Higher Order Sliding Mode Based Load Frequency Control for a Two-area Interconnected Power System

ALBERT POULOSE
S4 Mtech PS
TCR17EEPS03

Guided By

Dr. Ramesh Kumar. P
EEE Dept.

OUTLINE

INTRODUCTION

The load frequency control (LFC) is recognized as the automatic generation control (AGC) deals with the **frequency** and **active power** .

- Primary Control by Governor mechanism.
- Secondary Control or Supplementary control by
  - Integral controllers
  - Sliding mode controllers (SMC)

Higher order sliding mode (HOSM) control is introduced which exhibit better prospects for

- Fast and Finite time convergence.
- High precision control.

Normally used HOSM controllers are **Twisting** and **Super-twisting** controllers.

LITERATURE SURVEY

1. Sliding Mode Based Load Frequency Control for a Two-area Interconnected Power System- Jianping guo and Lili dong

- Non-reheat and reheat type turbines are used.
- The simulation results demonstrate that the control goal is successfully achieved despite the presences of load disturbance, parameter variations, and nonlinearities using conventional SMC.
- Compared with popularly used Integral controller and the simulation results show the superiority of the SMC based LFC to Integral based LFC in terms of settling time and overshoot percentage.

2. Second Order Sliding Mode Control Of Active Suspension System with Super twisting Algorithm and Disturbance Observer- Keyur Patel and Axaykumar Mehta

- A super-twisting controller is designed for the active suspension control of quarter car system.
- The chattering in the control input is attenuated and that improves the overall performance of the system.
- disturbance observer is used to estimate the disturbance in prior which improves the performance of the system.
- The stability of the system is also proved with the Lyapunov function.

LITERATURE SURVEY-Continue

3. Discrete-time twisting controller without numerical chattering: analysis and experimental results with an implicit method- Olivier Huber, Vincent Acary, Bernard Brogliato and Franck Plestan

- This paper presents the results of an experimental study of two discrete-time twisting controllers: the implicit and the explicit one.
- They sustain the theoretical superiority of the implicitly discretized version, as shown in previous work.

4. Load frequency control of interconnected five-area power system with pid controller- Avinash Sahu and Dr. L.B.Prasad

- Normalize the area control error (ACE), frequency error and tie-line power error despite the presence of system uncertainties and exterior load disturbance using PID controller.
- Controller shows fast response, less undershoot and small peak overshoots.
- It considered single area, two area and five area systems with PID controller.

PROBLEM FORMULATIION

- Optimal control of frequency, tie-line power flow and Area Control Error (ACE) of two area interconnected power system need to be solved using appropriate controller in the presence of disturbance.

DETAILED OBJECTIVE

- Design of HOSM controllers such as**Twisting** and **Super-twisting** controllers for optimal LFC of two area interconnected power system.

- **Comparison** of HOSM controllers with existing methods.

BLOCK DIAGRAM

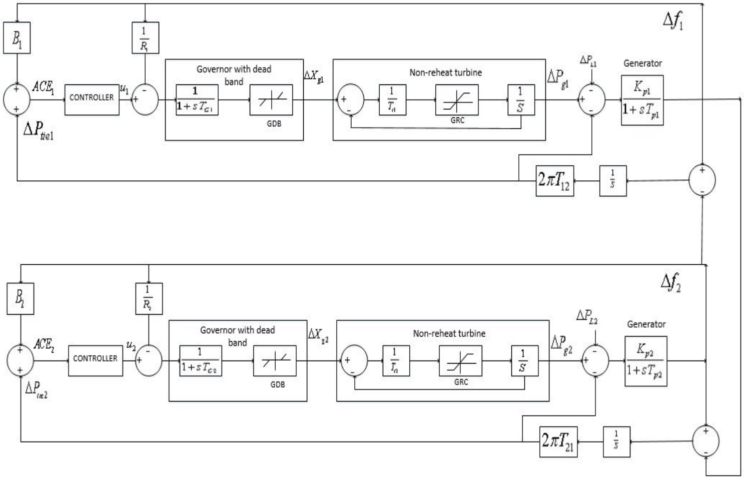


Figure: 1

Terms

ω = Rotational speed(rad/sec)
α = Rotational acceleration
δ = Phase angle of a rotating machine

T_{net} = Net torque in a machine
T_{mech} = Mechanical torque exerted on the machine by the turbine
T_{elec} = Electrical torque exerted on the machine by the generator

P_{net} = Net accelerating power
P_{mech} = Mechanical power input
P_{elec} = Electrical power output

I = Moment of inertia for the machine
M = Angular momentum of the machine

- All quantities (except phase angle) will be in per unit on the machine base.

Some basic relationships

$I\alpha = T_{net}$
M = ω I
P_{net} = ω T = $\omega(I\alpha)$ =M α

- Consider a single rotating machine has a steady speed of ω_0 and phase angle δ_0
- Due to various disturbances, the machine will be subjected to differences in mechanical and electrical torque, causing it to accelerate or decelerate torques.

$\Delta\omega \Rightarrow$ deviations of speed
$\Delta\delta \Rightarrow$ deviations of phase angle

Generally

$$P_{net} = P_{mech} - P_{elec}$$

here

$$\Delta P_{net} = \Delta P_{mech} - \Delta P_{elec}$$
$$= M\frac{d}{dt}(\Delta\omega)$$
$$= Ms\Delta\omega$$

ie.

$$\Delta\omega = \frac{1}{Ms}[\Delta P_{mech} - \Delta P_{elec}]$$

Relationship between mechanical and electrical power and speed change.

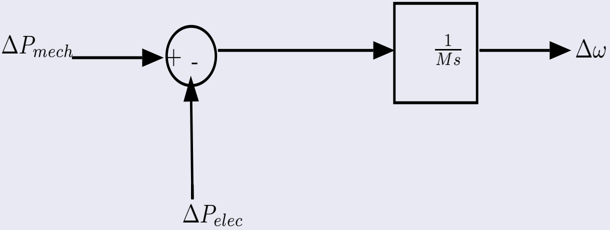


Figure: 2

Relationship between the change in load due to the change in frequency

$\Delta P_L = D\Delta\omega$

- D is expressed as percent change in load divided by percent change in frequency

Combined generator-load model

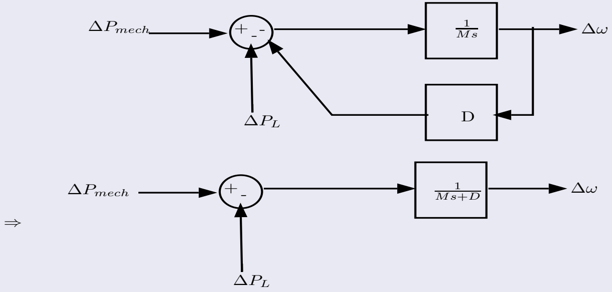


Figure: 3

SYSTEM MODELING-Continue

Prime mover Model

- Prime mover driving a generator unit may be a **steam turbine** or a **hydroturbine**.

Model for a non-reheat turbine

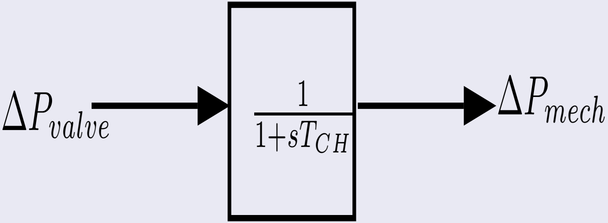


Figure: 4

- T_{CH} is the charging time constant
- ΔP_{valve} is the pu change in valve position from nominal

SYSTEM MODELING-Continue

Combined prime mover-generator-load model for a single generating unit

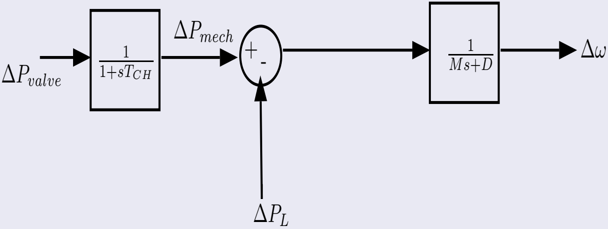


Figure: 5

- Governing mechanism **senses the machine speed** and **adjust the input valve** to change mechanical power output to compensate for load changes and to **restore frequency** to nominal value.
- To force the frequency error to zero,we must provide a **reset action**.
- Reset action is done by integrating the frequency error, which is the difference between actual speed and desired or reference speed

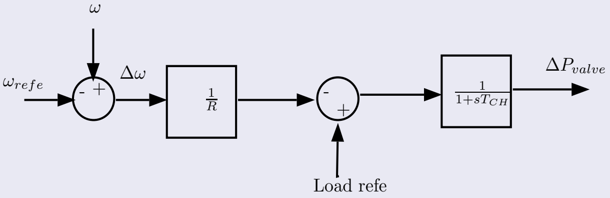


Figure: 6

- The value of R determines the change on the units output for a given change in frequency

$R = \frac{\Delta\omega}{\Delta P}$ pu

Block diagram of governor-prime mover-generator model

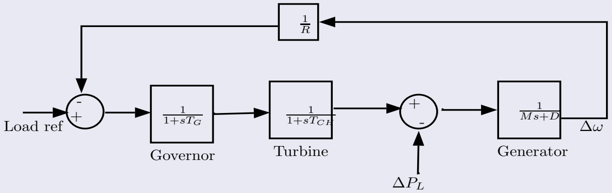


Figure: 7

- Power flow through transmission line can be modeled using **DC load flow** method.

$$P_{tieflow} = \frac{1}{X_{tie}}(\theta_1 - \theta_2)$$
$$\Delta P_{tieflow} = \frac{1}{X_{tie}}(\Delta\theta_1 - \Delta\theta_2)$$
$$= \frac{T}{s}(\Delta\omega_1 - \Delta\omega_2)$$

Where T=377 $\times \frac{1}{X_{tie}}$ is the **tie-line stiffness coefficient**

- The power flow over the transmission line will appear as positive load to one area and an equal but negative load to the other or vice versa,depending on the direction of flow.

SYSTEM MODELING-Continue

Block diagram of governor-prime mover-generator model-Interconnected system

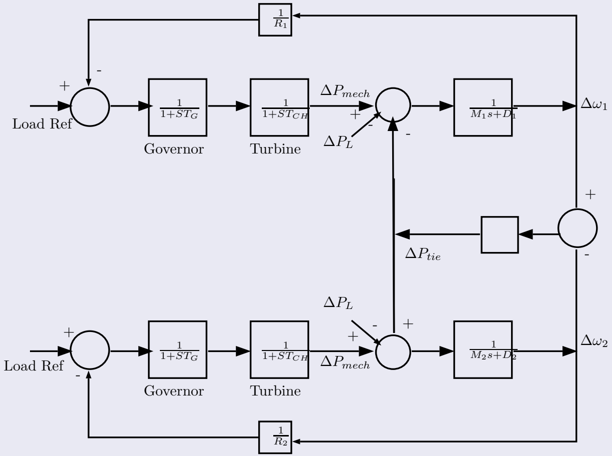


Figure: 8

FINAL BLOCK DIAGRAM

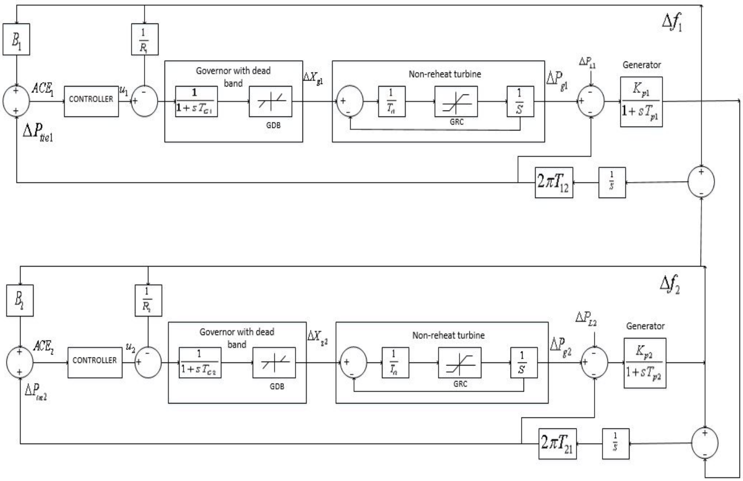


Figure: 9

SYSTEM MODELING-Continue

When disturbance or load change ΔP_{L1} occurs in area-1

Frequency change, $\Delta\omega = \frac{-\Delta P_{L1}}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}$

Change in net interchange power $\Delta P_{net-int1} = \frac{-\Delta P_{L1}\left(\frac{1}{R_2}+D_2\right)}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}$

We should adjust the generation in such a way
ΔP_{gen1}=ΔP_{L1} and ΔP_{gen2}=0

Objectives

- Hold **system frequency** at or very close to a specified nominal value.
- Maintain correct value of **interchange power** between control areas
- Maintain each units generation at the **most economic** value.

- The required change in generation is called as **Area Control Error(ACE)**
- ACE represents the shift in the areas generation required to restore frequency and net interchange to their desired values

The equation for ACE for each areas:

$$ACE_1 = -\Delta P_{net-\mathrm{int}1} - B_1 \Delta\omega$$
$$ACE_2 = -\Delta P_{net-\mathrm{int}2} - B_2 \Delta\omega$$

$B1, B2$ are called **Frequency Bias Factors**

By substituting

$$ACE_1 = \left(\frac{\Delta P_{L1}\left(\frac{1}{R_2}+D_2\right)}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}\right) - \left(\frac{1}{R_1} + D_1\right)\left(\frac{-\Delta P_{L1}}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}\right) = \Delta P_{L1}$$

$$ACE_2 = \left(\frac{-\Delta P_{L1}\left(\frac{1}{R_2}+D_2\right)}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}\right) - \left(\frac{1}{R_1} + D_2\right)\left(\frac{-\Delta P_{L1}}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2}\right) = 0$$

- The integral action of the supplementary controller will guarantee a reset of ACE to zero ,even when B_1 and $B_2$are not adjustable.

Automatic Generation Control (AGC) can be done by two control action

- Supplementary control action
- Tie-line control action

Supplementary control action

- Once a load change occurred,a supplementary control must act to restore the frequency to nominal value.
- This can be done by adding a reset control to the governor.

Normally used reset controller is **Integral Controller**

- Reset control action will force the frequency error to zero by adjustment of the reference set point.

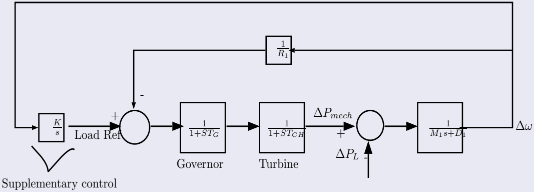


Figure: 10

Tie-line control action

- When two utilities interconnect their systems,they can **sell and buy power** with neighbouring systems.
- If one system has a **sudden loss of generation** unit,Units throughout all the interconnection will experience a **frequency change** and can help in frequency restoring.
- Control system must use **two informations**:
  1.The system frequency
  2.Net power flowing in or out over the tie lines.

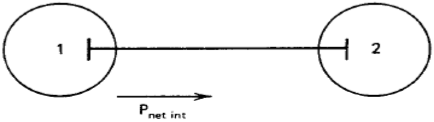
Case-1:If f decreasing and net interchange power leaving the system increase
$\Rightarrow$ Load increase has occurred **outside** the system.
Case-2:If f decreasing and net interchange power leaving the system decrease
$\Rightarrow$ Load increase has occurred **inside** the system.

SYSTEM MODELING-Continue

Generation Control

Tie-line frequency control actions for two-area system.

$\Delta\omega$	$\Delta P_{\text{net int}}$	Load change	Resulting control action
−	−	ΔP_{L_1} + ΔP_{L_2} 0	Increase P_{gen} in system 1
+	+	ΔP_{L_1} − ΔP_{L_2} 0	Decrease P_{gen} in system 1
−	+	ΔP_{L_1} 0 ΔP_{L_2} +	Increase P_{gen} in system 2
+	−	ΔP_{L_1} 0 ΔP_{L_2} −	Decrease P_{gen} in system 2



ΔP_{L_1} = Load change in area 1
ΔP_{L_2} = Load change in area 2

Figure: 10

- There are two main **advantages** of SMC

  1) **Dynamic behaviour** of the system can be controlled by the particular choice of the sliding function.
  2) The **closed loop response** becomes totally insensitive to some particular uncertainties which are bounded.

From practical point of view SMC allows for controlling nonlinear processes subject to **external disturbances** and **heavy model uncertainties.**

- SMC consist of two phases

Phase 1 :Sliding surface design
Phase 2 :Control input design

- The sliding surface depends on the tracking error together with a certain number of its derivatives
  ie, sliding surface $\sigma = \sigma\left(e, \dot{e}, \ddot{e}, ..., e^{(k)}\right)$
- The function σ should be selected in such a way that it is vanishing.
- $\sigma = 0$, gives rise to a **stable** differential equation.

Typical choice for the sliding manifold is

$$\sigma = \dot{e} + c_0 e$$
$$\sigma = \ddot{e} + c_1 \dot{e} + c_0 e$$
$$\sigma = e^{(k)} + \sum_{i=0}^{k-i} c_1 e^{(i)}$$

Finding a control action that directs the system trajectories onto the sliding manifold,or able to steer the σ variable to zero in finite time.

There are two parts in control input

- Bring the system tragectory to the sliding surface $\Rightarrow$ **Equivalent control**
- Maintain the system tragectory on the surface $\Rightarrow$ **Switching control**

Common feature of all sliding mode based techniques is that no precise information about the original system dynamics is requested, the controlled system being treated as a completely uncertain.

- Conventional SMC provide **robust and high-accuracy solutions** for a wide range of control problems under uncertainty conditions. However, **restrictions remain**.

Restriction-1

The constraint to be held at zero in conventional sliding modes of degree one, which means that the control needs to explicitly appear in the first time derivative of the constraint. Thus, one has to **search for an appropriate constraint**.

Restriction-2

High-frequency control switching may easily cause unacceptable practical complications (**chattering effect**).

- The chattering effect can degrade the system performance or may even lead to instability and may even damage the plant

TWISTING SMC

- The twisting controller is the first proposed second order SMC and the given task is accomplished exactly and in finite time by means of **discontinuous control** action.

formula

$u = -r_1 sign(\sigma) - r_2 sign(\dot{\sigma})$ where $r_2 \succ r_1$

- The twisting controller in the above equation guarantees the sliding variable dynamics to the desired value in finite time.

Block Diagram Realization

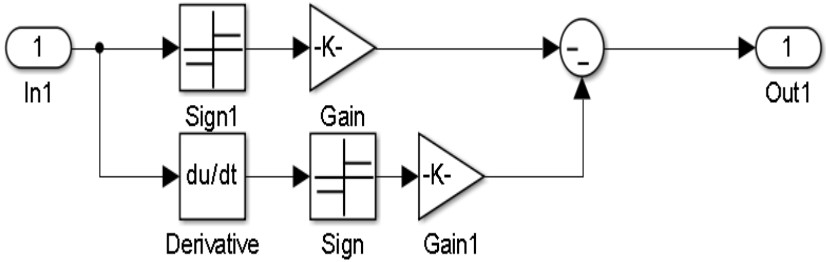


Figure: 11

TWISTING SMC-Continue

Control input

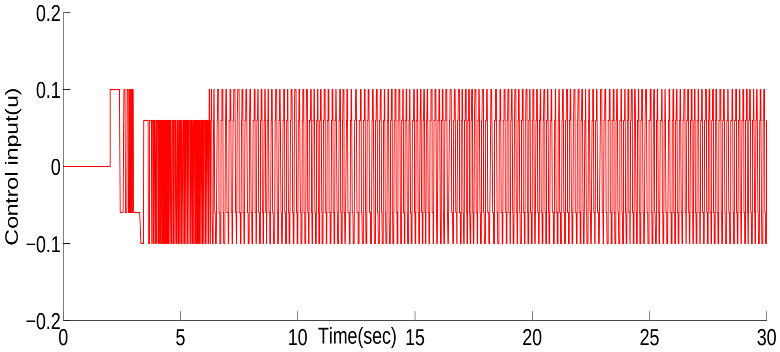


Figure: 12

TWISTING SMC-Continue

- The Twisting controller ensures finite time convergence and disturbance rejection with discontinues control action but it has the effect of **chattering**.

- Chattering is a **High frequency** movement that makes the state trajectories **Quick oscillation** around the sliding surface.

- **Degrade** the system effectiveness.
- **Fast damage** of mechanical parts of the system.

- Super-twisting controller is free from chattering due to continuous control action.

Algorithm

$$u = -k_1|\sigma|^{1/2} sign(\sigma) - k_2 \int sign(\sigma)\, dt$$

where $k_2 \succ k_1$

- The control action given by the super-twisting algorithm drives the sliding variable to the desired value in finite time.

SUPER-TWISTING SMC-Continue

Block Diagram Realization

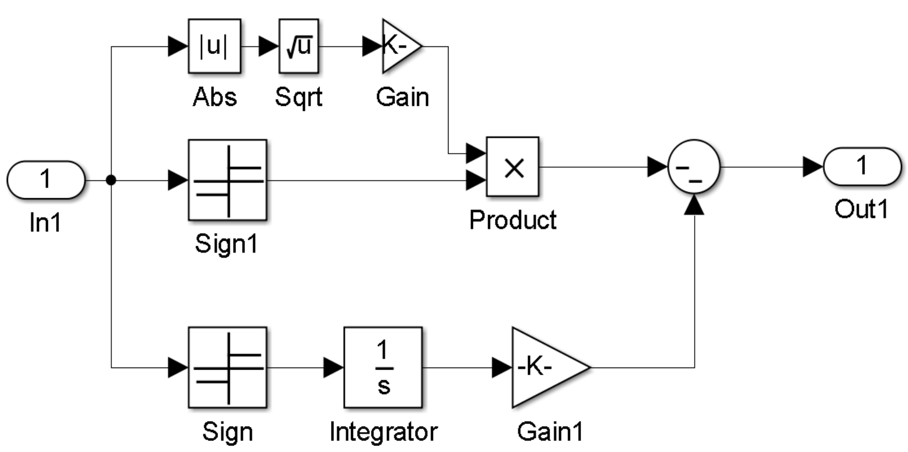


Figure: 13

SUPER-TWISTING SMC-Continue

Control input

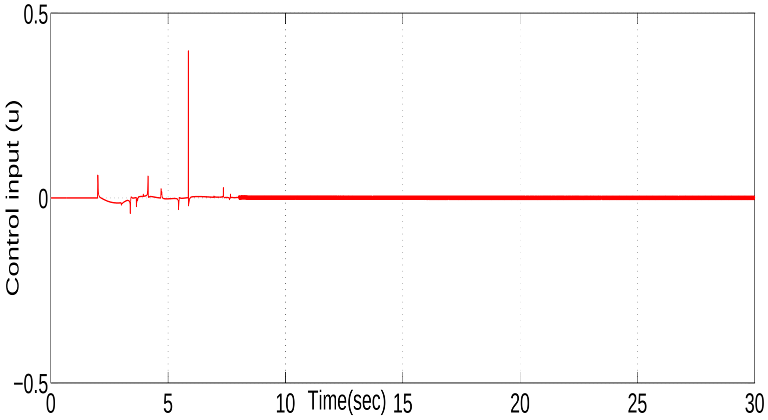


Figure: 14

SIMULATION PARAMETERS

The nominal system parameter values are listed as follows.

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

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

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

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

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

LOAD DISTURBANCE CONSIDERED FOR SIMULATION

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

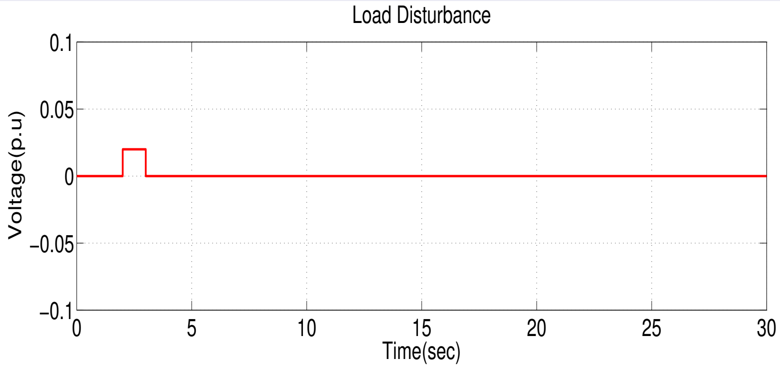


Figure: 15

SIMULATION DIAGRAM

Using Integral Controller

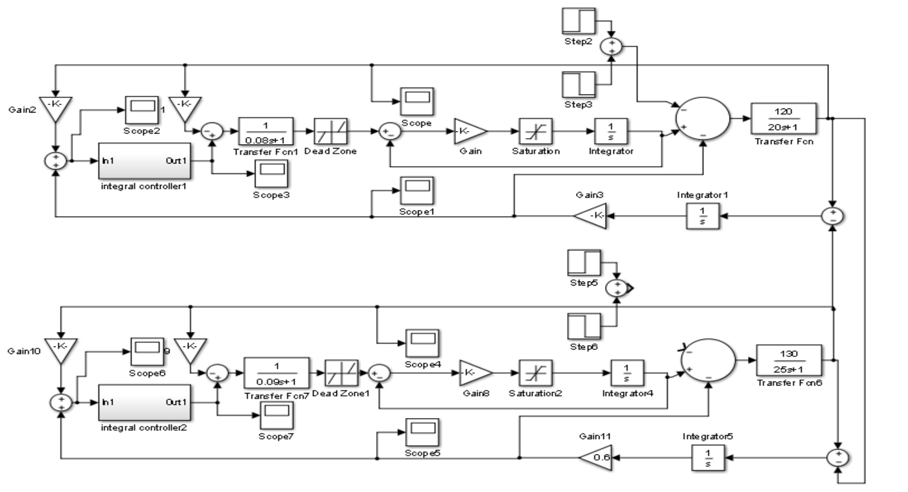
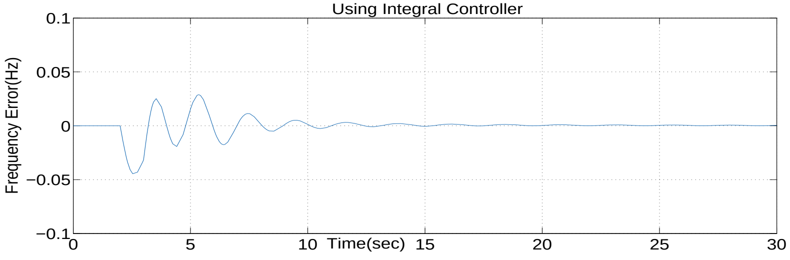


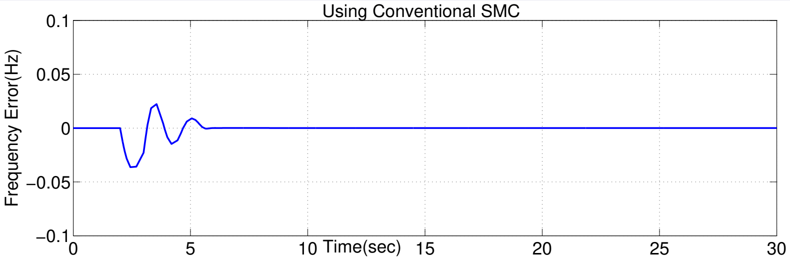
Figure: 16

Frequency v/s Time

Integral v/s Conventional SMC

Disturbance applied to one area: Area-1 at 2sec

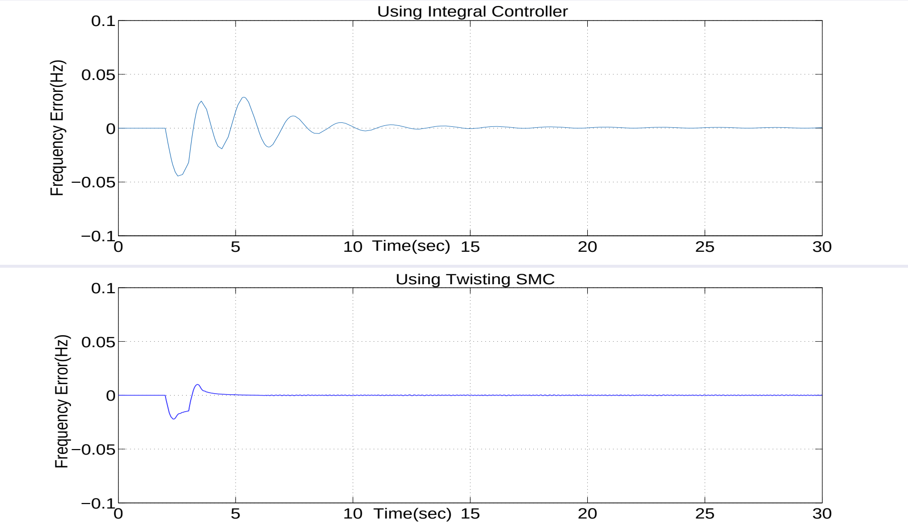




Frequency v/s Time

Integral v/s Twisting

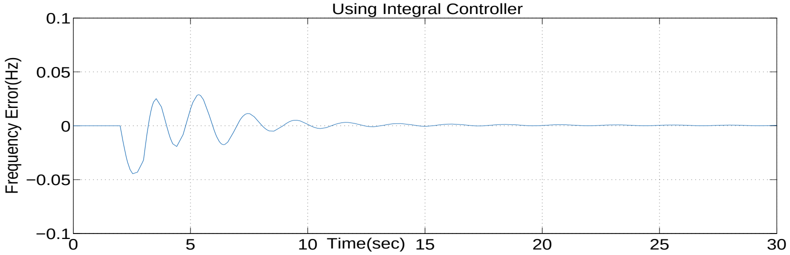
Disturbance applied to one area: Area-1 at 2sec

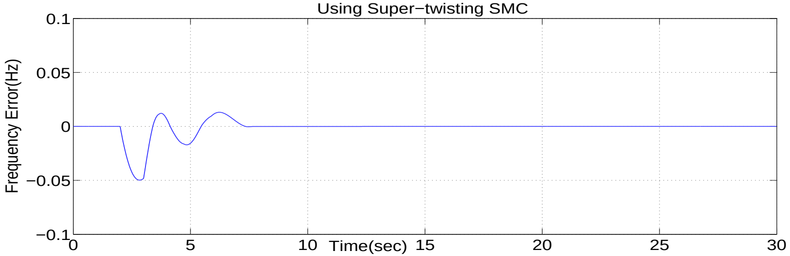


Frequency v/s Time-Continue

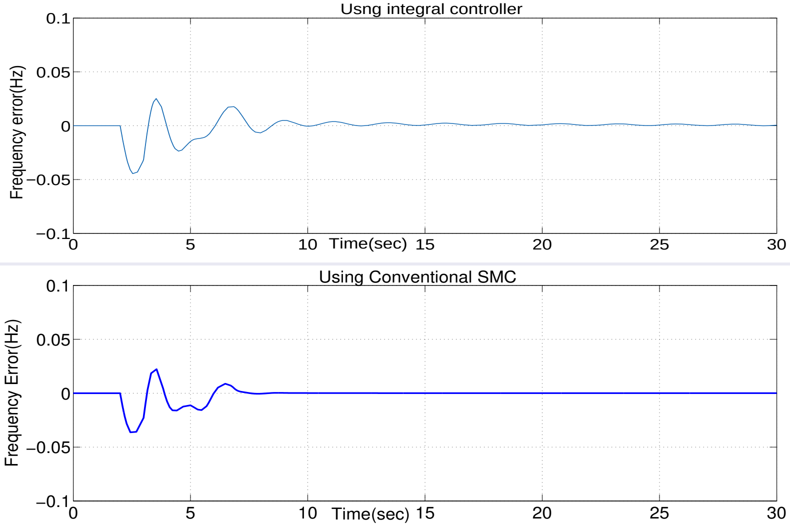
Integral v/s Super-Twisting

Disturbance applied to one area: Area-1 at 2sec

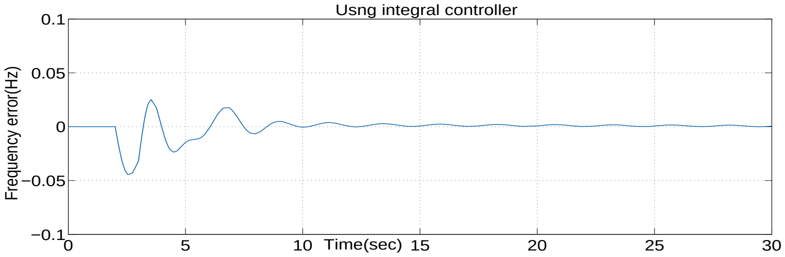


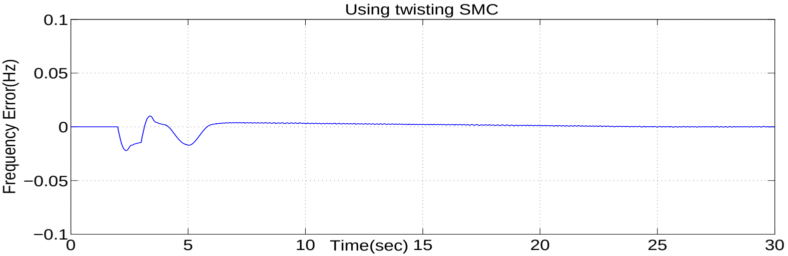


Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec



Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec





Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec

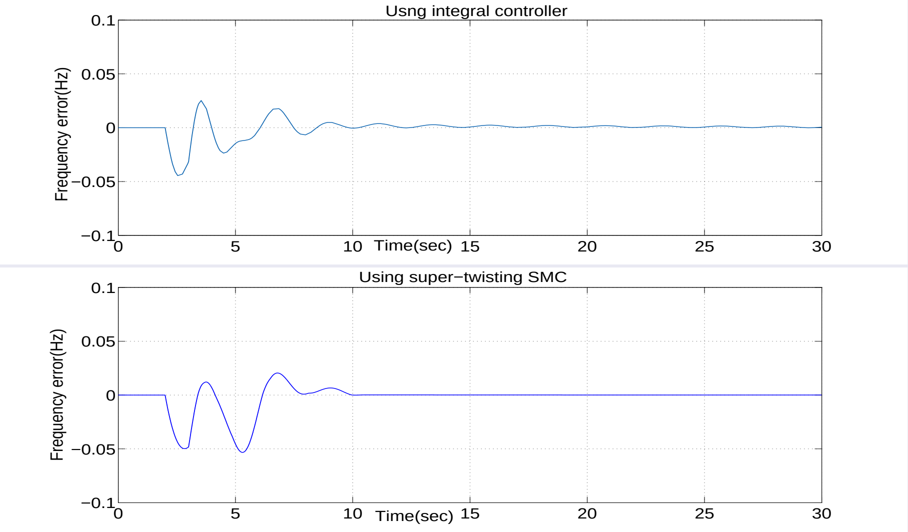


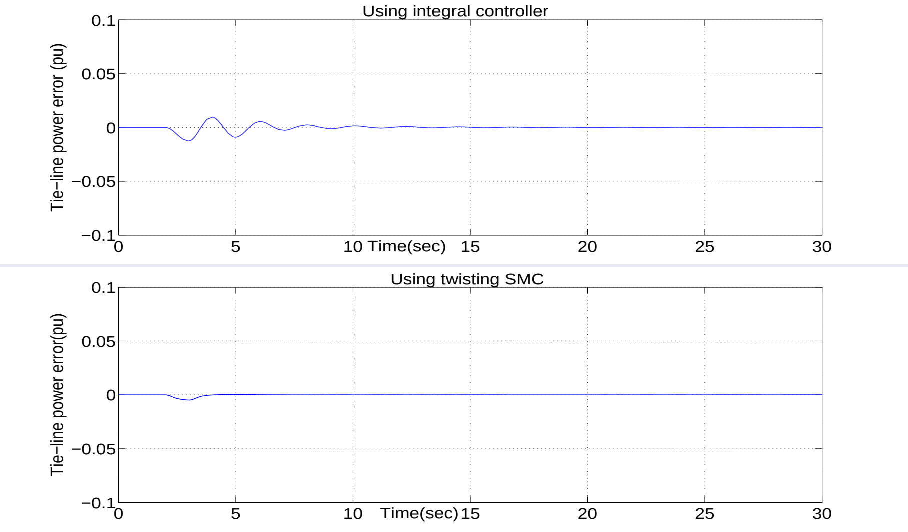
Table: Disturbance applied to **one area**

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: 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

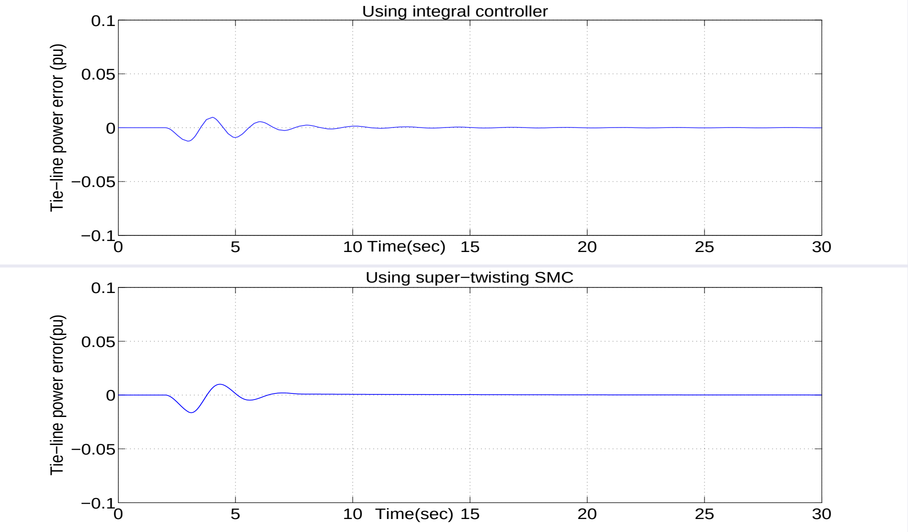
Disturbance applied to one area: Area-1 at 2sec



Tie-line power v/s Time-Continue

Integral v/s Super-Twisting

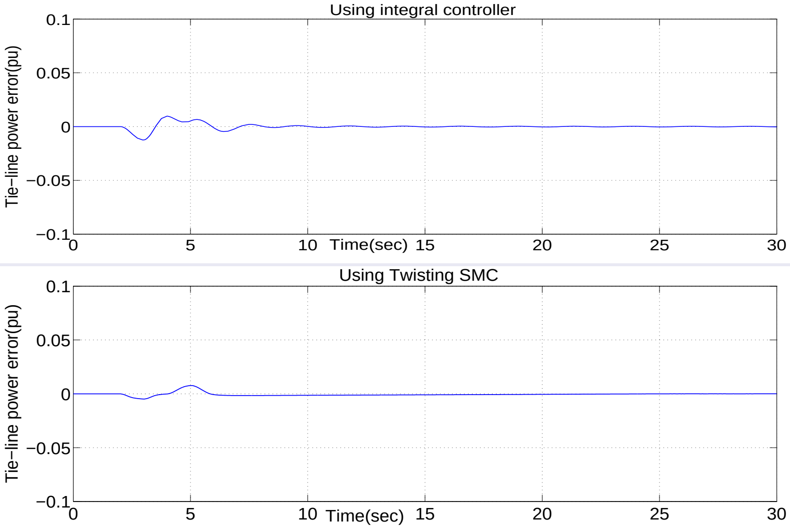
Disturbance applied to one area: Area-1 at 2sec



Tie-line power v/s Time-Continue

Integral v/s Twisting

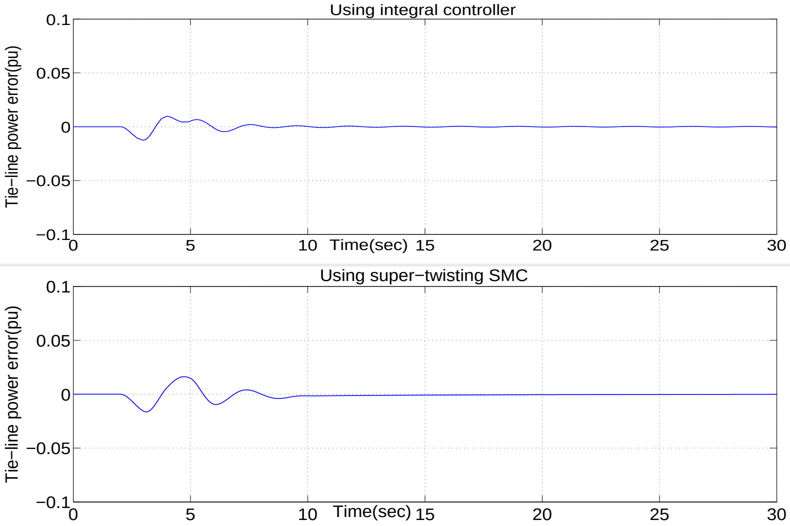
Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec



Tie-line power v/s Time-Continue

Integral v/s Super-Twisting

Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec



PERFORMANCE ANALYSIS

From Tie-line power v/s Time graph

Table: 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

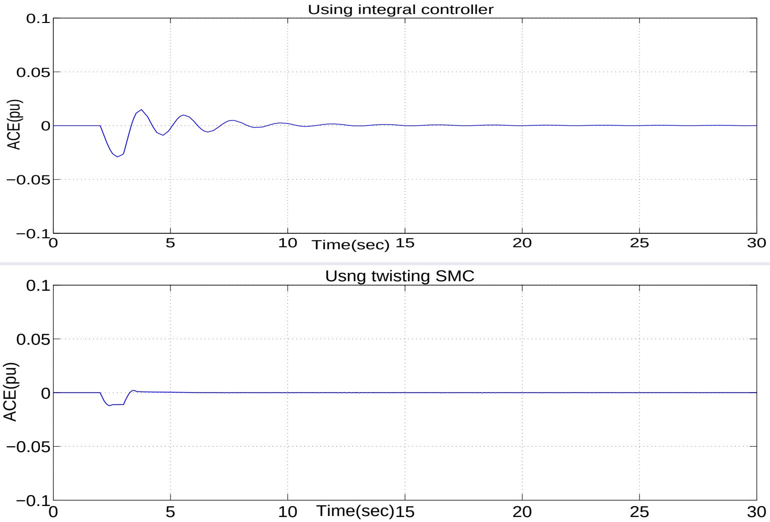
Table: Disturbance applied to **both areas**

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

ACE v/s Time

Integral v/s Twisting

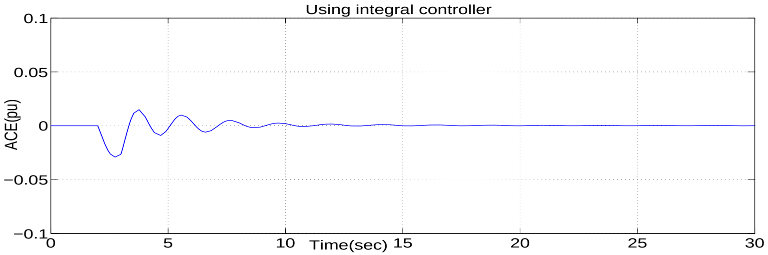
Disturbance applied to one area: Area-1 at 2sec

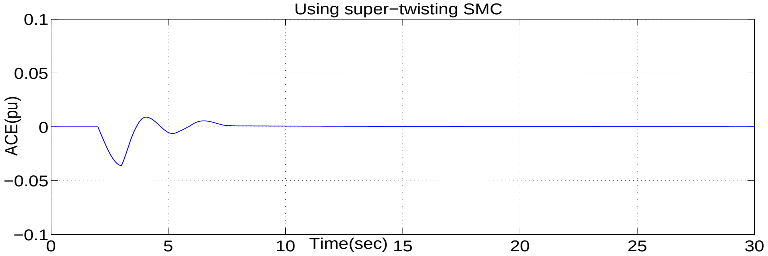


ACE v/s Time-Continue

Integral v/s Super-Twisting

Disturbance applied to one area: Area-1 at 2sec

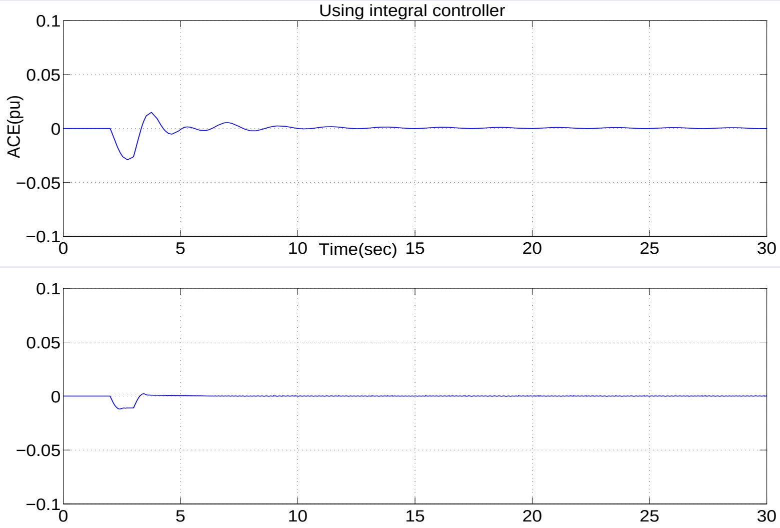




ACE v/s Time-Continue

Integral v/s Twisting

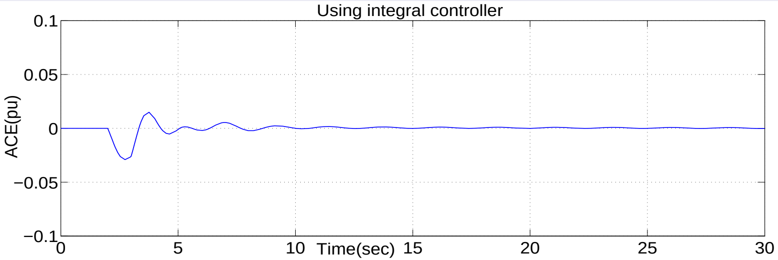
Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec



ACE v/s Time-Continue

Integral v/s Super-Twisting

Disturbance applied to both areas: Area-1 at 2sec and Area-2 at 4sec



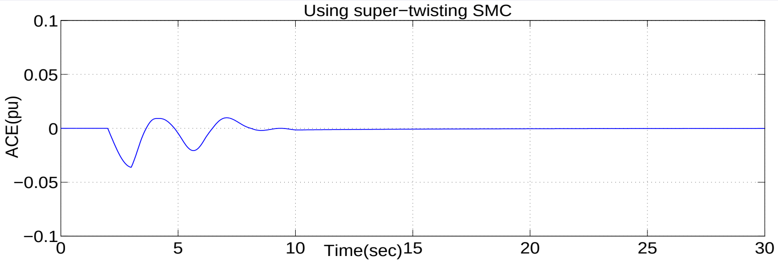


Table: Disturbance applied to **one area**

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: 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

CONCLUSION & FUTURE SCOPE

Twisting and Super-Twisting SMCs are much better than integral controller for the case of **convergence time, overshoots and undershoots** of frequency change, tie-line power change and ACE of two area interconnected system.

Twisting SMC is **discontinuous control** hence chattering will appear on the actuator and mechanical parts of the system but super-twisting SMC is free from chattering due to continuous control.

Instead of Twisting and Super-twisting algorithms, in future we can use other arbitrary order SMC algorithms for better performance.

PAPER/ JOURNAL WORKS

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Thank You!