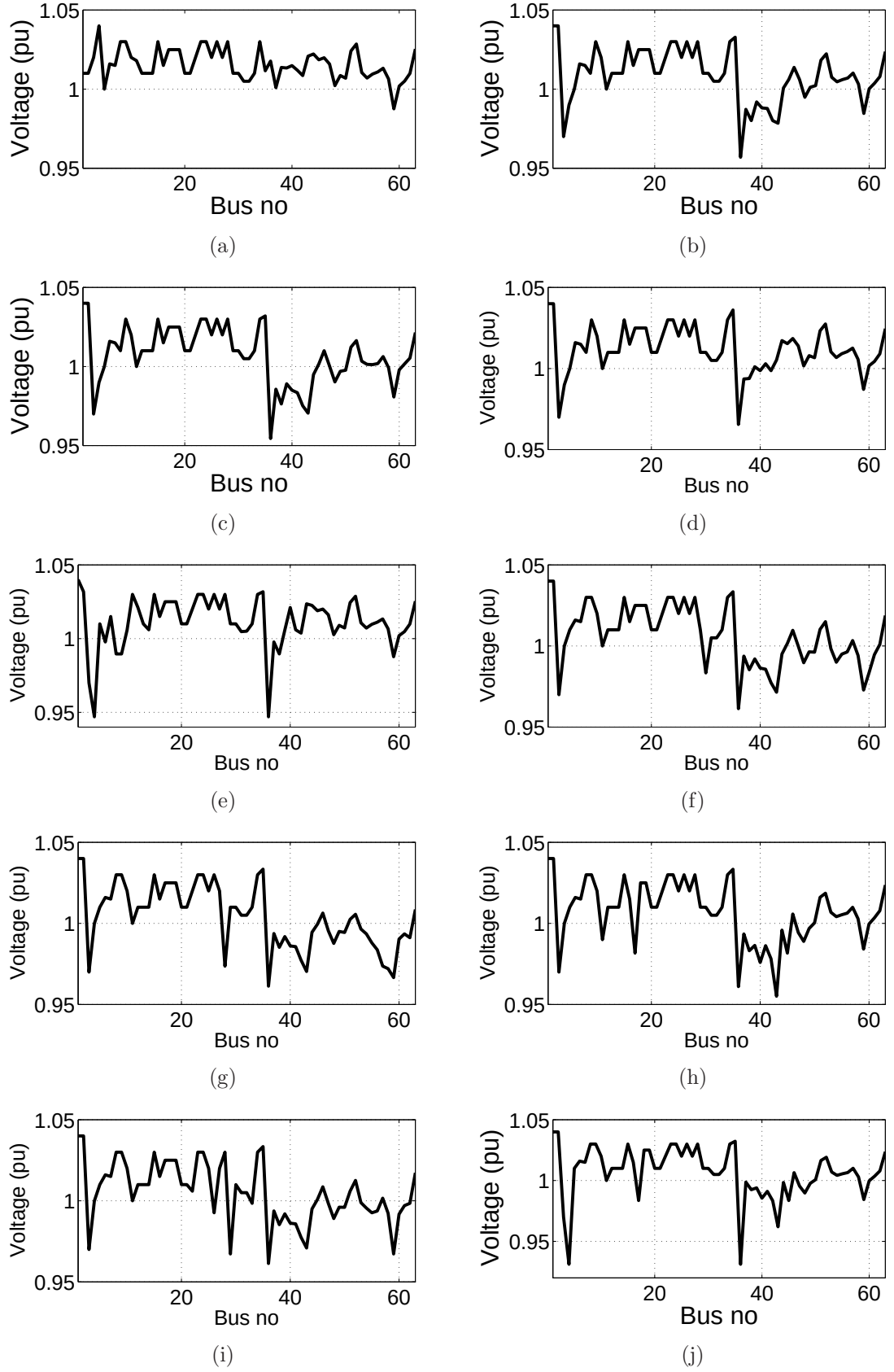


Figure G.2: Voltage profile of representative GB test system for the 2020 operating conditions. Plot **a** corresponds to Case-1 and so on.

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