Structurally constrained WAC design to mitigate low frequency oscillations induced by load disturbances

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Approval Sheet

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Abstract

This thesis introdues a strategy to design of wide area controller for damping the low frequency oscillations. The wide area controller is a state feedback or the output feedback controller. The thesis mainly focusses on the state feedback controller design. In this thesis designing of a state feedback H_∞ controller with structural constraints. With the main ideology of considering the load disturbances, And those disturbances are considered through the dynamic modeling of the ZIP load (which is not in the literature). And the formulation of performance channel with respect to the load disturbance in nominal load power is a challenging task that has been proposed in this thesis.

The design of the small signal model of the power system with generator unit, transmission line and load is required for the design of the wide area controller. The generator unit includes the generator, turbine, exciter, speed governing system and PSS model. The small signal modeling of the load is performed for the ZIP load model.

The study for damping of the interarea oscillations caused in the subsystems connected by tieline for load disturbances utilizing LQR control as well as H_∞ control techniques. The state feedback gain matrix is determined using the LQR control optimization, it considers the entire set of state variables as inputs. Whereas in the case of H_∞ optimization the states which are given as the input to the controller can be choosed such that a structural contraint on the state feedback gain from H_∞ control can be imposed by choosing the required states as inputs to the controller.

A 68-bus, 16- machine system is used for the case study. MATLAB/Simulink environment is used for statespace model design, the controller design and the time-domain analysis of the modeled controllers. H_∞ control is used to design a state feedback matrix with structural constraints involved.

Nomenclature

w	Disturbance input
x	System state vector
u	Control input
y	Measured output
y	Measured output
z	Performance output
A	System state matrix
B_u	Control input matrix
B_w	Disturbance input matrix
C_y	Measured output matrix
D_{yw}	Measurement input-output disturbance matrix
D_{yu}	Measurement input-output control matrix
C_z	Performance output matrix
D_{zw}	Performance input-output disturbance matrix
D_{zu}	Performance input-output control matrix
u_{wac}	Wide area control input to the system
Q	LQR state weight matrix
R	LQR input weight matrix
A_L	Incidence matrix represents location of loads
A_G	Incidence matrix represents location of generator
K_{LQR}	LQR state feedback controller gain matrix
K_∞	H_∞ state feedback controller gain matrix
x_G	States of generator unit
u_G	Inputs of generator unit
y_G	Outputs of generator unit
A_G	State matrix of generator unit
B_G	Control input matrix of generator unit
B_v	Disturbance input matrix of generator unit
X_d	d - axis steady state reactance
X_q	q - axis steady state reactance
X'_d	d - axis transient reactance
X'_q	q - axis transient reactance
X''_d	d - axis sub transient reactance
X''_q	q - axis sub transient reactance
X_{ls}	Armature leakage reactance
R_s	Stator resistance
R_{tl}	Transmission line resistance
R_{fd}	Field resistance
R_{1d}	$1d$ coil resistance
R_{1q}	$1q$ coil resistance
R_{2q}	$2q$ coil resistance
T'_{d0}	d - axis open circuit transient time constant

T'_{q0}	q - axis open circuit transient time constant
T''_{d0}	d - axis open circuit sub transient time constant
T''_{q0}	d - axis open circuit sub transient time constant
H	Rotor inertia constant
d_{fw}	Windage and friction coefficient
ω_s	Synchronous speed in radians per second
Ψ_d	Flux linkages along d - axis
Ψ_q	Flux linkages along q - axis
Ψ_{fd}	Flux linkages along field winding
Ψ_{1d}	Flux linkages along $1d$ - axis
Ψ_{2q}	Flux linkages along $2q$ - axis
Ψ_{1q}	Flux linkages along $1q$ - axis
i_d	d - axis current
i_q	q - axis current
i_{1d}	$1d$ - axis current
i_{1q}	$1q$ - axis current
i_{2q}	$2q$ - axis current
i_{fd}	Field current
X_{md}	Mutual reactance
X_{1d}	$1d$ - axis reactance
X_{1q}	$1q$ - axis reactance
X_{2q}	$2q$ - axis reactance
X_{fd}	Field reactance
v_{fd}	Voltage across field winding
V_D	Voltage across d - axis
V_Q	Voltage across q - axis
δ_r	Rotor angle
T_m	Generator output mechanical torque
ω_{cm}	COI speed with global reference frame
ω_{hp}	Speed of High pressure (HP) turbine
ω_{ip}	Speed of Intermediate pressure (IP) turbine
ω_{lp}	Speed of Low pressure (LP) turbine
T_{hp}	Torque of High pressure (HP) turbine
T_{ip}	Torque of Intermediate pressure (IP) turbine
T_{lp}	Torque of Low pressure (LP) turbine
H_{hp}	HP turbine inertia constant
H_{ip}	IP turbine inertia constant
H_{lp}	LP turbine inertia constant
k_{hpip}, k_{iplp}, k_{lpgn}	Shaft stiffness coefficients
d_{hp}	HP turbine windage and friction coefficient
d_{ip}	IP turbine windage and friction coefficient
d_{lp}	LP turbine windage and friction coefficient
G_{hp}	HP turbine torque factor

G_{ip}	IP turbine torque factor
G_{lp}	LP turbine torque factor
δ_{hp}	Angle of High pressure (LP) turbine
δ_{ip}	Angle of Intermediate pressure (LP) turbine
δ_{lp}	Angle of Low pressure (LP) turbine
ω_{ref}	Valve position
τ_{vl}	Steam valve time constant
τ_{ch}	Steam chest time constant
τ_{rh}	Reheater time constant
τ_{co}	Cross-over time constant
R	Frequency regulation
f_{ch}	Fraction of total turbine power shared by steam chest
f_{rh}	Fraction of total turbine power shared by Reheater
f_{co}	Fraction of total turbine power shared by Cross-over
τ_{sn}	Sensor time constant
τ_{a}	Amplifier time constant
$\tau_{wo,2}$	Washout time constant
G_{a}	Amplifier Gain
$G_{wo,2}$	Washout Gain
v_{sn}	Voltage sensed by sensor
v_{pss}	PSS voltage
$v_{wo,2}$	Washout voltage
G_{ll}	Stabilizer Gain
τ_{ll}	Lead-lag time constant
$\tau_{wo,1}$	Washout time constant
P_{load}	Load active power

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Chapter 1

Introduction

The power system has many components like generator unit, transmission line and loads. These individual components has subsystems in them. For example, generator unit has exciter, turbine, speed governing system and power system stabilizer. And the loads can be of different types like constant power, constant current and constant impedance loads. Now, this system is modeled using the dynamic modeling approach.

The disturbances in power system will lead to instability of the system. There will be oscillations in the system due to these instabilities and those can be damped using different control techniques which are discussed in the literature.

The traditional approach to damping control is to add power system stabilizer in the power system. These are single loop local controllers, because controllers with multiple input signals, especially remote ones, are more expensive to implement. The traditional PSS approach, however, may not be attractive for all systems, especially those with nuclear units. A PSS may have to be placed on a less dominant unit, which is at best sub-optimal from a controllability and observability standpoint.

Unless tuning PSS there are many wide area control techniques which are used for stabilizing the power system disturbances. There are different control techniques for different situations encountered.

There are different instabilities in the system like frequency instability, rotor angle and voltage instability. Rotor angle instability is addressed in thesis. And the instability is caused due to the disturbances in load.

A state feedback control is modeled using two different techniques 1. LQR and 2. H_∞ norm optimizations. And the obtained state feedback matrix is utilized as the wide area input signal to the exciter model to damp the oscillations in rotor angle of the generator. To do so a mathematical model of the power system is required. In succeeding section the desired model for the power system is stated.

1.1 Desired small signal model of the power system

$$\dot{x} = Ax + B_w w + B_u u \quad (1.1)$$

$$z = C_z x + D_{zw} w + D_{zu} u \quad (1.2)$$

$$y = C_y x + D_{yw} w + D_{yu} u \quad (1.3)$$

In the above model, the generator unit, network and load model are considered. A dynamic model for ZIP Load (constant impedance, constant current and constant power) is made. In the literature even if the ZIP load is used the dynamic model concept is not addressed. This thesis has dynamic modeling of the ZIP load as mentioned in 4.1, is a novelty of this thesis.

The performance channel is computed based on the load disturbances. Disturbances in the nominal power is considered. Here, in the above set of equations z is the performance output and y is the measured input. Above state space equations can be rearranged as one plant matrix (P) as follows:

$$P = \left[\begin{array}{c|cc} A & B_w & B_u \\ \hline C_z & D_{zw} & D_{zu} \\ C_y & D_{yw} & D_{yu} \end{array}\right]$$

1.2 Stability studies for power system

Power system stability is the capacity of the system to regain the operating equilibrium at a given initial condition with respect to physical disturbances with most of the system variables bounded. The disturbances are due to load changes, generator outages, line or voltage outage.[1]

The power system instability may be caused due to different conditions. Instability problem has been one of the maintaining synchronous operations. As most of the power generation is obtained from the synchronous generators, the synchronism of all the generators is satisfactory option for the system stability.

The instability in system may be occurred due to sudden change in load voltage. The loads that feed to large areas will lead to severe instability in the system or may lead to collapse of the system loading to block-outs. Small instabilities in the system are very frequent and the system automatically stabilizes by modifying the system parameters to an equilibrium point. System functions satisfactorily under this equilibrium point and that changed system output is supplied to load. The system must be able to survive in various situations such as transmission line shorting, loss of load, loss of generator or the loss of tie line between the subsystems.

For example, if there is any short-circuit in the system and that critical component is isolated by the protective relay then there will be a change in the power transfers, motor speeds and bus voltages. The voltage variations will actuate the motor and generator regulators. The speed changes will actuate the prime mover governors of the generator and motor. The change in tie-line loading will stimulate the generation controls.

In addition to this the devices used for unit protection may have change in the parameters and may lead to their operation and effect the performance of system. Power system stability is divided into rotor angle stability, voltage stability and frequency stability.

1.2.1 Detailed discussion on rotor angle stability

The capacity of system to sustain the synchronism even after a disturbance is induced in it. The stability problem involves the study of electro-mechanical oscillations inherent in power system. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as the rotors oscillate.

1.2.2 Low frequency oscillation in power systems

The oscillations which exist for a very long time in the system are the low frequency oscillation sin the power system, these will cause adverse effects in the system and impose stability issues in the system. The most predominant swinging effect is occurred when the frequency is in the range of $<$2.0 Hz. Specifically, the inter-area modes are addressed by the wide area controllers, and these are effective for the frequencies $<$ 1.0 Hz. The concept of the local and inter area modes are discussed in the below description. Unless local and inter area modes there are also others as stated below. [2]

Now a days the power system, small-signal stability is by enlarge a problem of inadequate damping in the oscillations caused due to disturbances. Widely there are four types of stability concerns as stated below:

- Local area modes: This type of mode is because of the oscillations of a generator w.r.t the power system. The disturbances are seen to be existing at only one generating station or a small area. Hence they are called local modes. Frequency oscillations for this mode is in the range of 1 to 2 Hz

- Inter-area modes: This mode is occurred due to the oscillations in many generators w.r.t. the power system. Inter area modes are caused because of poorly tied areas. The frequency of oscillations for this mode is in the range of 0.1 to 1 Hz. The inter area modes are difficult to control.

- Control modes: These are due to the disturbances caused in the generating unit and the control devices. poorly tuned power system stabilizers, excitation systems speed governing systems, HVDC converters and static var compensators are sources of these control mode instability.

- Torsional modes: These are caused due to the inter connected components of the power system. The predominant disturbances caused in the system are rotational disturbances caused due to turbines and generators. The poorly connected shaft between turbine and generator may cause instability which are called torsional modes. These modes cause interaction with excitation controls, speed governor, HVDC devices.

In this project, the Inter area modes are addressed. And the oscillations caused by these modes can be damped out by the wide area controller.

1.3 Introduction of the dynamical system

The state space model is designed based on the dynamical behavior of a system. Dynamical model of a system is set of mathematical equations explaining in a compact form and in quantitative way how the system evolves over time, usually under the effect of external excitations. [3] The basic concept of small signal modeling of a dynamic and algebraic system is as follows:

$$\frac{dx}{dt} = f(x, y) \tag{1.4}$$
$$g(x, y) = 0 \tag{1.5}$$

Now, let the equilibrium point of the system is (x_0, y_0), then if there is any small perturbation is observed in system the follows equations follow:

$$\frac{d\Delta x}{dt} = \frac{\partial f}{\partial x}(x_0, y_0)\Delta x + \frac{\partial f}{\partial y}(x_0, y_0)\Delta y \tag{1.6}$$
$$\frac{\partial g}{\partial x}(x_0, y_0)\Delta x + \frac{\partial g}{\partial y}(x_0, y_0)\Delta y = 0 \tag{1.7}$$

Usually a dynamical system is represented as follows:

$$\dot{x}(t) = f(x(t), u(t)) \tag{1.8}$$
$$y(t) = g(x(t), u(t)) \tag{1.9}$$

Where, $x(t)$ is called as a single valued and time varying state variables, $u(t)$ is single valued and time varying input, $y(t)$ is the single valued and time varying outputs. f, g are the functions with state variables and control input as the dependents. For a Muti-variable, Multi input and multi output, linear time-invariant system equations are:

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{A}\boldsymbol{X}(t) + \boldsymbol{B}\boldsymbol{U}(t) \tag{1.10}$$
$$\boldsymbol{Y}(t) = \boldsymbol{C}\boldsymbol{X}(t) + \boldsymbol{D}\boldsymbol{U}(t) \tag{1.11}$$

State variables $\boldsymbol{X}(t)$ represent the entire dynamic behavior of the system and are minimal in number. Now they are defined as follows:

$$\boldsymbol{X}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ . \\ . \\ . \\ x_n(t) \end{bmatrix}_{n\text{x}1} \tag{1.12}$$

Then the n state variables define the behavior of system. State space is the n - dimensional space created by the n state variables.

1.4 Stability analysis of a homogeneous system

The stability of system is explained using the homogeneous or natural system which means it doesn't have any external input to the system and response is a natural response. Hence, the dynamical system mentioned in the equations (1.10, 1.11) can be represented as follows:

$$\dot{\boldsymbol{X}} = \boldsymbol{AX} \tag{1.13}$$

The system stability can be determined using the concept of modal matrices. Modal matrices are indifferent from the state matrix $\boldsymbol{A}$. The modal matrix has diagonal elements and can be utilized for better analysis of the system. Whereas the state matrix $\boldsymbol{A}$ is a non-diagonal matrix which will lead to the cross compounded elements and there would be interrelated state elements, these cause a difficulty in performing the stability analysis. Hence, we convert the state matrix to a modal matrix which is a diagonal matrix.

Now we consider a matrix D_p which is similar to that of the state matrix A, and the matrix D_p is also invertible. Now the matrix D_p is the matrix which can be represented as follows:

$$\boldsymbol{X}(t) = \boldsymbol{D_p L(t)} \tag{1.14}$$

Now the new state equation can be obtained by the following set of formulation:

$$\boldsymbol{D_p}\dot{\boldsymbol{L}}(t) = \boldsymbol{AD_pL}(t) \tag{1.15}$$

$$\dot{\boldsymbol{L}}(t) = \boldsymbol{D_p}^{-1}\boldsymbol{AD_pL}(t) \tag{1.16}$$

Now the matrix so obtained after post and pre-multiplication of the state matrix with D_p we get a diagonal matrix. And it is represented by Γ. Now the diagonal matrix will help in decoupling the states into single states. Now let diagonal elements of Γ is represented as the vector as below:

$$\Gamma = [g_1 g_2 ... g_n]^T \tag{1.17}$$

Now the solution for new state equation which is in terms of Γ with the initial condition substituted in it is given as:

$$\dot{l}_i(t) = l^{g_i} l_i(0) fori = 1, 2, 3 \ldots n \tag{1.18}$$

Assessment of the stability of the system based on the eigen values which are calculated above is as follows:

1. Being the eigen values on the left half of the complex plane intends that the system is stable. In equation (1.15), the eigen values move more towards the left half of the complex plane as the time reaches infinity. And the physical meaning of it is that the state variable is settling down to initial condition of the system states. This concept is called as asymptotic stability.

2. Even if one eigen value is on the right side of the complex plane. That means the eigen value has a positive real part. This makes the system unstable, and even one eigen values will make the system stability miserable. And cannot be settled to initial condition. Hence the system will be unstable. This concept is called as the aperiodic instability.

3. If the eigen values are on the imaginary axis of the complex plane. Then the system will oscillate and the oscillations are observed to be the around the x-axis.

1.5 Wide area monitoring system (WAMS)

Wide Area Measurement System is technology which enhances the situational exposure and access in the power system of present and future grids. WAMS basically utilizes the real time synchro phasor data to estimate the present situation of grid that helps us for the betterment in improving the stability and reliability of the grid. WAMS architecture plays a crucial role in real time and data demanding systems. PMU data acquisition, decision making are the important factors which are based on PMU data and the depiction of activities based on judgement, determines the architectural details of WAMS.[4]

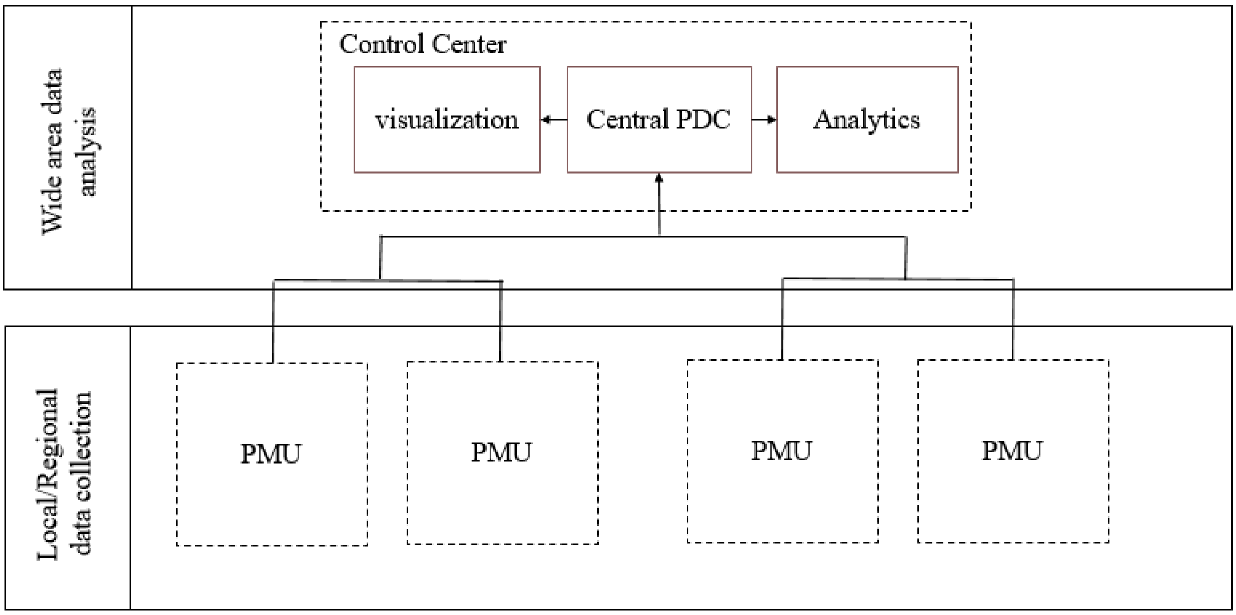

Figure 1.1: Structural design of wide area monitoring system

In a WAMS system, the measurements are obtained from PMUs and the data is synchronized. The data so measured by PMU is obtained from the communication network. This data is received and concentrated at a control device wherein the data is likely to give its appropriate defensive corrective and takes care of few protecting measures. Here the phasor measurement unit is the device which measures the synchro phasor of any measured quantity. I also measures the system frequency and the effect of change at which the measurements are made from sensors. The sensors could be like current transformers (CT) and potential transformers (PT). PMU measures the real active power in MW and reactive power in MVAr.

PMU plays a crucial role in WAMS. As the number of PMUs in the system increase the system will become more accurate in the process of data acquisition and help in the effective utilization of the acquired data.

1.6 Organization of thesis

- **Chapter 1:** The desired structure of the small signal model and the components used in the system is discussed. Causes for the instabilities in power system and low frequency oscillations observed in the system are stated. The concept of dynamical system and how the state space model is formulated from the dynamical equations is mentioned. Eigen value analysis of a system for stability study is also stated. The outline of WAMS and its architecture is explained.

- **Chapter 2:** The literature survey on different control techniques for different contingences and disturbances encountered in the power system is done.

- **Chapter 3:** The small signal model of the generating unit consisting of generator, turbine, speed governing system, excitation system and power system stabilizer. And also how all these the individual components models are integrated is also formulated.

- **Chapter 4:** The network and load model for transmission line and ZIP load respectively. Also the integration of network and load model with the generator model is also formulated in this chapter. The dynamical model of the load is done considering the load disturbance and the disturbance is in nominal power.

- **Chapter 5:** definition of LQR controller and the design of it is mentioned in this section. Definition of H_∞ norm, H_∞ norm optimization is mentioned. Design of performance channel which is done with respective to the load disturbance considered. Also the realization of measured output y as the observable states is discussed. This is how the structural constraint in the state feedback matrix is achieved.

- **Chapter 6:** A case study is made for the 16 machine, 68 bus system and the LQR and H_∞ norm optimization techniques are applied and the dynamic responses of rotor angle is obtained. Also the eigen value correction between the open loop nad closed loop system is observed.

Chapter 2

Literature Survey

It is inferred from [5], There are many components connected in the power system. They are, high voltage transmission network, distributed through the distribution network then supplied to the load. We also have voltage regulators to maintain the proper terminal voltage profile all over the network. Huge power systems consists of many states, multiple inputs through actuators and sensors. As well as we also have multiple outputs from the measuring devices. These huge system cannot be handled by single loop PSS controller for stabilizing the system disturbances. Hence new control techniques emerged for the control of power system.

It is stated in the paper [6], that a thyristor-controlled series capacitor (TCSC) is reinforced to 15-machine, 5-area power system to control the disturbances occurred, to which global signal measurements are given. The method used is linear quadratic Gaussian (LQG) damping control scheme. Loop transfer recovery (LTR) is then applied to reinforce controller robustness in the case of faults and unknown disturbances.

In the following paper [7], For huge power systems there will be tie lines which connect different subsystems, now if these tie lines are poorly connected inter area oscillations are difficult to control using the decentralized controls. The concept of $l-1$ penalty is introduced to structurally constrained optimization problem. And this penalty is imposed on the feedback matrix. Thus improving the performance of the system.

In this paper [8], Design sparse and block sparse feedback gains that minimize the variance amplification using H_2 norm for distributed systems. They incorporated two steps. First, sparsity pattern of feedback gains by incorporating sparsity-promoting penalty functions into the optimal control problem. Second, A optimize feedback gains subject to structural constraints is determined by the identified sparsity patterns. There are several methods of H_2 norm used in the system to incorporate the structural constraint.

In this paper [9], A centralized damping controller is designed for the power grid inter area oscillations. This paper considered the line flows and the current injections as the inputs which is observed to improve the effectiveness of the design. Design of controller is mixture of H_2/H_∞ output-feedback control with regional pole placement and is solved by the linear matrix inequality (LMI) approach. Controller is tuned for achieving the robustness with linear techniques.

In the paper [10], this paper addresses the load aspects in wide area controller design. Both dynamic and static loads are considered. To determine the load dynamic response of the load states

H_2 norm optimization is used.

The paper [11] states that, the oscillations in tie-line connected power system considering that there are many operating points using Linear Quadratic Regulator technique can be damped out. Similarly, H_∞ norm optimization can also be done. And the later is observed to give better performance compared to the prior technique.

In this paper [12], Necessary and sufficient conditions are given for pole/zero cancellations in the close-loop transfer function from input disturbances to error signals in the general H_∞ problem. These pole/zero cancellations can place restrictions on the suitability of particular H_∞ design procedures. This will be shown by reference to a typical two-block design procedure.

In this paper [13], some open problems in the area off dynamic output feedback control design is discussed. Firstly, the structurally constrained decentralized control problem. And its roust and reliable control is also determined. The condition for decentralized and quadratic stabilizability is given and used to provide a solution to the H_2 norm optimization problem. A numerical cross decomposition algorithm is also discussed.

The paper [14], aim is to asses the capability of emerging synchronized phasor measurement technology in improving the overall stability of Hydro-Quebec's transmission system through supplementary modulation of voltage regulators. Singular value and eigen value analysis is performed for system dynamic interactions. Extensive analysis on the implementation of PSS and the synchro condenser placement in the sites is made. PSS with speed sensitive local loop and global loop with wide area measurement is incorporated. The control strategy used here is implemented for five control sites.

In this paper [15], In this paper tuning of power system stabilizer is discussed. The technique is based on linear matrix inequalities (LMI) is utilized for mixed H_2/H_∞ design under pole region constraints. The uncertainties considered are load changes due to generation variations. It is represented using a linear transformation. The design is done by solving the standard LMI problem.

This paper has [16] stated that, The main issue in the huge power system is that the oscillations caused are of low frequency and are not properly controlled. The concept of wide area signal as the control input is fair enough for controlling the system, but to get a better performance the concept of introducing time delay to the wide area signal which is used as control input is an option. But in this case both stabilizing and destabilizing the system is also possible. This can make the system even worse than the present stage. So, two types of delayed feedback techniques are developed in this paper. The wide area transmission signal and the controller is designed based on the concept of H_∞ norm optimization. This problem equation has spectral abscissa and complex stability radius. And another controller is based on higher order mixed sensitivity. Along with this a pole placement constraint is also imposed during the design of the controller. The paper had a comparative study between the low order and a high order controller. The low order controller are more effective than the latter in terms of the performance.

Chapter 3

Small Signal Modeling of the power system

The simplest representation of the linear, time invariant models are follows:

$$\dot{x} = Ax + Bu \tag{3.1}$$

$$y = Cx + Du \tag{3.2}$$

is a set of first order differential equations. Where A is the system matrix, and relates the current state with respect to the state change Δx. B is the control matrix, and determines how the system input effects the state change. If there is no effect of the input on state change then B matrix will be zero. Matrix C represents the relation between output and the system state. Matrix D is feed forward matrix and it lets the output of system effect the input of system directly.The basic feed forward matrix fot most of the components is zero. Hence, the D matrix is the zero matrix.

The small signal modeling of the power system has the following components:

- Generating Unit Model
- Network Model
- Load Model

3.1 Generating Unit

These are the following components of the generating unit:

- Generator
- Turbine
- Speed governor
- Excitation system
- Power system stabilizer

3.1.1 Generator modeling

This section presents the basic dynamic equations of the three phase balanced symmetric synchronous machine. The simplified schematic of the synchronous machine.

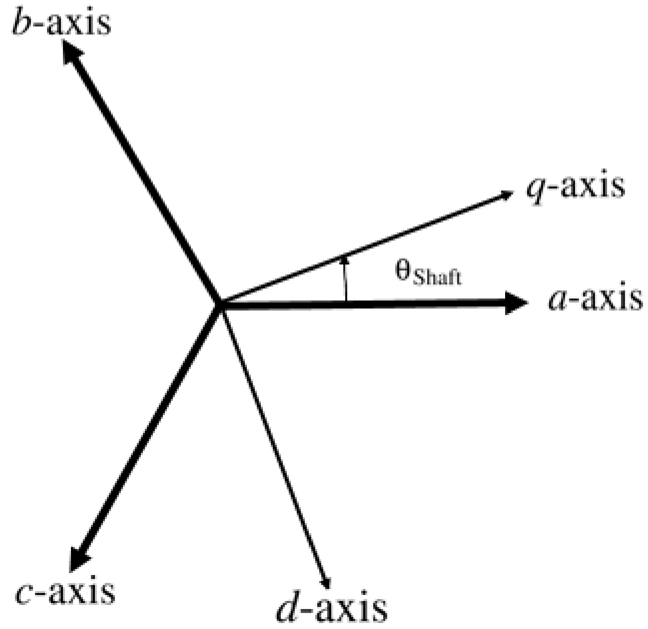

Figure 3.1: Phasor diagram to represent the convention used

The coil orientation, assumed polarities, and the rotor position reference are mentioned in the above figure. The stator windings are 120 electrical degrees apart and are assumed to be having an sinusoidal distribution. The circles with dots and x's represent the direction of current flow in the windings.[17]

In the above figure(3.1) the q - axis leads d-axis, and the angle θ is made by the q-axis with respect to a-axis in the anti-clockwise direction. All the quantities during dynamical modeling are per unit except speed.

Using the above convention abc system is transformed into dq format using following transformation matrix.

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} sin(\theta) & sin(\theta - \frac{2\pi}{3}) & sin(\theta + \frac{2\pi}{3}) \\ cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{3.3}$$

Voltage, current and flux are transformed using the above transformation matrix. This transformation is Park's transformation.

3.1.2 Generator unit modeling

The assumptions made during the modeling of the generator are stator has three coils each in one phase of a, b and c. And the rotor has four coils namely $1q$, $1d$, $2q$, fd. All these coils are symmetrically balanced and are 90 electrical degrees apart.

The generator modeling is done using the dynamic equations which are mentioned as follows:

$$\frac{d\Psi_{d_i}}{dt} = -\omega_{s_i}(R_{s_i} + R_{tl_i})i_{d_i} + \omega_{s_i}\Psi_{q_i} + \omega_{s_i}V_{d_i} \tag{3.4}$$

$$\frac{d\Psi_{q_i}}{dt} = -\omega_{s_i}(R_{s_i} + R_{tl_i})i_{d_i} + \omega_{s_i}\Psi_{q_i} + \omega_{s_i}V_{q_i} \tag{3.5}$$

$$\frac{d\Psi_{fd_i}}{dt} = -\omega_{s_i}R_{fd_i}i_{fd_i} + \omega_{s_i}V_{fd_i} \tag{3.6}$$

$$\frac{d\Psi_{1q_i}}{dt} = -\omega_{s_i}R_{1q_i}i_{1q_i} \tag{3.7}$$

$$\frac{d\Psi_{1d_i}}{dt} = -\omega_{s_i}R_{1d_i}i_{1d_i} \tag{3.8}$$

$$\frac{d\Psi_{2q_i}}{dt} = -\omega_{s_i}R_{2q_i}i_{2q_i} \tag{3.9}$$

$$\frac{d\omega_i}{dt} = \frac{\omega_{s_i}}{2H}(T_{m_i} + \Psi_{d_i}i_{q_i} - \Psi_{q_i}i_{d_i} - d_{fw_i}\omega^2) \tag{3.10}$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_{cm} \tag{3.11}$$

The equations for fluxes are written as follows, they are represented in terms of reactance and current. X_d, X_q are the stator reactances. X_{1d}, X_{1q}, X_{2q}, X_{fd} re the rotor reactances.

$$\Psi_d = (X_d + X_{tl})i_d + X_{md}i_{fd} + X_{md}i_{1d} \tag{3.12}$$

$$\Psi_{fd} = X_{md}i_d + X_{fd}i_{fd} + X_{md}i_{1d} \tag{3.13}$$

$$\Psi_{1d} = X_{md}i_d + X_{md}i_{fd} + X_{1d}i_{1d} \tag{3.14}$$

$$\Psi_q = (X_q + X_{tl})i_q + X_{mq}i_{1q} + X_{mq}i_{2q} \tag{3.15}$$

$$\Psi_{1q} = X_{mq}i_q + X_{1q}i_{1q} + X_{mq}i_{2q} \tag{3.16}$$

$$\Psi_{2q} = X_{mq}i_q + X_{mq}i_{1q} + X_{2q}i_{2q} \tag{3.17}$$

The reactances used in the above equations are called as model parameters and are calculated using the following formulae.

$X_{md} = X_d - X_{ls}$

$X_{mq} = X_q - X_{ls}$

$$X_{fd} = \frac{X_{md}^2}{X_d - X_{d'}}$$
$$X_{1q} = \frac{X_{mq}^2}{X_q - Xq'}$$
$$X_{lfd} = X_{fd} - X_{md}$$
$$X_{l1q} = X_{1q} - X_{mq}$$
$$X_{1d} = X_{md} + \frac{(X_d'' - X_{ls}X_{lfd}X_{md})}{X_{lfd}X_{md} - (X_d'' - X_{ls})X_{md} - (X_d'' - X_{ls})X_{lfd}}$$
$$X_{2q} = X_{mq} + \frac{(X_q'' - X_{ls}X_{l1q}X_{mq})}{X_{l1q}X_{md} - (X_q'' - X_{ls})X_{mq} - (X_q'' - X_{ls})X_{l1q}}$$
$$X_{l1d} = X_{1d} - X_{md}$$
$$X_{l2q} = X_{2q} - X_{mq}$$
$$R_{fd} = \frac{X_{fd}}{\omega_s T'_{d0}}$$
$$R_{1q} = \frac{X_{1q}}{\omega_s T'_{q0}}$$
$$R_{1d} = \frac{1}{\omega_s T''_{do}} \frac{X_{md}X_{lfd} + X_{md}X_{l1d} + X_{l1d}X_{lfd}}{X_{md} + X_{lfd}}$$
$$R_{2q} = \frac{1}{\omega_s T''_{qo}} \frac{X_{mq}X_{l1q} + X_{md}X_{l2q} + X_{l1q}X_{l2q}}{X_{md} + X_{l1q}}$$

Using the above mentioned dynamic equations the small signal modeling of the generator unit are as shown below:

$$\dot{x_{gn}} = A_{gn}x_{gn} + B_u u_{gn} + B_v V_{gn} \tag{3.18}$$
$$y_{gn} = C_{gn}x_{gn} + D_{gn}u_{gn} \tag{3.19}$$

The matrices related to input are divided into two parts so as to incorporate the disturbance input component in the system. Disturbance created by this input is controlled using the wide area controller.

The states, inputs and outputs of the generator unit are as follows: Where,

$$x_{gn_i} = [\Delta\Psi_{d_i} \quad \Delta\Psi_{q_i} \quad \Delta\Psi_{1d_i} \quad \Delta\Psi_{2q_i} \quad \Delta\Psi_{fd_i} \quad \Delta\Psi_{1q_i} \quad \Delta\omega_i \quad \Delta\delta]^T \tag{3.20}$$

$$u_{gn_i} = [\Delta T_{m_i} \quad \Delta V_{fd_i} \quad \Delta\omega_{cm}]^T \tag{3.21}$$

where, ω_{cm} is common reference frame speed, For a multi-machine system, the angle of reference rotating axis with respect to the stationary axis is given by the weighted average of all the machine angles with respect to the same stationary axis

$$\Delta\omega_{cm} = \frac{\sum_{j=1}^{N_G} w_{g_j}\Delta\omega_i}{\sum_{j=1}^{N_G} w_{g_j}} \tag{3.22}$$

where, w_{g_i} = weight for each generator and $\Sigma w_{g_i} = 1$.

Common global reference frame is the center-of-inertia (COI) in which weight factors are taken equal to inertia constants

$$V_{gn_i} = [\Delta V_{D_i} \quad \Delta V_{Q_i}]^T \tag{3.23}$$

V_{gn_i}, will contribute to the disturbance input for the system

$$y_{gn_i} = [\Delta i_{D_i} \quad \Delta i_{Q_i} \quad \Delta \omega_i \quad \Delta \delta_i]^T \tag{3.24}$$

Initialization of the generator unit

There are few steps that has to be followed for the initialization of system states which are mentioned in the equation (3.20). They are:

To get the initialized values of the states we need the generator terminal bus voltage(LV), active and reactive power generator output.

- At First perform the load flow for the considered IEEE bus system.
- Using the load flow results the generator input current phasor is calculated using the following formula, it has a minus sign as the current input is calculated from the output power of the generator:

$$\bar{I} = -\frac{P - jQ}{\bar{V}^*} \tag{3.25}$$

- Get the d-axis and q-axis voltage or current quantities with respective to the Kron's reference frame based upon the relationship between dq phasor and the steady-state phasor.

$$V_Q = Real\{\bar{V}\} \tag{3.26}$$

$$V_D = -Imag\{\bar{V}\} \tag{3.27}$$

$$i_Q = Real\{\bar{I}\} \tag{3.28}$$

$$i_D = -Imag\{\bar{I}\} \tag{3.29}$$

- The generator angle is determined using the above voltage and current phasor. This angle is with respective to the synchronously rotating reference frame

$$\delta_r = tan^{-1}\left\{\frac{R_s i_D - V_D - X_q i_Q}{V_Q - X_q i_D - R_s i_Q}\right\} \tag{3.30}$$

- The generator field voltage v_{fd} is determined using the below formula:

$$v_{fd} = \left(\frac{R_{fd}}{X_{md}}\right)\left\{(X_q - X_d)i_d + \sqrt{(R_s i_D - V_D - X_q i_Q)^2 + (V_Q - X_q i_D - R_s i_Q)^2}\right\} \tag{3.31}$$

- Field current is determined using the following formula:

$$i_{fd} = \frac{v_{fd}}{R_{fd}} \tag{3.32}$$

- Now the initial values of all other states are determined using the following formulae. Here, the initial rotor speed is synchronous speed(ω_s):

$$\Psi_d = X_d i_d + X_{md} i_{fd} \tag{3.33}$$

$$\Psi_{fd} = X_{md} i_d + X_{fd} i_{fd} \tag{3.34}$$

$$\Psi_{1d} = X_{md} i_d + X_{md} i_{fd} \tag{3.35}$$

$$\Psi_q = X_q i_q \tag{3.36}$$

$$\Psi_{1q} = X_{mq} i_q \tag{3.37}$$

$$\Psi_{2q} = X_{mq} i_q \tag{3.38}$$

$$i_{1d} = 0 \tag{3.39}$$

$$i_{1q} = 0 \tag{3.40}$$

$$i_{2q} = 0 \tag{3.41}$$

$$T_m = -\Psi d i_q + \Psi_q i_d + d_{fw} \omega_s^2 \tag{3.42}$$

The initial values of the states are used in the calculation of system matrices, Now the A_{gn}, B_{gn}, C_{gn} and D_{gn} for the above generator dynamic equations are as follows:

$$A_{gn_i} = \begin{bmatrix} -\omega_s(R_s+R_{tl})Y_d & \omega_s & -\omega_s(R_s+R_{tl})Y_{md} & 0 & -\omega_s(R_s+R_{tl})Y_{md} & 0 & \Psi_q(0) & -\omega_s V_D sin(\delta_i(0)) + \omega_s V_Q cos(\delta)_i(0) \\ -\omega_s & \omega_s(R_s+R_{tl})Y_q & 0 & -\omega_s(R_s+R_{tl})Y_{mq} & 0 & -\omega_s(R_s+R_{tl})Y_{mq} & \Psi_d(0) & -\omega_s V_D cos(\delta_i(0)) + \omega_s V_Q sin(\delta)_i(0) \\ -\omega_s R_{1d} Y_{md} & 0 & -\omega_s R_{1d} Y_{1d} & 0 & -\omega_s R_s Y_d & 0 & 0 & 0 \\ 0 & -\omega_s R_{2q} Y_{md} & 0 & -\omega_s R_{2q} Y_{2q} & 0 & -\omega_s R_{2q} Y_{mq} & 0 & 0 \\ -\omega_s R_{fd} Y_{md} & 0 & -\omega_s R_{fd} Y_{md} & 0 & -\omega_s R_{fd} Y_{fd} & 0 & 0 & 0 \\ 0 & -\omega_s R_{1q} Y_{mq} & 0 & -\omega_s R_{1q} Y_{mq} & 0 & -\omega_s R_{1q} Y_{1q} & 0 & 0 \\ \frac{\omega_s}{2H} i_q(0) - Y_d \Psi_q(0) & \frac{\omega_s}{2H} - i_d(0) - Y_q \Psi_d(0) & \frac{-\omega_s}{2H} Y_{md}\Psi_q(0) & \frac{-\omega_s}{2H} Y_{md}\Psi_d(0) & \frac{-\omega_s}{2H} Y_{md}\Psi_q(0) & \frac{-\omega_s}{2H} Y_{mq}\Psi_d(0) & \frac{-d_{fw}\omega_s^2}{H} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{3.43}$$

$$B_{u_i} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \omega_s & 0 \\ 0 & 0 & 0 \\ \frac{\omega_s}{2H} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.44}$$

$$B_{v_i} = \begin{bmatrix} -\omega_s cos(\delta_i(0)) & -\omega_s sin(\delta_i(0)) \\ -\omega_s sin(\delta_i(0)) & \omega_s cos(\delta_i(0)) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.45}$$

$$C_{gn_i} = \begin{bmatrix} -Y_d cos(\delta_i(0)) & -Y_q cos(\delta_i(0)) & -Y_{md} cos(\delta_i(0)) & -Y_{mq} cos(\delta_i(0)) \\ -Y_d sin(\delta_i(0)) & -Y_q sin(\delta_i(0)) & -Y_{md} sin(\delta_i(0)) & -Y_{mq} sin(\delta_i(0)) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix.$$
$$\left. \begin{matrix} -Y_{md} cos(\delta_i(0)) & -Y_{mq} cos(\delta_i(0)) & 0 & 0 \\ -Y_{md} sin(\delta_i(0)) & -Y_{mq} sin(\delta_i(0)) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{matrix} \right] \tag{3.46}$$

$$D_{u_i} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.47}$$

$$D_{v_i} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.48}$$

3.1.3 Turbine modeling

For the turbine modeling steam turbine is used. Steam is the main element which gives energy for turning the turbine. Now the steam flow is, the supply of the steam starts from the boiler and the steam so obtained is sent to the steam chest. Now the duty of the steam chest is to increase the pressure of the steam and is sent to the turbine set. There could be many different types of turbine setups. Here, I have considered high pressure (HP), intermediate pressure (IP) and low pressure turbine (LP). So, stem goes through all these stages. The steam can be either reheated after sent to the HP turbine or can be reheated at the cross over between IP and LP. The dynamics in the turbine are formulated based on the delays in steam chest, reheat and crossover piping. Now, there are different types of turbine setups. Here, tandem setup is considered. And in this setup all the stages of the turbine are placed in the same shaft.

K_{ab} represents the shaft stiffness coefficient between a and b components.

The dynamics of turbine are as follows:

$$\frac{d\omega_{hp}}{dt} = \left(\frac{\omega_s}{2H_{hp}}\right)\Big\{T_{hp} - K_{hpip}(\delta_{hp} - \delta_{ip}) - d_{hp}\omega_{hp}^2\} \tag{3.49}$$

$$\frac{d\omega_{ip}}{dt} = \left(\frac{\omega_s}{2H_{ip}}\right)\Big\{T_{ip} - K_{hpip}(\delta_{hp} - \delta_{ip}) - K_{iplp}(\delta_{ip} - \delta_{lp}) - d_{ip}\omega_{ip}^2\} \tag{3.50}$$

$$\frac{d\omega_{lp}}{dt} = \left(\frac{\omega_s}{2H_{lp}}\right)\Big\{T_{lp} - K_{iplp}(\delta_{ip} - \delta_{lp}) - K_{lpgn}(\delta_{lp} - \delta) - d_{lp}\omega_{lp}^2\} \tag{3.51}$$

$$\frac{d\delta_{hp}}{dt} = \omega_{hp} - \omega_s \tag{3.52}$$

$$\frac{d\delta_{hp}}{dt} = \omega_{hp} - \omega_s \tag{3.53}$$

$$\frac{d\delta_{hp}}{dt} = \omega_{hp} - \omega_s \tag{3.54}$$

$$T_m = K_{lpgn}(\delta_{lp} - \delta) \tag{3.55}$$

Initialization of the turbine

The turbine states and the inputs are initialized based on the following formulae:

$$\omega_{hp}(0) = \omega_{ip}(0) = \omega_{lp}(0) = \omega_s \tag{3.56}$$

$$T_{hp}(0) = \frac{G_{hp}}{G_{hp} + G_{ip} + G_{lp}}\left\{T_m(0) + (d_{hp} + d_{ip} + d_{lp})\omega_s^2\right\} \tag{3.57}$$

$$T_{ip}(0) = \frac{G_{ip}}{G_{hp} + G_{ip} + G_{lp}}\left\{T_m(0) + (d_{hp} + d_{ip} + d_{lp})\omega_s^2\right\} \tag{3.58}$$

$$T_{lp}(0) = \frac{G_{lp}}{G_{hp} + G_{ip} + G_{lp}}\left\{T_m(0) + (d_{hp} + d_{ip} + d_{lp})\omega_s^2\right\} \tag{3.59}$$

$$\delta_{lp}(0) = \frac{T_m(0)}{K_{lpgn}} + \delta(0) \tag{3.60}$$

$$\delta_{ip}(0) = \frac{T_m(0) + d_{lp}\omega_s^2 - T_{lp}(0)}{K_{iplp}} + \delta_{lp}(0) \tag{3.61}$$

$$\delta_{hp}(0) = \frac{T_m(0) + d_{lp}\omega_s^2 + d_{ip}\omega_s^2 - T_{lp}(0) - T_{ip}(0)}{K_{hpip}} + \delta_{ip}(0) \tag{3.62}$$

Small signal modeling of turbine

The small signal model of the turbine is as follows:

$$\dot{\boldsymbol{x_{tb}}} = \boldsymbol{A_{tb}x_{tb}} + \boldsymbol{B_{tb}u_{tb}} \tag{3.63}$$

$$\boldsymbol{y_{tb}} = \boldsymbol{C_{tb}x_{tb}} + \boldsymbol{D_{tb}u_{tb}} \tag{3.64}$$

Now the states that have been used for the modeling of turbine are:

$$x_{tb_i} = [\Delta\omega_{hp_i} \quad \Delta\omega_{ip_i} \quad \Delta\omega_{lp_i} \quad \Delta\delta_{hp_i} \quad \Delta\delta_{ip_i} \quad \Delta\delta_{lp_i}]^T \tag{3.65}$$

The inputs of turbine are as follows:

$$u_{tb_i} = [\Delta T_{hp_i} \quad \Delta T_{ip_i} \quad \Delta T_{lp_i} \quad \Delta\delta_i]^T \tag{3.66}$$

The output of turbine is ΔT_m.

Now the A_{tb}, B_{tb}, C_{tb}, D_{tb} of the turbine are:

$$\mathbf{A_{tb_i}} = \begin{bmatrix} -\frac{d_{hp}\omega_s^2}{H_{hp}} & 0 & 0 & -\frac{K_{hpip}\omega_s}{2H_hp} & \frac{K_{hpip}\omega_s}{2H_{hp}} & 0 & \\ 0 & -\frac{d_{ip}\omega_s^2}{H_ip} & 0 & \frac{K_{hpip}\omega_s}{2H_{ip}} & -\frac{(K_{hpip}+K_{iplp})\omega_s}{2H_ip} & \frac{K_{iplp}\omega_s}{2H_{ip}} & \\ 0 & 0 & -\frac{d_{ip}\omega_s^2}{H_{lp}} & 0 & \frac{K_{iplp}\omega_s}{2H_{lp}} & 0 & -\frac{(K_{iplp}+K_{lpgn})\omega_s}{2H_{lp}} \\ 1 & 0 & 0 & 0 & 0 & 0 & \\ 0 & 1 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 1 & 0 & 0 & 0 & \end{bmatrix} \tag{3.67}$$

$$\mathbf{B_{tb_i}} = \begin{bmatrix} \frac{\omega_s}{2H_{hp}} & 0 & 0 & 0 \\ 0 & \frac{\omega_s}{2H_{ip}} & 0 & 0 \\ 0 & 0 & \frac{\omega_s}{2H_{lp}} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.68}$$

$$\mathbf{C_{tb_i}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & K_{lpgn} \end{bmatrix} \tag{3.69}$$

$$D_{tb_i} = \begin{bmatrix} 0 & 0 & 0 & K_{lpgn} \end{bmatrix} \tag{3.70}$$

3.1.4 Speed governing system modeling

The high pressured steam at high temperature is converted to rotational energy by the steam turbine. Steam turbines are configured based on the unit size and the steam conditions. In tandem compound turbine all the sections are on one shaft, and in cross compound turbine there are two shafts each connected to a generator and driven by one or more turbine sections. However it is operated as a single unit.

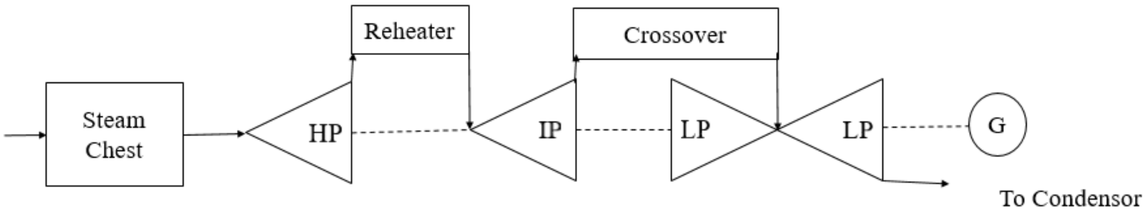

Figure 3.2: Tandem compound turbine with single reheat

Fossil fueled units can be of tandem compound or cross design. The tandem compound turbine is used for the modeling.

As mentioned in the previous section turbine has HP, IP and LP(refer Fig:3.2).

Dynamics of the speed governor:

$$\frac{d\rho_{vl}}{dt} = \frac{1}{\tau_{vl}}\left\{P_{ref} - \frac{1}{R}(\omega - \omega_{ref}) - \rho_{vl}\right\} \tag{3.71}$$

$$\frac{df_{ch}}{dt} = \frac{1}{\tau_{ch}}(\rho_{vl} - f_{ch}) \tag{3.72}$$

$$\frac{df_{rh}}{dt} = \frac{1}{\tau_{rh}}(f_{ch} - f_{rh}) \tag{3.73}$$

$$\frac{df_{co}}{dt} = \frac{1}{\tau_{co}}(f_{rh} - f_{co}) \tag{3.74}$$

$$T_{hp} = G_{hp}f_{ch} \tag{3.75}$$

$$T_{ip} = G_{ip}f_{rh} \tag{3.76}$$

$$T_{lp} = G_{lp}f_{co} \tag{3.77}$$

Initialization of the speed governing system

The initial value of the states are determined using the following formulae:

$$\rho_{vl}(0) = f_{ch}(0) = f_{rh}(0) = f_{co}(0) = \frac{T_{hp}(0) + T_{ip}(0) + T_{lp}(0)}{G_{hp} + G_{ip} + G_{lp}} \tag{3.78}$$

$$P_{ref} = \rho_{vl}(0) \tag{3.79}$$

The small signal model of the speed governing system is as follows:

The states of system are:

$$\dot{x_{sc_i}} = [\Delta\rho_{vl_i} \quad \Delta f_{ch_i} \quad \Delta f_{rh_i} \quad \Delta f_{co_i}]^T \tag{3.80}$$

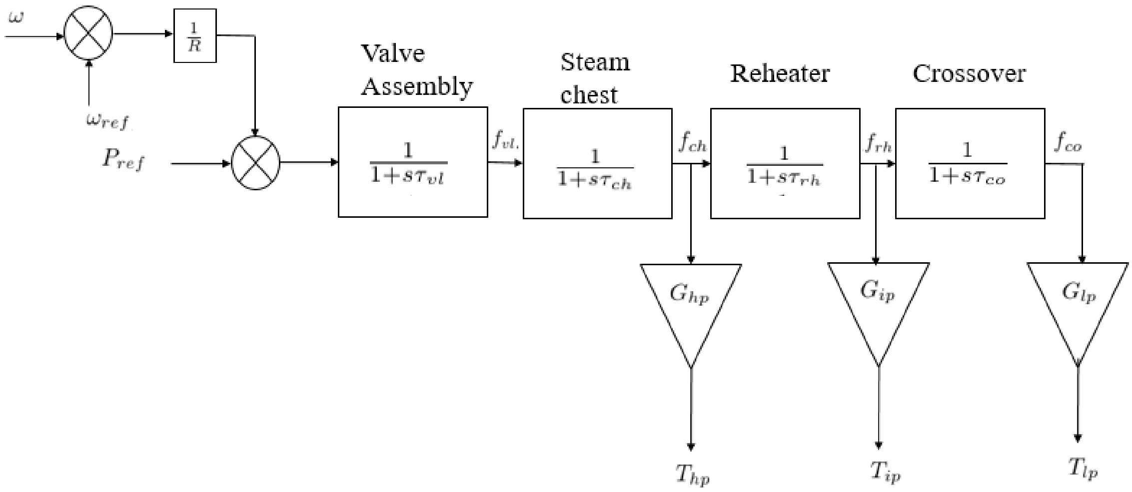

Figure 3.3: Speed governing system block diagram

The inputs of speed governor is $\Delta\omega_i$ The outputs are:

$$y_{sc_i} = [\Delta T_{hp_i} \quad \Delta T_{ip_i} \quad \Delta T_{lp_i}]^T \tag{3.81}$$

The $A_{sc}, B_{sc}, C_{sc}, D_{sc}$

$$A_{sc} = \begin{bmatrix} -\frac{1}{\tau_{vl}} & 0 & 0 & 0 \\ \frac{1}{\tau_{ch}} & -\frac{1}{\tau_{ch}} & 0 & 0 \\ 0 & \frac{1}{\tau_{rh}} & \frac{1}{\tau_{rh}} & 0 \\ 0 & 0 & \frac{1}{\tau_{co}} & \frac{1}{\tau_{co}} \end{bmatrix} \tag{3.82}$$

$$B_{sc} = \begin{bmatrix} -\frac{1}{R\tau_{vl}} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.83}$$

$$C_{sc} = \begin{bmatrix} 0 & G_{hp} & 0 & 0 \\ 0 & 0 & G_{ip} & 0 \\ 0 & 0 & 0 & G_{lp} \end{bmatrix} \tag{3.84}$$

$$D_{sc} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.85}$$

3.1.5 Excitation system modeling

The excitation system of large generator contains the following components[1]:

1. Exciter: Exciter is the device which supplies dc power to the synchronous machine field winding, creating the power stage of excitation system

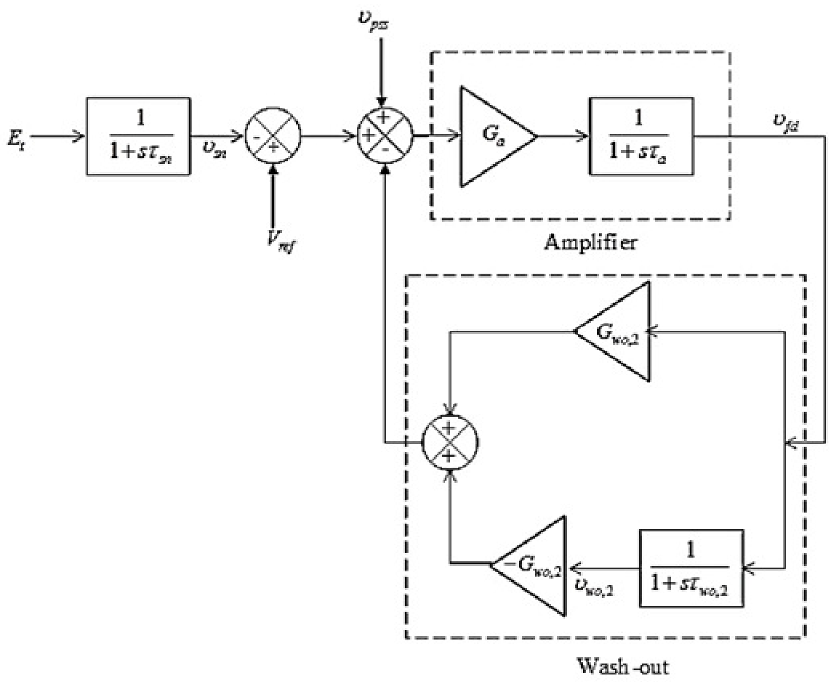

Figure 3.4: Excitation system block diagram

2. Regulator: The regulator processes and amplifies the input control signals to a certain level and forms an appropriate control for the exciter, this combines both regulating and excitation system stabilizing functions

3. Terminal voltage sensor and load compensation: The terminal voltage sensor will give the rectified and filtered terminal voltage, this sensor provides the dc quantity as the output. Now the sensor output voltage is compared with the desired voltage. Now the so obtained error signal is added to the power system stabilizer voltage. This voltage now goes for amplification. The load concept which is used to maintain constant voltage at a particular point which is far away from the generating unit.

4. Power system stabilizer: Power system stabilizer supplies an extra input signal to the regulator as mentioned in the previous point, which helps in minimizing the power system oscillations. There are other input signals part from the input to the exciter that can be used to decrease the oscillations. They are, rotor speed, accelerating power and frequency deviation

5. Limiters and protective circuit: The limiters and protective circuit is a wide array of control and protective devices which guarantee that the exciter limits and the synchronous generator limits are not crossed. The limiters are of various varieties like voltage limiter, field current limiter etc., All these limiters that are used in the system are summed using a summing point.

The generator terminal voltage is as follows:

$$E_t = \sqrt{(V_Q + k(i_Q R_{tl} + i_D X_{tl}))^2 + (V_D + k(i_D R_{tl} + i_Q X_{tl}))^2} \tag{3.86}$$

The dynamical equations of system used are as follows:

$$\frac{dv_{sn}}{dt} = \frac{1}{\tau_{sn}}(E_t - v_{sn}) \tag{3.87}$$

$$\frac{dv_{fd}}{dt} = \frac{1}{\tau_a}\Big\{ - G_a v_{sn} - (1 + G_a G_{wo,2})v_{fd} + G_a G_{wo,2} v_{wo,2} + G_a V_{ref} + G_a v_{pss}\Big\} \tag{3.88}$$

$$\frac{dv_{wo,2}}{dt} = \frac{1}{\tau_{wo,2}}(v_{fd} - v_{wo,2}) \tag{3.89}$$

$$E_t = |V_Q - jV_D - (i_Q - ji_D)(R_{tl} + jX_{tl})| \tag{3.90}$$

States of the excitation system are:

$$x_{ex_i} = [\Delta v_{sn_i} \quad \Delta V_{fd_i} \quad \Delta v_{wo,2_i}]^T \tag{3.91}$$

Inputs of the excitation system are:

$$u_{ex_i} = [\Delta V_{pss_i} \quad \Delta i_{D_i} \quad \Delta i_{Q_i} \quad \Delta V_{D_i} \quad \Delta V_{Q_i}]^T \tag{3.92}$$

The outputs are, ΔV_{fd_i}

Now the small signal model of the excitation system for the above mentioned dynamical equations is as follows:

The initialization of exciter model i done using the following equations:

$$v_{sn}(0) = |V_Q(0) - jV_D(0) - \big\{i_Q(0) - ji_D(0)\big\}(R_{tl} + jX_{tl})| \tag{3.93}$$

$$v_{wo,2}(0) = v_{fd}(0) \tag{3.94}$$

$$V_{ref} = \frac{v_{fd}(0)}{G_a} + v_{sn}(0) \tag{3.95}$$

The A_{ex}, B_{ex}, C_{ex} and D_{ex} are:

$$A_{ex} = \begin{bmatrix} -\frac{1}{\tau_{sn}} & 0 & 0 \\ \frac{G_a}{\tau_a} & -\frac{1+G_a G_{wo,2}}{\tau_a} & \frac{G_a G_{wo,2}}{\tau_a} \\ 0 & \frac{1}{\tau_{wo,2}} & -\frac{1}{\tau_{wo,2}} \end{bmatrix} \tag{3.96}$$

$$B_{ex} = \begin{bmatrix} 0 & \frac{1}{\tau_{sn}}\frac{\partial E_t}{\partial i_D} & \frac{1}{\tau_{sn}}\frac{\partial E_t}{\partial i_Q} & \frac{1}{\tau_{sn}}\frac{\partial E_t}{\partial V_D} & \frac{1}{\tau_{sn}}\frac{\partial E_t}{\partial V_Q} \\ \frac{G_a}{\tau_a} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.97}$$

$$C_{ex} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \tag{3.98}$$

$$D_{ex} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.99}$$

3.1.6 Modeling of power system stabilizer(PSS)

The power system stabilizer is usually used to induce a signal to the exciter. The additional signal is added to the exciter to stabilize the power system dynamics. The inputs for the power system stabilizer are system frequency. The PSS is designed by tuning the PSS gain with some constraints on the PSS time constants.

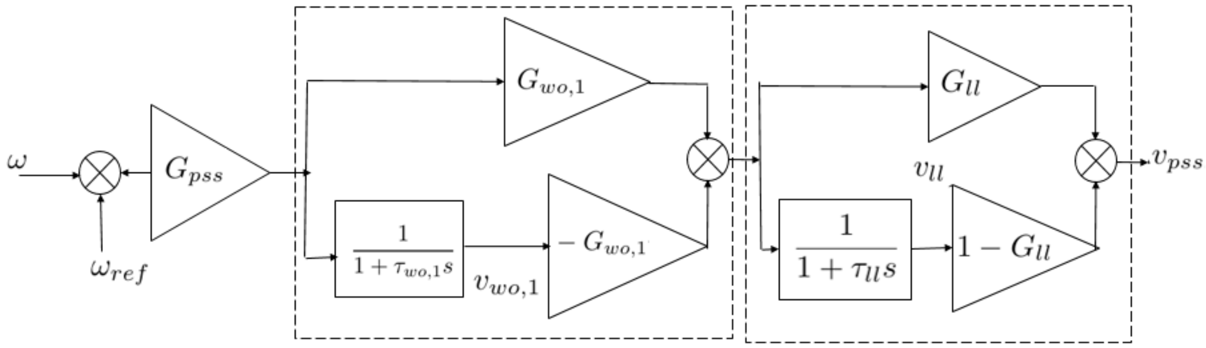

Figure 3.5: Block diagram of PSS

This is done so by tuning the PSS gain (G_{PSS}) in the system. Here, the gain is already tuned. The dynamical equations of the system are as follows:

$$\frac{dv_{wo,1}}{dt} = \frac{1}{\tau_{wo,1}} \{G_{pss}(\omega - \omega_{ref}) - v_{wo,1}\} \tag{3.100}$$

$$\frac{dv_{ll}}{dt} = \frac{1}{\tau_{ll}} \{G_{pss}G_{wo,1}(\omega - \omega_{ref}) - G_{wo,1}v_{wo,1} - v_{ll}\} \tag{3.101}$$

$$v_{pss} = -G_{ll}G_{wo,1}v_{wo,1} + (1 - G_{ll})v_{ll} + G_{pss}G_{wo,1}G_{ll}(\omega - \omega_{ref}) \tag{3.102}$$

The states of assumed PSS model is as follows:

$$x_{pss_i} = [\Delta v_{wo,1_i} \quad \Delta v_{ll_i}]^T \tag{3.103}$$

The inputs are:

$$u_{pss_i} = \Delta\omega_i \tag{3.104}$$

The outputs are:

$$y_{pss_i} = \Delta v_{pss_i} \tag{3.105}$$

Initialization of the PSS is done using the following equations:

$$v_{wo,1}(0) = 0 \tag{3.106}$$

$$v_{ll}(0) = 0 \tag{3.107}$$

$$v_{pss}(0) = 0 \tag{3.108}$$

$$A_{pss} = \begin{bmatrix} -\frac{1}{\tau_{wo,1}} & 0 \\ -\frac{G_{wo,1}}{\tau_{ll}} & -\frac{1}{\tau_{ll}} \end{bmatrix} \tag{3.109}$$

$$B_{pss} = \begin{bmatrix} \frac{G_{pss}}{\tau_{wo,1}} \\ \frac{G_{pss}G_{wo,1}}{\tau_{ll}} \end{bmatrix} \tag{3.110}$$

$$C_{pss} = \begin{bmatrix} -G_{ll}G_{wo,1} & 1 - G_{ll} \end{bmatrix} \tag{3.111}$$

$$D_{pss} = G_{pss}G_{wo,1}G_{ll} \tag{3.112}$$

3.2 Combined state space model of the generator components

In the above mentioned sections the state-space model of individual components the generator are obtained. Now, these are combined by arranging the matrices as block diagonal elements as shown below:

$$\boldsymbol{A_{sys}} = \begin{bmatrix} \boldsymbol{A_{gn}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{A_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{A_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{A_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{A_{pss}} \end{bmatrix} \tag{3.113}$$

$$\boldsymbol{B_{sys,1}} = \begin{bmatrix} \boldsymbol{B_{u}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{B_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{B_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{B_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{B_{pss}} \end{bmatrix} \tag{3.114}$$

$$\boldsymbol{B_{sys,2}} = \begin{bmatrix} \boldsymbol{B_{v}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{B_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{B_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{B_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{B_{pss}} \end{bmatrix} \tag{3.115}$$

$$\boldsymbol{C_{sys}} = \begin{bmatrix} \boldsymbol{C_{gn}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{C_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{C_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{C_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{C_{pss}} \end{bmatrix} \tag{3.116}$$

$$\boldsymbol{D_{sys,1}} = \begin{bmatrix} \boldsymbol{D_{u}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{D_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{D_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{D_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{D_{pss}} \end{bmatrix} \tag{3.117}$$

$$\boldsymbol{D_{sys,2}} = \begin{bmatrix} \boldsymbol{D_{v}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{D_{tb}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{D_{sc}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{D_{ex}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{D_{pss}} \end{bmatrix} \tag{3.118}$$

Now there is a relation between the inputs and outputs of each individual components. And that leads to existence of off diagonal elements as well. And that is computed using the following procedure. Now, the relation between inputs and outputs are given by the following equation:

$$\boldsymbol{u_G} = \boldsymbol{T y_G} \tag{3.119}$$

Here, T is an incidence matrix, and which is as follows for the assumed set of inputs and outputs as mentioned in the previous sections:

$$\boldsymbol{T} = \begin{bmatrix} 0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1 \\ 1&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0 \end{bmatrix} \tag{3.120}$$

Now substituting the relation (3.117, 3.118) in the generalized state equation. We get the state equation for all the generators with all the generators included in considered power system:

$$\dot{\boldsymbol{x_G}} = (\boldsymbol{A_{sys}} + \boldsymbol{B_{sys,1}} \boldsymbol{T}(\boldsymbol{I} - \boldsymbol{D_{sys,1}} \boldsymbol{T})^{-1} \boldsymbol{C_{sys}}) \boldsymbol{x_G} + (\boldsymbol{B_{sys,1}} \boldsymbol{T}(\boldsymbol{I} - \boldsymbol{D_{sys,1}})^{-1} \boldsymbol{D_{sys,2}} + \boldsymbol{B_{sys,2}}) \boldsymbol{u} \tag{3.121}$$

The above equation can be realized as follows:

$$\dot{\boldsymbol{x_G}} = \boldsymbol{A_G x_G} + \boldsymbol{B_G u_G} + \boldsymbol{B_v V_{G,DQ}} \tag{3.122}$$

Chapter 4

Network, Load Modeling and integration of the power system components

4.1 Network and Load modeling

The most common practice in power system stability studies is to aggregate the load at bulk delivery points.Such an aggregation includes various types of physical loads. However, in behaviour point view, they can be categorized into constant impedance, constant current and constant power components. Such a model is popularly called as ZIP model. The corresponding equation to represent the active power($\boldsymbol{P_{load}}$) as a function of bus voltage($\boldsymbol{V}$).[19]

The ZIP model is represented as:

$$\boldsymbol{P_{load} = wP_0\Big\{\alpha_P V^2 + \beta_P V + \gamma_P\Big\} = f_p(w, V)} \tag{4.1}$$

Here, in the above equation w is the disturbance component that can be included in the load nominal power. $\boldsymbol{\alpha_P}$, $\boldsymbol{\beta_P}$ and $\boldsymbol{\gamma_P}$ represent the fractions of which the constant impedance, constant current and constant power loads are present at a particular bus. Hence, the active load power at a bus is the function of disturbance in nominal power and bus voltage.

Now, the small signal model of the load is obtained for the small perturbations in the voltage and the nominal power disturbance. And it is as follows:

$$\boldsymbol{\Delta P_{load} = \frac{\partial f_p}{\partial V}(1, V_0)\Delta V + \frac{\partial f_p}{\partial w}(1, V_0)\Delta w} \tag{4.2}$$

$\boldsymbol{V_0}$ is the initial values of the bus voltages obtained from the load flow(Newton-Raphson technique is used).

After solving the above equation (3.123, 3.124) and applying the same concept for reactive power ($\boldsymbol{Q_{load}}$) we get the following matrix equation:

$$\begin{bmatrix} V_{D0} & V_{Q0} \\ V_{Q0} & -V_{D0} \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} = \begin{bmatrix} \frac{\partial f_P}{\partial V_D} - i_{D0} & \frac{\partial f_P}{\partial V_Q} - i_{Q0} & \frac{\partial f_P}{\partial w} \\ \frac{\partial f_Q}{\partial V_D} + i_{Q0} & \frac{\partial f_Q}{\partial V_Q} - i_{D0} & \frac{\partial f_Q}{\partial w} \end{bmatrix} \begin{bmatrix} \Delta V_D \\ \Delta V_Q \\ \Delta w \end{bmatrix}$$

The above matrix equation can be rearranged and the load current for one particular load bus can be realized as follows:

$$\Delta i_{L,DQ,k} = Y_{L,DQ,k} \Delta V_{L,DQ,k} + K_{L,DQ,k} \Delta w_k \tag{4.3}$$

4.2 Integration of the power system components

The integration of the power system components include integrating generator, transmission network and the load models.

The integration is done based on the following concept, at every bus in the power system if we apply Kirchhoff's current law(KCL). And considering the current injected is positive and the current leaving as negative as the convention, then the following equation is obtained:

$$i_{bus} = i_{generator} - i_{load} \tag{4.4}$$

Now the bus, generator and load currents are substituted in the above equation. The transmission line is modeled as the Y_{bus}. The bus current is the product of bus admittance and bus voltage. Generator current is computed from the generator output equation. And load current is taken from the equation(3.125).

Here, A_L is the incidence matrix which will give the relation bus and the load components. This gives the location of loads in the power system.

A_G, is the incidence matrix which will give the relation bus and the generator components. This gives the location of generators in the power system.

Including all the above mentioned aspects in the equation, we get the following:

$$Y_{B,DQ} \Delta V_{DQ} = A_G^T C_G \Delta x_G - A_L^T Y_L A_L \Delta V_{DQ} - A_L^T K_L \Delta w \tag{4.5}$$

Rearrange the above equation for generator voltage,

$$(Y_{B,DQ} + A_L^T Y_L A_L) A_G^T \Delta V_{G,DQ} = A_G^T C_G \Delta x_G - A_L^T K_L \Delta w \tag{4.6}$$

Assume,

$$T_{DQ} = (Y_{B,DQ} + A_L^T Y_L A_L) A_G^T \tag{4.7}$$

Then the final equation for generator voltage is given by the following equation:

$$V_{G,DQ} = M_x x_G + M_w w \tag{4.8}$$

Consider the equation(3.122), the generator voltage obtained in equation (3.130) is substituted in it and the final state equation for the entire power system is obtained. And mentioned in equation (3.131).

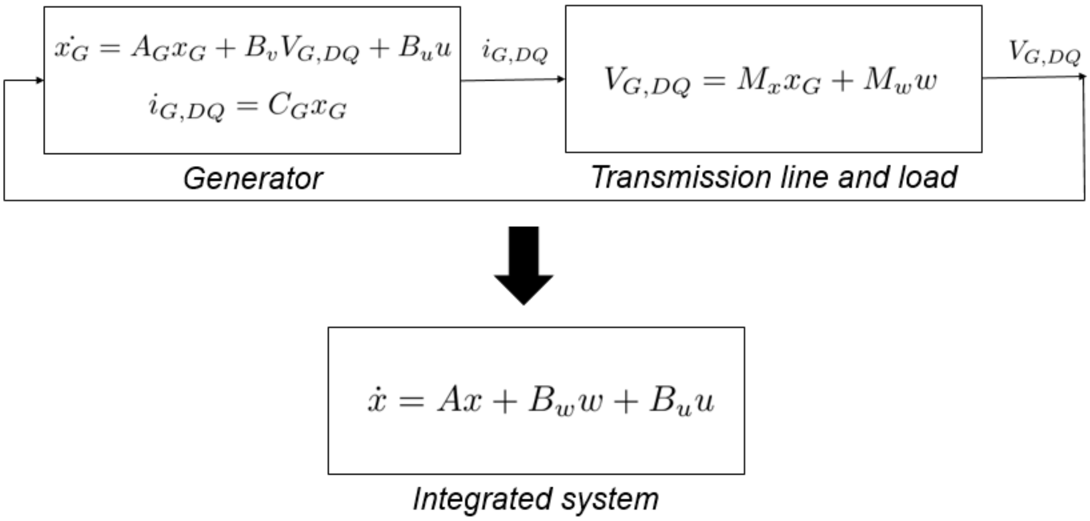

Figure 4.1: Integrating generator, transmission line and load units

Chapter 5

Wide area controller design

The controller design is done for the evaluation of state feedback matrix. Two methods are employed for its design.

5.1 WAC design using Linear-quadratic regulator (LQR) strategy

The main motive of an optimal problem is to minimize the cost while the dynamic system is operating. Dynamics of a system are represented using a set of LDE (Linear differential equations). The cost function problem is defined by a quadratic function and it is called as LQ problem. Now the controller used for optimizing the quadratic cost function is LQR. So, called because it regulates the linear quadratic cost function. LQR works for MIMO system.[20]

Reducing the quadratic cost function (QCF) is the main motive for the LQR optimization. The QCF is a function of control energy and system response. It is not easy to attain perfect performance using LQR. It is because the weighting matrices Q and R, these are formulated at the time of controller synthesis. And Q and R are chosen based on the disturbance input for the system.

Here, Q is a $[\boldsymbol{nxn}]$ matrix and R is a $[\boldsymbol{mxm}]$ matrix. The design problem is described as follows:

Given a state variable model of the form:

$$\dot{\boldsymbol{x}}(\boldsymbol{t}) = \boldsymbol{A}\boldsymbol{x}(\boldsymbol{t}) + \boldsymbol{B}\boldsymbol{u}_{\boldsymbol{wac}}(\boldsymbol{t}) \tag{5.1}$$

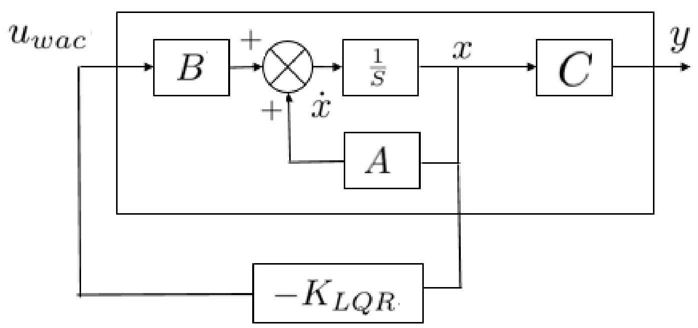

Figure 5.1: Closed Loop LQR Configuration

Where $\boldsymbol{x(t)}$ is the state vector with $\boldsymbol{n}$ state variables, $\boldsymbol{u(t)}$ is the control vector with $\boldsymbol{m}$ inputs, $\boldsymbol{A}$ is matrix of size $\boldsymbol{(n\text{x}n)}$ and should of full rank. Similarly, $\boldsymbol{B}$ is also a constant matrix whose size is $\boldsymbol{(n\text{x}m)}$ with full rank. These matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ has to be controllable pair.[21]

LQR optimization technique is basically obtained by minimizing cost function mentioned below:

$$\boldsymbol{J = \frac{1}{2}\int_0^\infty [X(t)^T Q X(t) + u_{wac}(t)^T R u_{wac}(t)] dt} \tag{5.2}$$

in which $\boldsymbol{Q}$ is positive definite and $\boldsymbol{R}$ is positive semi definite matrices. They are the state weighting matrix and input weighting matrix respectively for LQR optimization problem. According to the LQR control problem, the system (Equation 1.1) is controlled by the state feedback

$$\boldsymbol{u_{wac}(t) = -K_{LQR} X(t)} \tag{5.3}$$

and the algebraic riccati equation(ARE) is:

$$\boldsymbol{A^T P + PA - PR^{-1} B_u^T P + Q = 0} \tag{5.4}$$

we can determine the solution P and the gain $\boldsymbol{K_{LQR}}$

$$\boldsymbol{K_{LQR} = R^{-1} B_u^T P} \tag{5.5}$$

Matrices $\boldsymbol{Q, R}$ must be chosen wisely for obtaining a optimal value for the gain $\boldsymbol{K_{LQR}}$. Considering the eigen values, the observable states are determined and the weights are given high for the observable states and less for the non observable states. Now the closed loop complex poles will help in understanding the system performance. Main drawback of LQR controller is that can't work with constraints.

5.2 WAC controller design using $\boldsymbol{H_\infty}$ optimization technique

$\boldsymbol{H_\infty}$ control strategy is to design the controller, with best performance. In the $\boldsymbol{H_\infty}$ method, control problem must be a mathematical problem which optimizes the $\boldsymbol{H_\infty}$ norm and then determines controller gain that solves this optimization problem of minimizing the cost function. $\boldsymbol{H_\infty}$ technique has an benefit over existing control methods. In the $\boldsymbol{H_\infty}$ method the problem can be consisting of multi variables and there could be channels which are cross coupled. [22].

The main problem in the $\boldsymbol{H_\infty}$ strategy is the difficulty level in understanding and successfully applying the mathematics for a complicated model which is to be controlled is high. The controller gain so obtained from this system is only best w.r.t the cost function but not inevitably best in the case of usual performances measures such as settling time, energy expanded etc., These measures are usually used for evaluating the performance of the controller.

$\boldsymbol{H_\infty}$ is coined based on the space over which the mathematical optimization is possibly made. $\boldsymbol{H_\infty}$ is a Hardy space matrix valued function which is analytically bounded in the entire right half of the complex plane. And it is defined by the mathematical representation as $\boldsymbol{Re(s) > 0}$, the $\boldsymbol{H_\infty}$ norm is the maximum possible singular value in that space. The physical represented of the $\boldsymbol{H_\infty}$ norm can be explained by interpreting it as the maximum possible gain in any direction and at any frequency. And this is effectively the maximum magnitude of the frequency response. $\boldsymbol{H_\infty}$ method is to reduce the effect of perturbation caused due to disturbances in the system by establishing a proper closed loop controlling scheme. Depending on how the problem is formed, the effect of the $\boldsymbol{H_\infty}$ technique can be assessed in terms of stabilization of the system or the performance of the system.

$\boldsymbol{H_\infty}$ optimization is basically the optimization of the robust performance of the system. But achieving the robust stabilization id difficult. Both the above mentioned qualities in the controller can be achieved using a concept called as $\boldsymbol{H_\infty}$ loop shaping. This method of classical loop shaping will design the controller with concepts of multi variable frequency response. Thus we obtain good robust performance, and also optimizes the frequency response of the system which is near the system bandwidth further achieving the robustly stable control scheme.

$\boldsymbol{H_\infty}$ for the system[23]:

$$||G(s)||_\infty = sup \lim_{\omega} \bar{\sigma}[G(j\omega)] \tag{5.6}$$

The interpretation of $\boldsymbol{H_\infty}$ is as follows: $||G(s)||_\infty$ is "energy gain" from input $\boldsymbol{u}$ to output $\boldsymbol{y}$.

$$||G(s)||_\infty = \max \lim_{u(t)\neq 0} \frac{\int_0^\infty y^T(t)y(t)dt}{\int_0^\infty u^T(t)u(t)dt} \tag{5.7}$$

Now the $\boldsymbol{H_\infty}$ norm can be represented for different values as follows:

1. Signal norm: $||u(t)||_\infty = \max \lim_{t} |u(t)|$
2. Vector norm: $||x||_\infty = \max \lim_{i} |x_i|$
3. System norm: $||G(s)||_\infty = \max \lim_{\omega} \bar{\sigma}|G(\omega)|$

Formulation of $\boldsymbol{H_\infty}$ optimization problem:
Firstly, the plant is represented in standard configuration as follows:

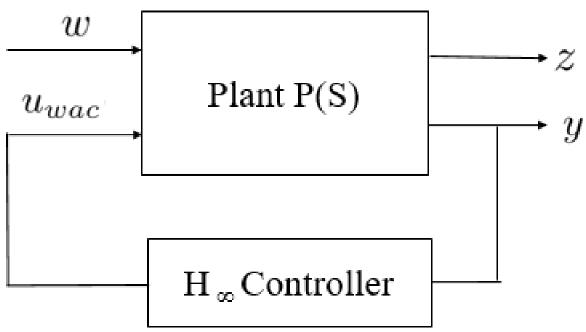

Figure 5.2: Standard $\boldsymbol{H_\infty}$ Configuration

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix}$$

The plant $\boldsymbol{P}$ has two inputs, the exogenous input $\boldsymbol{w}$, that includes disturbances, and the system input variables $\boldsymbol{u}$. There are two outputs, the performance $\boldsymbol{z}$, and the measured variables $\boldsymbol{v}$, that we use to control the system.[24]

The feed back given as follows: $\boldsymbol{u = K_{H_\infty}(s)y}$
The dependence of z on w is represented as: $\boldsymbol{z = F_l(P, K).w}$
The lower linear transformation function, $\boldsymbol{F_l}$ is defined as follows:

$$\boldsymbol{F_l = P_{11} + P_{12}K_{H_\infty}(I + P_{22}K_{H_\infty})^{-1}P_{21}} \tag{5.8}$$

Now the objective of $\boldsymbol{H_\infty}$ controller is to find controller K such that $\boldsymbol{F_l(P, K)}$ is minimized according to $\boldsymbol{H_\infty}$ norm.

In the above chapter(3.0) we have discussed how to get the state equation of entire power system. Now for the $\boldsymbol{H_\infty}$ controller design we require the equations for performance output and measured output of power system.

5.3 Computation of performance channel and measured outputs

It is the virtual output used for design of controller, the design is for minimization of performance output, for given a class of disturbance inputs. And it is defined as follows:

$$\boldsymbol{z = \begin{bmatrix} Q^{1/2} \\ 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ R^{1/2} \end{bmatrix} w = C_z x + D_{zw} w} \tag{5.9}$$

where, $\boldsymbol{Q}$, $\boldsymbol{R}$ are the weighting matrices. Mostly, these matrices are identity matrices multiplied with some weights. These weights will effect the damping ratio of system.

For simplicity the following condition is considered: $\boldsymbol{C_z D_{zw}^T = 0}$

The measured output are manipulated such that the system gives an state feed back matrix. This is done so by designing the $\boldsymbol{C_y}$ matrix. The system output matrix $\boldsymbol{C_y}$ is taken as the incidence matrix used to choose the required states (observable) are as the inputs of system. This ensures the structural constraint in state feedback matrix $\boldsymbol{K_{H_\infty}}$.

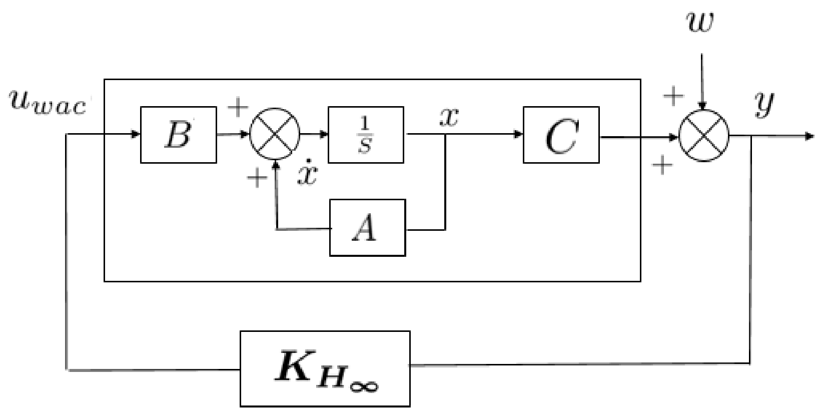

Figure 5.3: Closed Loop $\boldsymbol{H_\infty}$ Configuration

$$\boldsymbol{y = C_y x} \tag{5.10}$$

The state space representation of the controller is as follows:

$$\dot{\boldsymbol{x}}_{\boldsymbol{K}} = \boldsymbol{A}_{\boldsymbol{K}}\boldsymbol{x}_{\boldsymbol{K}} + \boldsymbol{B}_{\boldsymbol{K}}\boldsymbol{y} \tag{5.11}$$

$$\boldsymbol{u} = \boldsymbol{C}_{\boldsymbol{K}}\boldsymbol{x}_{\boldsymbol{K}} + \boldsymbol{D}_{\boldsymbol{K}}\boldsymbol{y} \tag{5.12}$$

The matrices $\boldsymbol{A}_{\boldsymbol{K}}$, $\boldsymbol{B}_{\boldsymbol{K}}$, $\boldsymbol{C}_{\boldsymbol{K}}$ and $\boldsymbol{D}_{\boldsymbol{K}}$ have same sizes as that of plant because the controller which is considered is full order controller. In the controller state space model, consider $\boldsymbol{B}_{\boldsymbol{K}} = \boldsymbol{C}_{\boldsymbol{K}} = \boldsymbol{0}$, and $\boldsymbol{A}_{\boldsymbol{K}}$ is unit matrix.

Now, the state feedback matrix $\boldsymbol{K}_{\boldsymbol{H}_{\infty}}$ can be deduced as follows:

$$\boldsymbol{u} = \boldsymbol{D}_{\boldsymbol{K}}\boldsymbol{y} \tag{5.13}$$

$$\boldsymbol{u} = \boldsymbol{D}_{\boldsymbol{K}}\boldsymbol{C}_{\boldsymbol{y}}\boldsymbol{x} \tag{5.14}$$

$$\boldsymbol{K}_{\boldsymbol{H}_{\infty}} = \boldsymbol{D}_{\boldsymbol{K}}\boldsymbol{C}_{\boldsymbol{y}} \tag{5.15}$$

The obtained $\boldsymbol{K}_{\boldsymbol{H}_{\infty}}$ matrix is a state feedback matrix with sparsity.

Chapter 6

Results

A case study is performed for 16-machine 68-bus system and the load at bus 18 is decreased by 40% and the performance of controller is measured using the generator COI speeds dynamic response. [25].

The following figure (5.1) has the generator speed (COI) dynamic response with LQR controller compared with the without controller case.

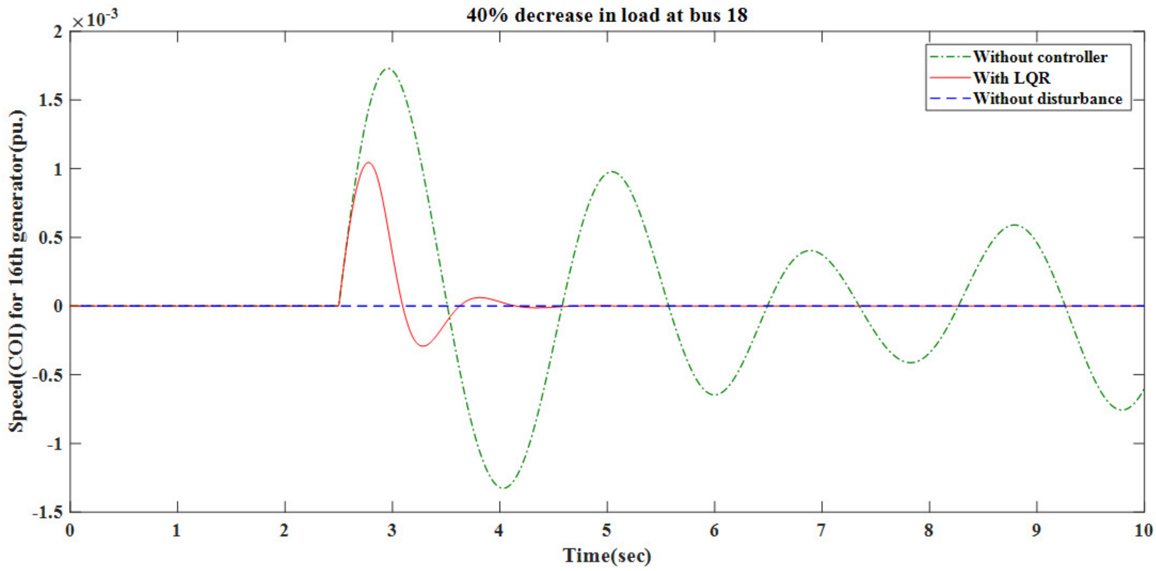

Figure 6.1: Generator speed (COI) dynamic response after load shedding at bus 18 with LQR controller.

The following figure (5.2) has the dynamic response of the generator speed COI with $\boldsymbol{H_\infty}$ controller compared with the with LQR controller case.

The figure (5.3) indicates the closed loop performance poles using LQR and $\boldsymbol{H_\infty}$ controller. The case study is performed for 16-machine 68 bus system for load disturbance at $\mathbf{18^{th}}$ bus

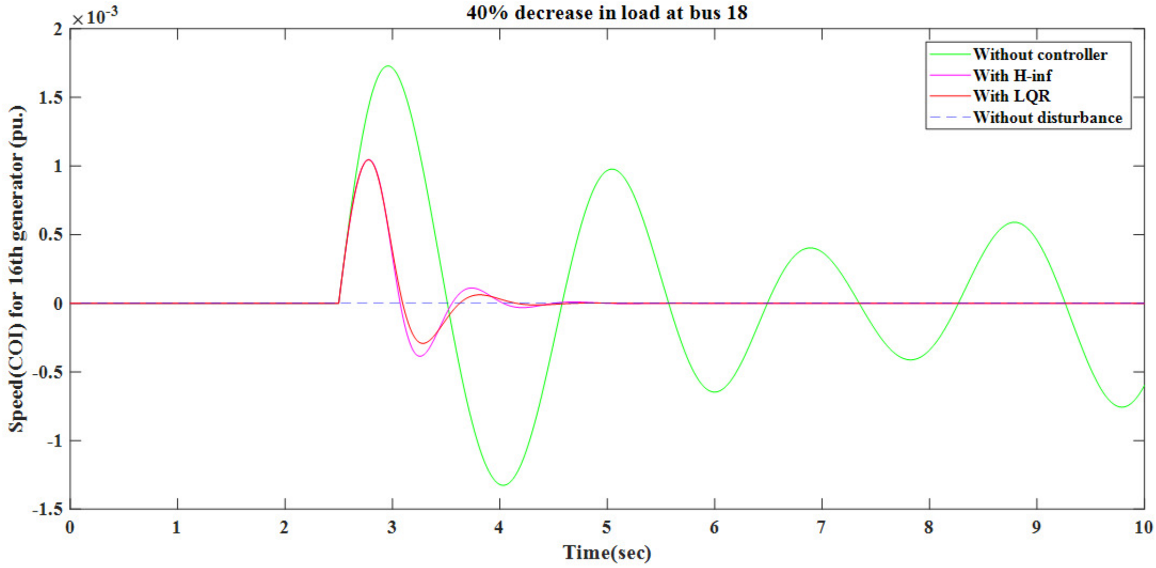

Figure 6.2: Generator speed (COI) dynamic response for load shedding at bus 18 with $\boldsymbol{H}_{\infty}$ controller.

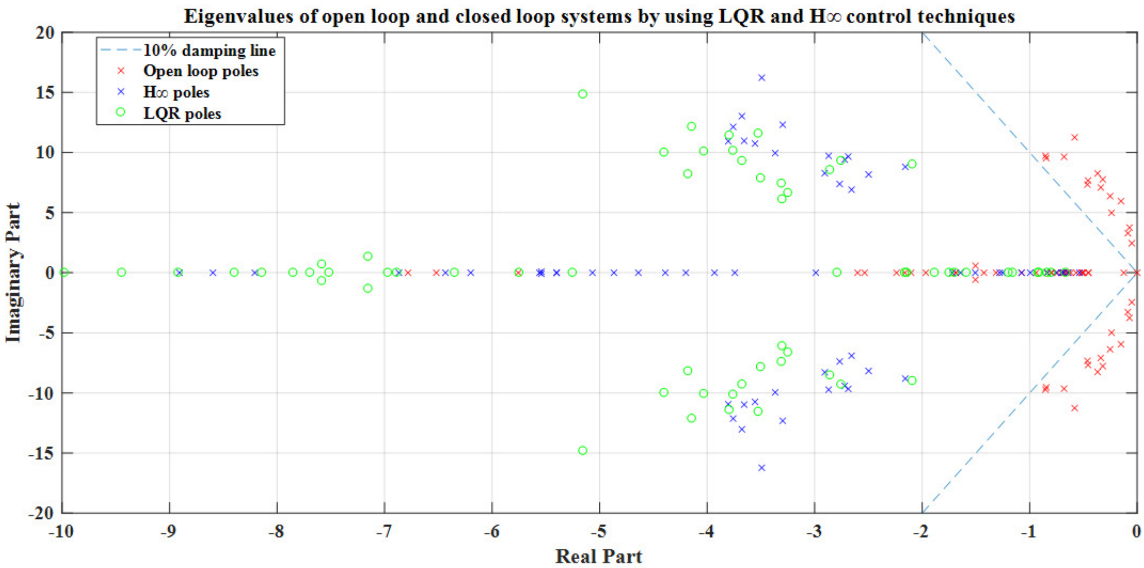

Figure 6.3: LQR and $\boldsymbol{H}_{\infty}$ controls eigen value analysis

Chapter 7

Conclusion

The inter area mode oscillations are addressed in this thesis. The oscillations considered in this work are due to the load disturbances caused due to the sudden variation in the nominal power at a particular load bus. This is handled by modeling the load using dynamic modeling. Also, a performance channel design played a crucial role in the design of controller. Here, a conventional LQR controller designed which uses the entire state vector as the input. Also a $\boldsymbol{H_\infty}$ controller is used wherein the state feedback gain is structured based on the required states.

In this thesis, the small signal modeling of the power system with generator unit, transmission line and load are explained. The generator unit modeling includes generator, turbine, speed governor, exciter, and power system stabilizer modeling. The small signal model is done considering the disturbance in nominal power of the load.

All the design of small signal model and the simulations are performed in MATLAB/Simulink. The case study is performed for IEEE 16-machine 68-bus system. The load disturbance considered is the percentage change in the nominal power (active or reactive) at a load bus. This disturbance causes oscillations in the rotor angle of the generator. Hence, the dynamic response of the rotor angle of all the generators are studied. Thus, controller performance is tested by observing the dynamic response of the rotor angle of the generator.

The LQR controller gives the stabilized results for the load disturbances caused in the generator states. $\boldsymbol{H_\infty}$ controller with structural constraints is designed for load disturbances. Now $\boldsymbol{H_\infty}$ optimization controller results are compared with the LQR controller results and the prior gives better performance with the structural constraints implemented on the feedback gain matrix.

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