HIGHER ORDER SLIDING MODE BASED LOAD FREQUENCY CONTROL FOR A TWO-AREA INTERCONNECTED POWER SYSTEM

A THESIS

submitted by

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Reg. No. TCR17EEPS03

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APJ ABDUL KALAM TECHNOLOGICAL UNIVERSITY, THRISSUR CLUSTER

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(http://gectcr.ac.in/)

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Thrissur Cluster

(https://ktu.edu.in/)

Bonafide Certificate

This is to certify that the Project Report titled **" HIGHER ORDER SLIDING MODE BASED LOAD FREQUENCY CONTROL FOR A TWO-AREA INTER-CONNECTED POWER SYSTEM"** is a bonafide record of the work carried out by **ALBERT POULOSE (Univ. Reg. No.TCR17EEPS03)** of Government Engineering College, Thrissur-680009, Kerala, India in partial fulfillment of the requirements for the award of **Degree of Master of Technology** in **Power Systems** of **APJ Abdul Kalam Technological University, Thrissur Cluster**. The Project report has been approved as it satisfies the academic requirements in respect of project work prescribed for the said degree.

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DECLARATION

I, **ALBERT POULOSE (Univ. Reg. No. TCR17EEPS03)**, hereby declare that this project report, entitled **" HIGHER ORDER SLIDING MODE BASED LOAD FREQUENCY CONTROL FOR A TWO-AREA INTERCONNECTED POWER SYSTEM"**, is a record of the original work done by me under the guidance of **Dr. Ramesh Kumar P**, Asst. Prof., Dept. of Electrical Engineering, Government Engineering College, Thrissur-680009, Kerala, India , and that this work has not formed the basis for the award of any degree / diploma /associateship / fellowship or a similar award, to any candidate in any University, to the best of my knowledge.

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June, 2019

COUNTERSIGNED

Signature of the Guide

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Abstract

Power system contains generation, transmission and distribution of electrical energy. It will transform the natural resources into a worthwhile high quality electrical energy. For the optimized use of electrical equipment, the electrical energy obtained should be at good quality under any load fluctuations i.e. the frequency and voltage should be at standard constant values. The swing in these parameters indicate the shifting of equipment's operating point and it will deteriorate the entire system. Hence we need a dominant control systems to oppose the load fluctuations through frequency control.

This project develops higher order sliding mode (HOSM) based controllers for load frequency control (LFC) of two area interconnected power system. The power system considered have non-reheat and reheat type thermal turbines, governors and generators are distributed in two areas respectively. A LFC scheme basically incorporates a control system having the capability to bring the frequencies of each area and tie line powers back to original set point values or very nearer to it effectively after the load change. Initially an integral controller is designed then which is used to compare performance of conventional sliding mode controller (SMC) and HOSM controllers (twisting and super-twisting) with the same nonlinearities such as governor dead band (GDB) and generation rate constraint (GRC). The controllers are analyzed in terms of frequency error, tie-line power error and area control error (ACE) through simulation in the MATLAB/Simulink environment.

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GEC	Government Engineering College
LFC	Load Frequency Control
SMC	Sliding Mode Control
HOSM	Higher Order Sliding Mode
SOSMC	Second Order Sliding Mode Control
GDB	Governor Dead Band
GRC	Generation Rate Constraint

Chapter 1

INTRODUCTION

The power system can be simply defined as the interconnection of control areas. The speed of the generators in the control area changes frequently to maintain the frequency of the entire system. Due to sudden load changes in the control area, there will be a changes in the frequency, not only in the control area but also in the interconnected control areas. The process of maintaining the frequency of the system during load changes is called load frequency control (LFC).
The two main objectives of LFC are as follows

- To maintain the frequency at a desired standard level in the power system.
- To control the change in tie line power between control areas.

There are mainly three types of errors such as frequency error, tie-line power error and area control error (ACE). Frequency error is the frequency deviation from standard normal frequency value. Tie-line power error is proportional to the integral of frequency error and which shows the deviation from scheduled value of interchange power. A conventional ACE is the linear combination of frequency error and tie-line power error.

When the error is large governor action is introduced and the generator output adjusted to nullify the effect of load disturbance. This type of governor action is called the primary control.

The governor action will bring the frequency near to the standard value. But it does not ensure the desired value based on other interconnected systems. Hence we introduce the secondary control in addition to primary control. It uses a controller which brings the frequency to the desired. Normally one of the popular controller is integral controller.

But it has the drawback of slow response of operation.

In a two area system, the two areas are interconnected by tie lines and thus a load change affects the frequencies in both the areas. Therefore the LFC of two area interconnected power system generally incorporates proper control system, which ensures frequency and tie line power of each area to its predefined value, when the sudden change in load occurs.

1.1 Motivation

LFC is one of the important method which determines the stability of the power system. The conventional integral controllers are slow in operation and are not robust against system uncertainties and disturbances. Several other controllers have been developed and are given in the literature survey have their own advantages and disadvantages.

Thus its necessary to develop a controller which has faster response and it is insensitive to system uncertainties and disturbances. Such a controller will result in a stable and robust power system.

1.2 Objectives of the Work

The objective of this project can be divided into two

- Design of twisting and super-twisting sliding mode controllers (SMC) for optimal LFC of two area interconnected power system.
- Comparison of higher order sliding mode (HOSM) controllers with existing commonly used integral controller.

1.3 Methodologies Adopted

In this project two types of second order SMCs such as twisting controller based on twisting algorithm and super-twisting controller based on super-twisting algorithm are proposed for the LFC problem using Matlab/Simulink tool. The results are compared with commonly used integral controller for LFC application.

1.4 Outline of the Thesis

The following section outlines the content of the project report.

- Chapter 1: This chapter explains introduction to the project work and describes the motivation, objectives and methodologies of the work.
- Chapter 2: In this chapter a detailed literature survey has been given. Includes LFC, two area interconnected power system, different controllers for LFC and SMCs are explained in detail. The literature survey of SMC includes details about the conventional SMC, chattering effect and HOSM controllers.
- Chapter 3: This chapter demonstrates the modeling of the two area interconnected power system. It briefs about the modeling of components of power system i.e turbine, governor and generator. It also explains about the various control loops in the power system.
- Chapter 4: In this chapter a detailed study of sliding mode control has been provided. It also explains about the second order sliding mode and also details about the design of sliding mode control for a single area system and two area system.
- Chapter 5: This chapter explains about the simulation of LFC for a single area and two area system. Simulation is carried out for two conditions i.e for load disturbance and parameter uncertainty.
- Chapter 6:The conclusion and future scope of the work has been explained in this chapter.

Chapter 2

LITERATURE REVIEW

The literature review done to acquire knowledge about the concepts required to complete this project has been given in this chapter.

2.1 Load Frequency Control (LFC)

The main objective of LFC is to maintain the frequency at a predefined value and to maintain the scheduled interchange of power through the tie-lines. Concordia et al [1] and Cohn [2] have described the basic importance of frequency and tie-line bias control in case of interconnected power system. The revolutionary concept of optimal control (optimal regulator) for LFC of an interconnected power system was first stated by Elgerd [3].

The LFC is recognized as the automatic generation control (AGC) deals with the frequency and active power. It has two goals, one is to maintain the frequency of the system to the anticipated value and another goal is to maintain the interchange power between tie line at its scheduled value for any riot condition [4]. The LFC can be done in various ways. A discrete or continuous model of power system given in [5]. Earlier centralized controller based techniques has been used, which is highly reliable and low cost. But it causes communication delays in interconnected power system and it requires high computational and storage complexities with distance travel [6].

In 1980's decentralized control technique is presented to overcome the drawbacks of centralized method [7]. Because of its reliability and efficiency, it becomes a dominant control method in power system [8]. Each area in the interconnected power system have its own decentralized control based on locally available state variables. Its control objectives are analogous to the centralized controller and which eradicates the computational complications.

2.2 LFC Related Power System Models

For more than last three decades researches are going on load frequency control of power system. Linearized models of multi area power systems are considered so far for best performance. K. C. Divya et al [9] has presented the hydro-power system simulation model. They have taken an assumption of same frequencies of all areas, to overcome the difficulties of extending the traditional approach. The model was obtained by ignoring the difference in frequencies between the control areas.

E. C. Tacker et al [10] has discussed the LFC of interconnected power system and investigated the formulation of LFC via linear control theory. A comparison between three relatives was made to the ability for motivation of the transient response of system variables. Later, the effect of generation rate constraint (GRC) and governor dead band (GDB) were introduced in these studies, by considering both discrete and continuous power system.

2.3 LFC Related Control Techniques

The research on different classical control techniques revealed that it will results in comparatively large transient frequency deviation and overshoots [3, 11]. Moreover, generally the settling time of frequency deviation for the system is relatively long (10 to 20 seconds). Fosha and Elgerd [4] were the two persons who first presented their work on optimal LFC regulator using optimal control theory. A power system of two identical areas interconnected through tie-line having non reheat turbine is considered for investigation.

R. K. Cavin et al [16] has considered the problem of LFC for an interconnected system from the theory of optimal stochastic system point of view. An algorithm based on control strategy was developed which gives improvised performance of power system for both small and large signal modes of operation. The special attractive feature of the control scheme proposed here was that it require the recently used variables. That are deviation in frequency and scheduled inter change deviations are taken as input.

In W. Tan [17] paper, conventional PI/PID control is typically used as a decentralized control method. These controllers are not easy to tune but simple to implement. However, they infer from the problem of long settling time and large overshoot in frequency's transient response. In addition, PI/PID controllers are not robust enough for system uncertainties and disturbances. Therefore, an advanced controller has to be developed to improve the transient response of load frequency and to enhance the control quality of power systems despite the presence of load disturbances and system uncertainties.

In recent years, many diverse control algorithms have been proposed. They are robust control algorithms includes fuzzy logic [18], neural networks [19], predictive control model [20], optimal control [21]. In general, approaches to design LFC is classified into several categories such as classical techniques, adaptive methods, variable structure methods, robust control methods and methods based on artificial intelligence.

2.4 Sliding Mode Control (SMC)

SMC is a robust variable structure control technique which has been effectively implemented under uncertainty conditions in abundant electro-mechanical plants. The SMC's main advantage is the invariance to matched uncertainties, order reduction, simplicity of design and robustness against disturbance. It is a powerful tool for control nonlinear uncertain systems. But this method has some problems like restrictions on relative degrees and chattering effects [20].

In recent times, number of efforts are made to overcome the problem of chattering in SMC by introducing new control methods such as sliding sector method, method of adding a boundary layer around the switching surface, sigmoid approximations and high gain control with saturation etc. Apart from these, an approach called higher order sliding mode (HOSM) control [22] is the current important topic of research. The HOSM controllers are promising to embrace the advantages of conventional SMCs to higher relative degree systems. It upholds the standard SMC gain and delivers unchattered finite time convergence.

Among various second order sliding mode controllers, one of the first algorithm proposed for nonlinear systems is twisting algorithm explained by Emelyanov et al in [23]. This controller is able to drive the output and its derivative to zero in finite time simultaneously. The main drawback of twisting controller is that it requires the derivative of output.

In order to avoid the problem due to the usage of derivative of output in second order SMC Levant introduce the super-twisting algorithm [24]. The standard super-twisting algorithm deals with time dependent Lipschitz disturbances and unknown control coefficient. Recently modifications on it allow to deal with uncertainties, perturbations and control coefficient depend on both time and state explained by Castillo et al in [25].

Chapter 3

MODELING OF TWO AREA INTERCONNECTED POWER SYSTEM

This chapter explains about the modeling of power system components and their interconnection. For a multi area interconnected system, each area consists of turbine, generator, primary control by governor and secondary control by any one of controllers. All the models are explained in this chapter.

3.1 Fundamental load frequency control loops

The active power balance determines the frequency of the power system. Any change in the demand at any part of the network results in a change in the system frequency, Thus frequency is an index to determine imbalance between active power generation and the load. The small imbalance that occurs will be taken care by the kinetic energy of the rotating system. If the imbalance is large the frequency will go beyond the working range of the plant. Thus LFC plays the important role in maintaining the balance between active power and the frequency.

Figure 3.1 shows the block diagram of a synchronous generator with basic frequency control loops in a two area interconnected system. ΔP_g is the output of speed governor, ΔP_m is the mechanical power output from the turbine, u is the output from the speed changer motor, Δf is the frequency error, ΔP_L is the load disturbance and ω is the angular

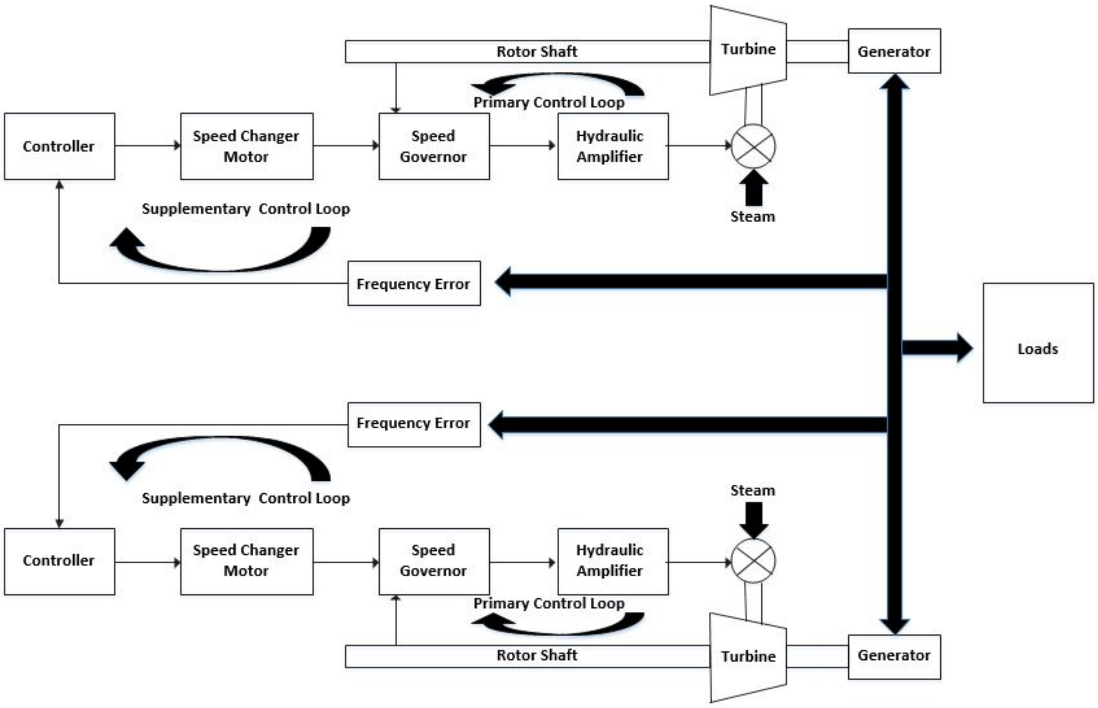

Figure 3.1: Block diagram of a generator with basic frequency control loops.

velocity. The mechanical power output from the turbine is controlled by controlling the valve which regulates the flow of steam or water on to the turbine. Steam or water have to flow continuously to meet the demand or else there will be continuous changes in the frequency. Governor is used to sense the frequency change through the control loops and the hydraulic amplifier is used to provide the force to position the valves against the pressure from the steam or water. Now, if a load change occurs the governor will sense the change in frequency which occurs in the power system and take action accordingly to increase the generation in order to bring back the frequency to the desired value. This is known as the primary frequency control. Primary frequency control alone is not capable of bringing back the frequency to the desired value. A supplementary control action is done to adjust the load reference point through the speed changer motor. This is achieved by usage of popularly used integral controllers or other advanced controllers.

3.2 Frequency response modeling

Here we are looking at a nonlinear model of two interconnected thermal power system shown in Figure 3.2. It consists of two single areas connected to each other by tie line.The area on top is referred as area 1, and the one at the bottom is referred as area 2. Each

Table 3.1: PARAMETERS USED IN BLOCK DIAGRAM

$\Delta P_{L1}, \Delta P_{L2}$	Load disturbance in area 1 and area 2.
$\Delta f_1, \Delta f_2$	Frequency error in area 1 and area 2.
$\Delta P_{tie1}, \Delta P_{tie2}$	Tie line power change between area 1 and area. 2
$\mathrm{ACE}_1, \mathrm{ACE}_2$	Area control error in area 1 and area 2.
u_1, u_2	Control input in area 1 and area 2.
B_1,B_2	Frequency response coefficient of area 1 and area 2.
$\Delta X_{g1}, \Delta X_{g2}$	Valve/gate position change of the power system in area 1 and area 2.
R_1,R_2	Speed droop coefficient of area 1 and area 2.
$\Delta P_{g1}, \Delta P_{g2}$	Mechanical power in area 1 and area 2.
T_{12}, T_{21}	Tie-line coefficients in area 1 and area 2.
T_{G1}, T_{G2}	Time constants of governors in areas 1 and area 2.
ΔP_v	The input of speed governor.
T_t	Steam chest time constant.
K_r	Reheat coefficient.
T_r	Reheat time constant.
K_p	Power system gain constant.
T_p	Power system time constant.

area contains generator, turbine, governor and controller. The turbine used is different for two areas. Reheat type turbine is used in area 1 and non-reheat type turbine in area 2. The nonlinearities considered are GDB and GRC which has been shown separately in the Figure 3.2. The occurrence of disturbance in any area affects both areas frequency and power flow through tie-lines, resulting a significant ACE value for each area. The twisting controllers placed in each area will bring the varying factors to steady state zero value. Table 1 shows the parameters used in the block diagram.

A governor is mainly designed for improving the frequency response in about 20 seconds following disturbances (such as an abrupt generator loss etc.). The transfer function of a governor $G_H\left(s\right)$ is given by

$$G_H\left(s\right) = \frac{\Delta X_g\left(s\right)}{\Delta P_V\left(s\right)} = \frac{1}{1+sT_G} \tag{3.1}$$

The range of governor time constant is $80ms \leq T_G \leq 100ms$ and the expression for input of speed governor is $\Delta P_v = u_i - \frac{1}{R_i}\Delta f_i \; (i=1,2)$. Equation (3.1) represents the

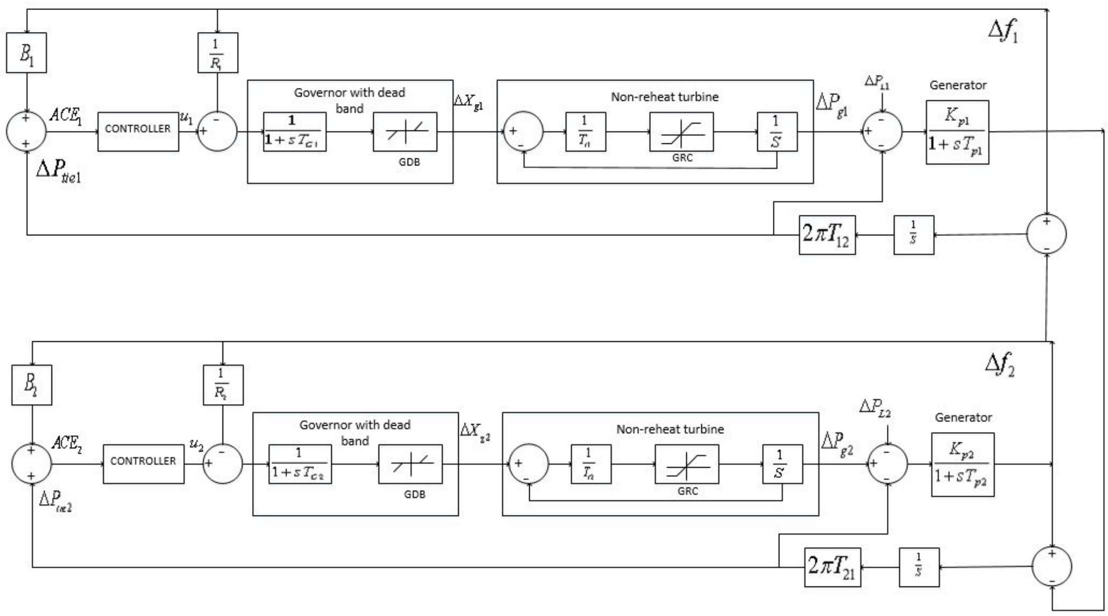

Figure 3.2: A nonlinear interconnected two-area power system with controller.

governor's linear model excluding the dead band. The governor's non-linearity is GDB. The governor may not react immediately for a change in the input signal until the input reaches a specified value known as the dead band. The dead band's value is 0.036. As the change of input frequency is ranging between ± 0.036Hz, there are no output responses for the governor. The rate of change for the generation of electricity is known as GRC which has maximum and minimum limits shown by a saturation block in the Figure 3.2. A typical thermal unit value for GRC is 3 $\%$/min, which is bounded by ± 0.0005 p.u.MW/sec for the AGC to prevent excessive control.

A thermal turbine is used to transform the thermal energy from pressurized steam into mechanical power which is directly given to the generator. Here we are using reheat and non-reheat type turbines for two areas respectively. If we use the same steam for number of times is called as reheat type turbine otherwise it is non reheat type turbine. A non-reheat turbine's transfer function $G_T(s)$ is expressed by

$$G_T(s) = \frac{\Delta P_g(s)}{\Delta X_g(s)} = \frac{1}{1 + sT_t} \tag{3.2}$$

Normally the value of steam chest time constant range is $100ms \leq T_t \leq 500ms$. Equation (3.2) represents the linear model of the turbine excluding GRC. A reheat turbine's transfer function $G_{TRH}(s)$ is given by

$$G_{TRH}(s) = \frac{\Delta P_g(s)}{\Delta X_g(s)} = \frac{1 + sK_rT_r}{(1 + sT_t)(1 + sT_r)} \tag{3.3}$$

A generator changes over the mechanical power received from the turbine into electrical power. The transfer function for a generator $G_p(s)$ is shown as

$$G_p(s) = \frac{\Delta f(s)}{\Delta P_g(s) - \Delta P_L(s) - \Delta P_{tie}(s)} = \frac{K_p}{1 + sT_p} \tag{3.4}$$

The controller must ensure the frequency error to zero and maintain tie line power to a scheduled value in a multi-area power system. The term ACE refers to the sum of the terms of frequency and tie line power error. Finally, the main objective becomes the control of ACE value to zero for any kind of nonlinear disturbances. The tie line power error and ACE are defined as

$$\Delta P_{tiei} = \frac{2\pi T_{ij}}{S}(\Delta f_i - \Delta f_j) \tag{3.5}$$

$$ACE_i = B_i\Delta f_i + \Delta P_{tie} \tag{3.6}$$

where j=2 as i=1 and j=1 as i=2.

For system variables and their derivatives, we assume zero initial conditions in the following equations. For area 1, an ordinary differential equation (ODE) model can be obtained from (3.4) to represent the relationship between the mismatch power $(\Delta P_{g1} - \Delta P_{L1} - \Delta P_{tie1})$ and the frequency error (Δf_1).

$$\Delta\dot{f}_1 = \left(\frac{K_{p1}}{T_{p1}}\right)(\Delta P_{g1} - \Delta P_{tie1} - \Delta P_{L1}) - \left(\frac{1}{T_{p1}}\right)\Delta f_1 \tag{3.7}$$

The relationship between mechanical power and the change in position of the valve/gate in area 1 is obtained from (3.2).

$$\Delta\dot{P}_{g1} = \left(\frac{1}{T_{t1}}\right)\Delta X_{g1} - \left(\frac{1}{T_{t1}}\right)\Delta P_{g1} \tag{3.8}$$

The relationship between the control input, the frequency error and the position of the valve / gate changes from (3.1)

$$\Delta \dot{X}_{g1} = \left(\frac{1}{T_{G1}}\right) u_1 - \left(\frac{1}{T_{G1}R_1}\right) \Delta f_1 - \left(\frac{1}{T_{G1}}\right) \Delta X_{g1} \tag{3.9}$$

The tie-line power error in area 1 is linearly proportional to the integral of frequency error between areas 1 and 2. From (3.5), the model is

$$\Delta \dot{P}_{tie1} = 2\pi T_{12} \left(\Delta f_1 - \Delta f_2\right) \tag{3.10}$$

For the case of area 2

$$\Delta \dot{f}_2 = \left(\frac{K_{p2}}{T_{p2}}\right) \left(\Delta P_{g2} - \Delta P_{tie2} - \Delta P_{L2}\right) - \left(\frac{1}{T_{p2}}\right) \Delta f_2 \tag{3.11}$$

$$\Delta \dot{P}_{g2} = \left(\frac{1}{T_{t2}}\right) \Delta X_{g2} - \left(\frac{1}{T_{t2}}\right) \Delta P_{g2} \tag{3.12}$$

$$\Delta \dot{X}_{g2} = \left(\frac{1}{T_{G2}}\right) u_2 - \left(\frac{1}{T_{G2}R_2}\right) \Delta f_2 - \left(\frac{1}{T_{G2}}\right) \Delta X_{g2} \tag{3.13}$$

$$\Delta \dot{P}_{tie2} = 2\pi T_{21} \left(\Delta f_2 - \Delta f_1\right) \tag{3.14}$$

Chapter 4

SLIDING MODE CONTROL

This chapter explains about the conventional and higher order sliding mode controllers. Then it explains the design of SMC of a two area interconnected power system.

4.1 Sliding mode controller

Sliding mode control (SMC) has generated great interest worldwide since a survey paper published by Utkin in 1977. SMC has been successfully applied in a wide spectrum of systems including multi-input and multi-output systems, nonlinear systems, discrete systems, large scale and infinite-dimension systems. SMC is a robust control method. The major advantage of sliding mode control is that it is insensitive to the plant parameter variations and disturbances. SMC is capable of decoupling high order systems into low order systems, which reduces the complexity of feedback design. Also, SMC is suitable for nonlinear systems, high order systems, and complex systems. SMC has been proven to be applicable in a large scope of problems, such as robotics, electric drives, process control, and vehicle and motion control.

The purpose of SMC is to drive the plant trajectory to a sliding surface and to maintain the trajectory on the sliding surface in subsequent time. The first step of designing a SMC is to select a sliding surface. The feedback controller has different controller gains depending on whether a systems trajectory is above or below the surface.

4.2 Conventional sliding mode controller

The design of conventional SMC consists of design of sliding surface and control input includes switching control and equivalent control. The switching control is a discontinuous which maintain the system trajectory on the surface and the equivalent control forces the system states to continue on the surface. Generally, it consists of two phase such as reaching phase and sliding phase. Reaching phase indicates the movement of system trajectories to the sliding surface and sliding phase corresponds to the movement of system states through the surface. The surface will direct the states to origin in phase plane means the error produced state variables are forced to zero. Finally, the sliding motion offers the convergence state variables to desired value. This will nullify the error produced due to faults. But conventional SMC have the problem of chattering. Chattering is the vibrations produced on the mechanical parts of the system due to high frequency discontinuous control input which leads to failure of system.

4.3 Higher order sliding Mode controller

The HOSM controller removes the restriction of relative degree and chattering by the use of continuous controller. There are few widely used controllers for second order SMC such as sub-optimal controller, terminal sliding mode controllers, twisting controllers and super-twisting controllers. Among them my project deals with the application of Twisting and Super-twisting algorithms for developing controllers for LFC problem. Hence these are explained in detail below.

4.3.1 Twisting controller

The twisting controller is one of the first second order SMC presented in [12]. For the second order SMC the control input u should appear on the second derivative of system state and for twisting SMC u should be in second derivative of sliding variable σ i.e relative degree 2.

$$\ddot{\sigma}(x,t) = p(x,t) + q(x,t)\,u \tag{4.1}$$

for all $(x, t) \in R^n \times R_+$

$0 \leq K_m \leq |q\,(x, t)| \leq K_m$ and $|p\,(x, t)| \leq K_a$

The twisting controller's control law

$$u = -r_1 sign\,(\sigma) - r_2 sign\,(\dot{\sigma}) \tag{4.2}$$

with the conditions

$$\begin{aligned} &(r_1 + r_2)\,K_m - K_a > (r_1 - r_2)\,K_M + K_a \\ &(r_1 - r_2)\,K_m > K_a \end{aligned} \tag{4.3}$$

This controller brings the states to equilibrium in finite time with a discontinuous control action. For the case of HOSM controller, the error variable can be directly substitute as sliding variable σ and properly chosen gain values to the control input will force the sliding variable to zero in finite time despite of any matched perturbation. Now consider the case of LFC problem, here the error variable ACE and its derivative is used to design the twisting controller as in (4.2). The convergence of ACE will ensure the settling of frequency error and tie-line power errors. The designed controller can be used for both area 1 and area 2 due to its similarity.

4.3.2 Super-twisting controller

Super-Twisting sliding mode control has many superiorities. Firstly, it is robust to external interferences and system uncertainties, and it can accurately track and regulate the system. Secondly, it only needs output information and does not require the time derivatives of the output. Consequently, the control law is relatively simple, reducing the computational burden, achieving wide application. Thirdly, the chattering caused by traditional sliding mode control algorithm can be effectively avoided, and the output signal can be continuous without chattering.

Consider the dynamic system for area 1 and area 2

$$\begin{aligned}
\Delta\dot{f}_1 &= \left(\tfrac{K_{p1}}{T_{p1}}\right)\left(\Delta P_{g1} - \Delta P_{tie1} - \Delta P_{L1}\right) - \left(\tfrac{1}{T_{p1}}\right)\Delta f_1 \\
\Delta\dot{P}_{g1} &= \left(\tfrac{1}{T_{t1}}\right)\Delta X_{g1} - \left(\tfrac{1}{T_{t1}}\right)\Delta P_{g1} \\
\Delta\dot{X}_{g1} &= \left(\tfrac{1}{T_{G1}}\right)u_1 - \left(\tfrac{1}{T_{G1}R_1}\right)\Delta f_1 - \left(\tfrac{1}{T_{G1}}\right)\Delta X_{g1} \\
\Delta\dot{P}_{tie1} &= 2\pi T_{12}\left(\Delta f_1 - \Delta f_2\right)
\end{aligned} \tag{4.4}$$

$$\begin{aligned}
\Delta\dot{f}_2 &= \left(\tfrac{K_{p2}}{T_{p2}}\right)\left(\Delta P_{g2} - \Delta P_{tie2} - \Delta P_{L2}\right) - \left(\tfrac{1}{T_{p2}}\right)\Delta f_2 \\
\Delta\dot{P}_{g2} &= \left(\tfrac{1}{T_{t2}}\right)\Delta X_{g2} - \left(\tfrac{1}{T_{t2}}\right)\Delta P_{g2} \\
\Delta\dot{X}_{g2} &= \left(\tfrac{1}{T_{G2}}\right)u_2 - \left(\tfrac{1}{T_{G2}R_2}\right)\Delta f_2 - \left(\tfrac{1}{T_{G2}}\right)\Delta X_{g2} \\
\Delta\dot{P}_{tie2} &= 2\pi T_{21}\left(\Delta f_2 - \Delta f_1\right)
\end{aligned} \tag{4.5}$$

The aim is to implement super-twisting SMC on system (4.4) and (4.5). Here we have output information and all the states of the system. So we don't need to design an observer for this system. The controller can be directly designed based on the information of states. Also the relative degree of the system is 4, so super-twisting SMC cannot stabilize the system easily. Therefore, it is necessary to consider a sliding surface of relative degree 1 for the application of super-twisting SMC.

The sliding surface is designed using the given states and output of the system. The controller designed can be used for both areas because of its similarity. So we don't require to design it again separately.
Sliding surface is

$$\sigma = c_1\Delta\dot{f}_1 + c_2\Delta\dot{P}_{g1} + c_3\Delta\dot{X}_{g1} + c_4\Delta\dot{P}_{tie1} \tag{4.6}$$

The state trajectories of the closed-loop system can be driven onto the sliding surface in finite time and further asymptotic stability of the states are established with the control law:

$$u = -\sum_{i=1}^{n-1} c_i x_{i+1} - \lambda_1 |\sigma|^{1/2} sign\left(\sigma\right) - \lambda_2 \int_0^t sign\left(\sigma\right)dt + k_n sign\left(e\right) \tag{4.7}$$

with the condition that λ_2 ¿ λ_1 where n is the relative degree, x is the state variables, e is the error that is ACE for this system and c_i,k_n,λ_1,λ_2 are constants. By properly tuning these constants we will get a control input which will nullify the effect of fault on system.

The discontinued high-frequency switching term sign(σ) is hidden under square root and other one on under integral term hence the overall equation becomes continuous. This controller brings the states to equilibrium in finite time by a continuous control action.

Chapter 5

SIMULATION & RESULTS

In this chapter simulation of the load frequency control of a two area interconnected system is detailed. Initially the load frequency control is done using the integral controller and then it's performance is compared with the conventional sliding mode controller and HOSM controllers such as twisting super-twisting controllers. The simulations are done for a system with load disturbance and parameter uncertainties such as governor dead band (GDB) and generation rate constraint (GRC).

5.1 Load disturbance considered for simulation

Step pulse of 0.02pu magnitude with unit period applied at 2sec

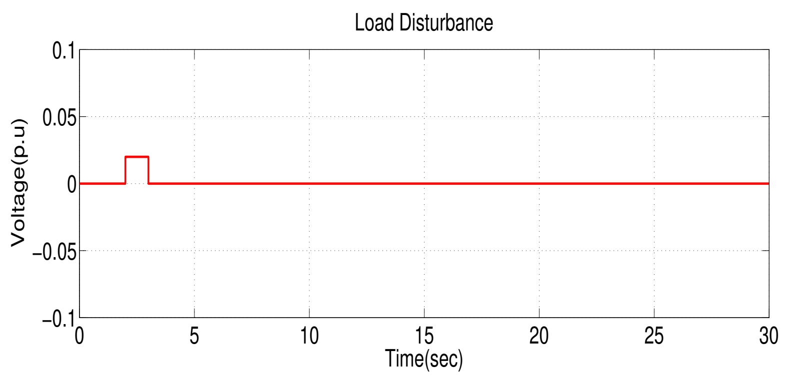

Figure 5.1: Load disturbance

5.2 Simulation of two area interconnected system

In order to compare controllers, we use Matlab/Simulink tool. Here we did the simulations on two area interconnected system with GDB and GRC nonlinearities. We have two cases

Case A: Disturbance applied to one area

We compare the controllers by applying a load disturbance of 0.02 pu on area 1 at 2 sec for a simulation time of 30 sec. There is no load disturbance added to area 2. Figure 5.2 to 5.4 show the frequency error, tie-line power error and ACE for both areas under the control of conventional sliding mode controller, twisting controller, super-twisting controller and an integral controller.

Case B: Disturbance applied to both areas

We compare the controllers by applying a load disturbance of 0.02 pu on area 1 at 2 sec and on area 2 at 4 sec for a simulation time of 20 sec. Figure 5.5 to 5.7 show the frequency error, tie-line power error and ACE for both areas under the control of conventional sliding mode controller, twisting controller, super-twisting controller and an integral controller.

For the above two cases, all of the errors are driven to zeros by all controllers successfully. The settling time for the twisting SMC is shorter and it is superior than that of others but the mechanical parts associated with the system gets problem due to discrete action of controller. Hence the super-twisting controller gets priority due to its continues control action.

Table 5.1: From Frequency v/s Time graph: Disturbance applied to **one area**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	20	0.03	-0.04
2	Conventional SMC	5.5	0.025	-0.035
3	Twisting SMC	4	0.01	-0.02
4	Super-Twising SMC	7	0.02	-0.05

Table 5.2: From Frequency v/s Time graph: Disturbance applied to **both areas**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	20	0.025	-0.04
2	Conventional SMC	7.5	0.025	-0.035
3	Twisting SMC	20	0.01	-0.02
4	Super-Twising SMC	10	0.02	-0.052

Table 5.3: From Tie-line power v/s Time graph: Disturbance applied to **one area**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	15	0.01	-0.015
2	Twisting SMC	3.5	0	-0.01
3	Super-Twising SMC	8	0.01	-0.02

Table 5.4: From Tie-line power v/s Time graph: Disturbance applied to **both areas**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	9	0.01	-0.02
2	Twisting SMC	6	0.01	-0.005
3	Super-Twising SMC	9.5	0.02	-0.15

Table 5.5: From ACE v/s Time graph: Disturbance applied to **one area**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	20	0.03	-0.04
2	Twisting SMC	4	0.01	-0.02
3	Super-Twising SMC	7	0.02	-0.05

Table 5.6: From ACE v/s Time graph: Disturbance applied to **both areas**

Case	Controller	Settling time	Overshoot	Undershoot
1	Integral	15	0.015	-0.03
2	Twisting SMC	3	0.005	-0.01
3	Super-Twising SMC	10	0.01	-0.35

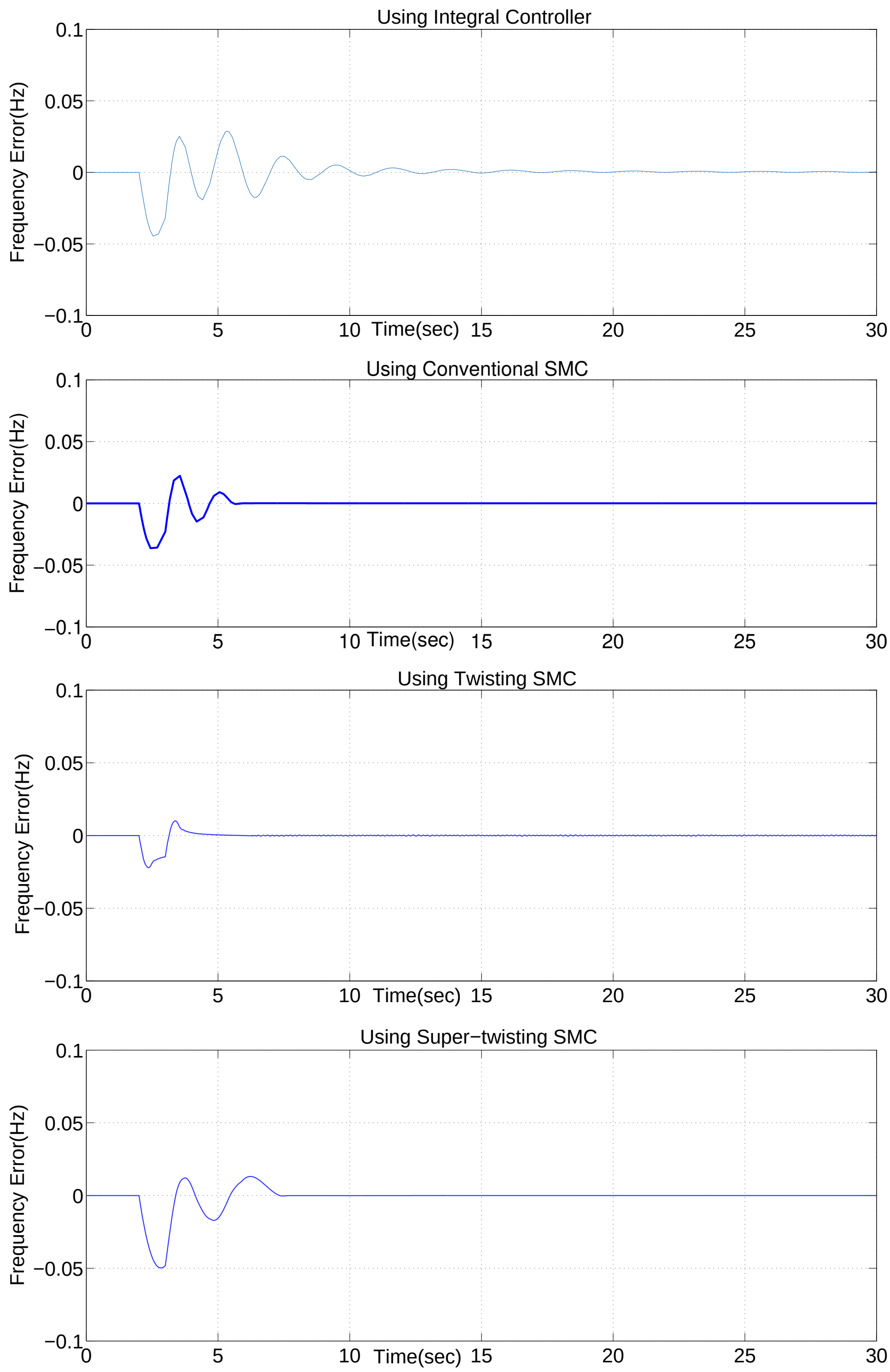

Figure 5.2: Frequency v/s Time graph when disturbance applied to one area.

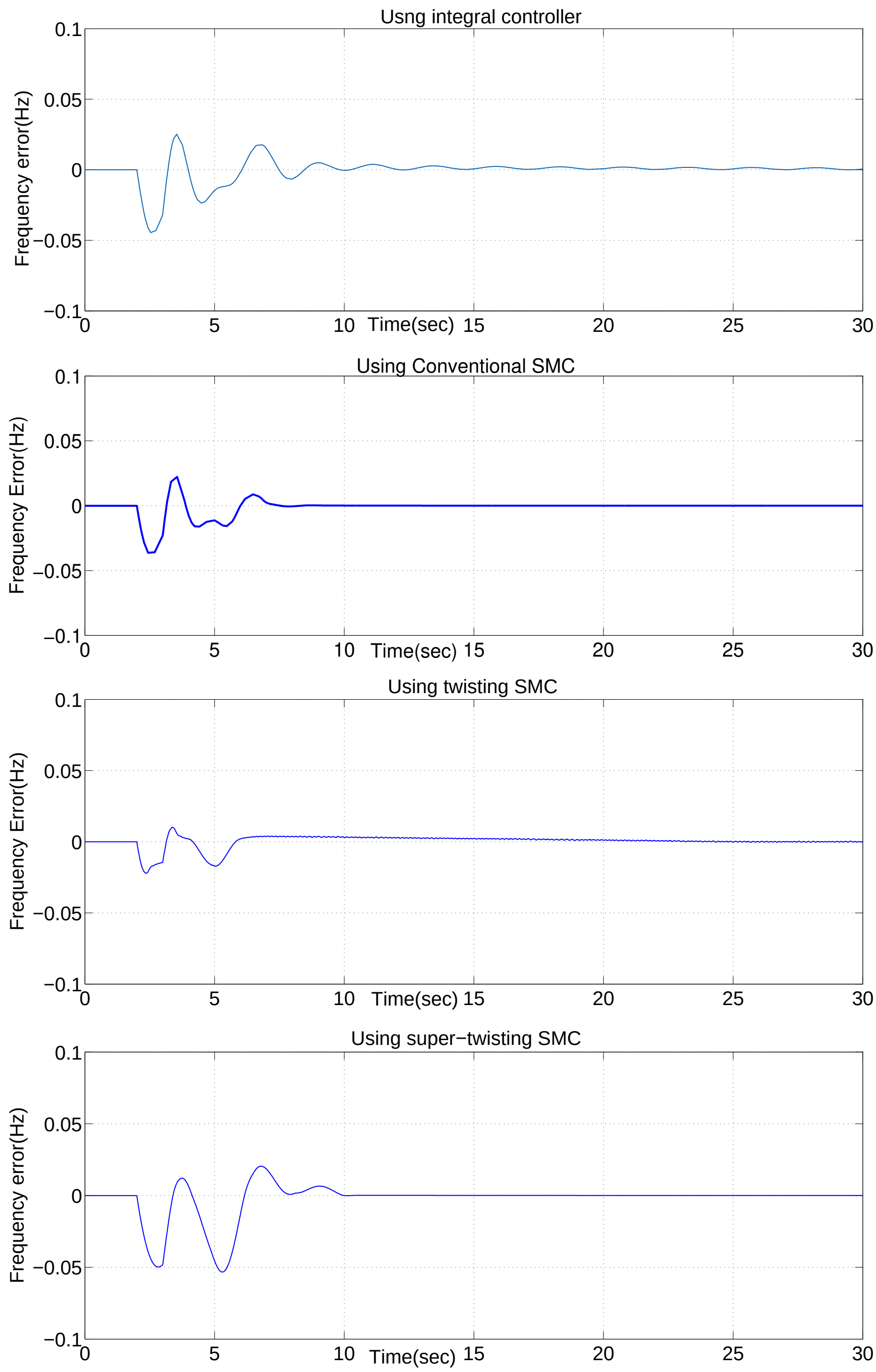

Figure 5.3: Frequency v/s Time graph when disturbance applied to both areas.

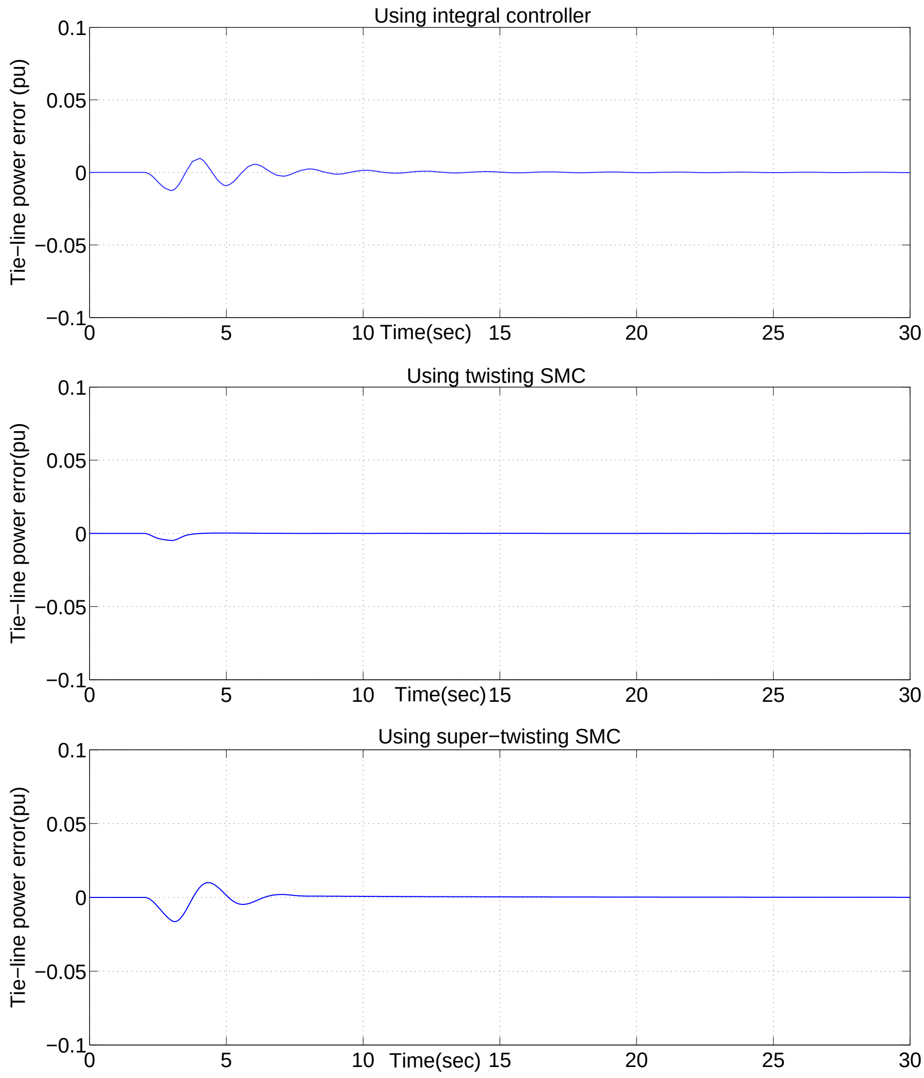

Figure 5.4: Tie-line power v/s Time graph when disturbance applied to one area.

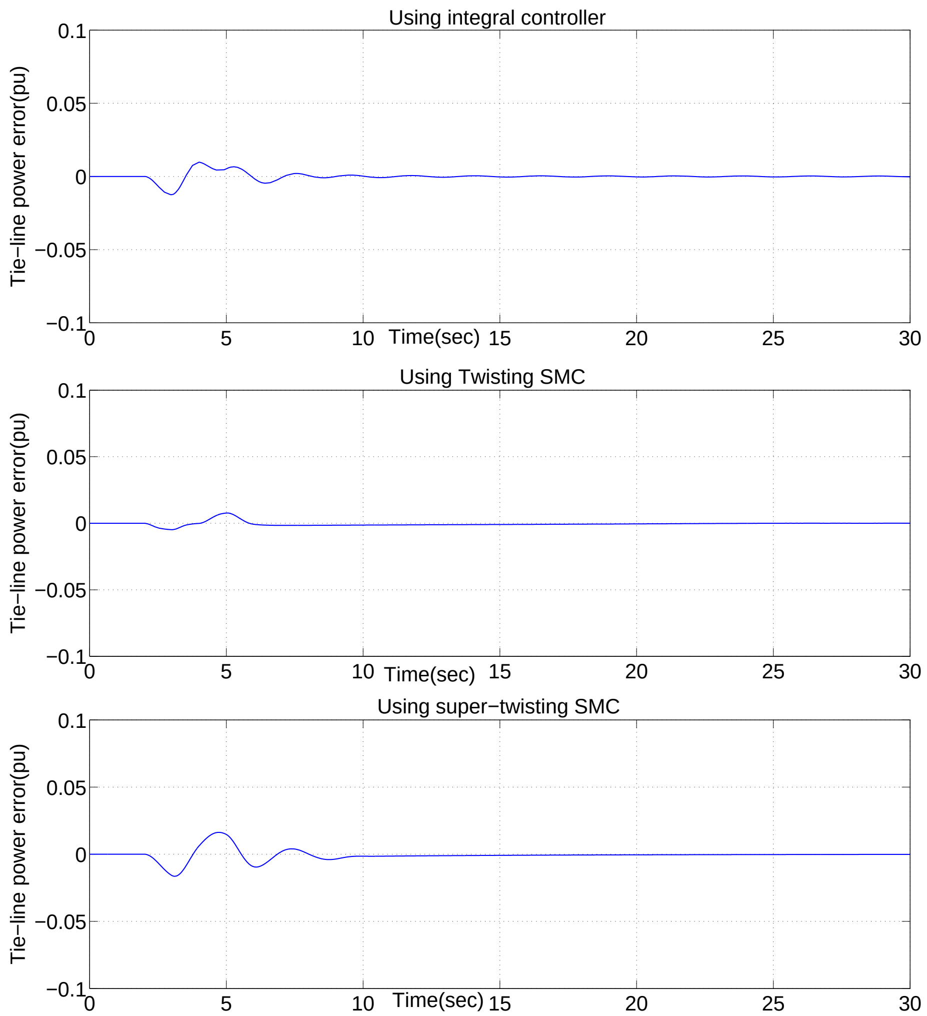

Figure 5.5: Tie-line power v/s Time graph when disturbance applied to both areas.

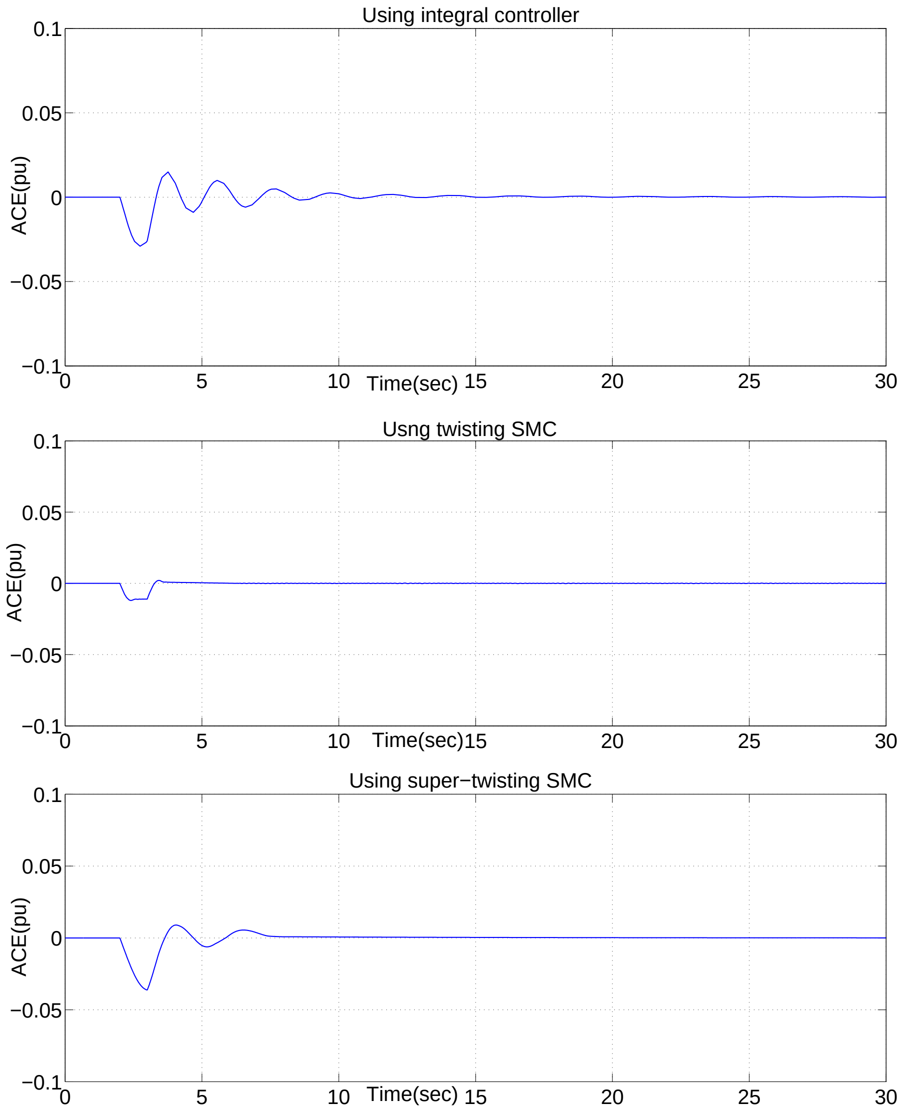

Figure 5.6: ACE v/s Time graph when disturbance applied to one area.

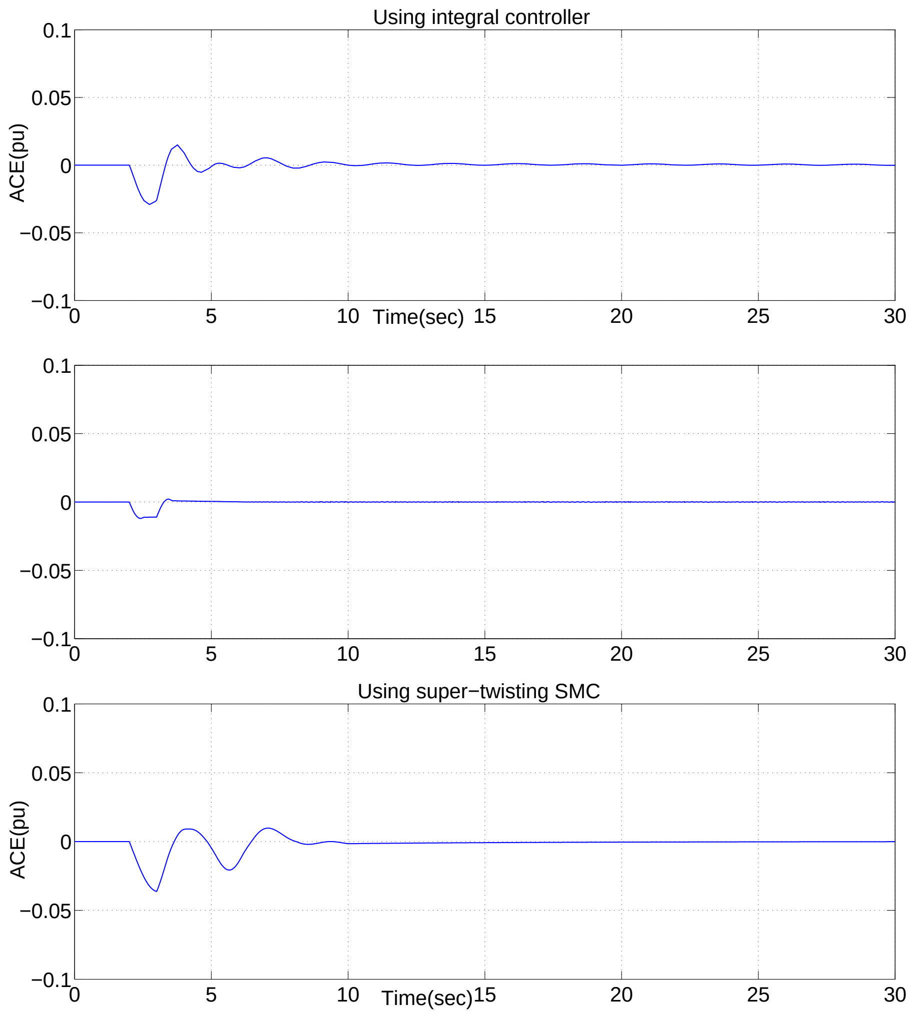

Figure 5.7: ACE v/s Time graph when disturbance applied to both areas.

Chapter 6

CONCLUSION & SCOPE OF FUTURE WORK

In this project, twisting and super-twisting SMC controllers are proposed for the LFC. The two area interconnected thermal power system considered have non linearities GDB and GRC. The non-reheat type of turbine is used for one area and reheat for other one. The mathematical model of the system is derived for analysis and two cases has been considered by apply a disturbance to one area and to both areas. Our control goal is to bring the value of ACE to zero even the presence of disturbance.

The results of the simulation show the convergence of ACE, which successfully includes frequency and tie-line error terms to zero and analyzed it separately. Twisting and supertwistiing SMCs are superior in terms of settling time, overshoots and undershoots than integral controller and which is validated using simulation results. However the super-twisting controller is always becomes popular choice among people due to the continuous control action and there b y allowing uncertainty.

Publications Related to this Work

6.1 Journals

- Albert poulose and Ramesh kumar. P, "Performance Analysis of Load Frequency Control on Two Area Interconnected Power System using Super-Twisting Controller,".

6.2 Conferences

- Albert poulose and Ramesh kumar. P, "Performance Analysis of Load Frequency Control for a Two-area Interconnected Power System using Twisting Control," *International Conference on Intelligent Computing and Control Systems*, [ICICCS-2019]-IEEE, 15-17 May 2019.

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APPENDIX

The nominal system parameter values are listed as follows.

$T_{g1} = 0.08s, T_{g2} = 0.09s$
$T_{t1} = 0.3s, T_{t2} = 0.4s$
$T_{p1} = 20s, T_{p2} = 25s$

$K_{p1} = 120Hz/pu.MW, K_{p2} = 130Hz/pu.MW$

$R_1 = 2.4Hz/pu.MW, R_2 = 2.6Hz/pu.MW$

$B_1 = 0.425puMW/Hz, B_2 = 0.44pu.MW/Hz$

$2\pi T_{12} = 0.545pu.MW/rad$
$2\pi T_{21} = 0.6pu.MW/rad$

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