M. Tech (Power System) Sweety kumari yadav 2022

STUDY ON IMPACT OF POWER SYSTEM INERTIA DURING DISTURBANCES IN POWER SYSTEM

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN

POWER SYSTEM

Submitted by:
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CANDIDATE'S DECLARATION

I, Sweety kumari yadav, Roll No. 2K20/PSY/19 student of M.Tech. Power System, hereby declare that the project dissertation titled "Study On Impact Of Power System Inertia During Disturbances In Power System" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

Place: Delhi Sweety kumari yadav

Date: STUDENT

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CERTIFICATE

I hereby certify that the Major Project titled "Study On Impact Of Power System Inertia During Disturbances In Power Syatem" which is submitted by Sweety Kumari Yadav, Roll No. 2K20/PSY/19, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi PROF. S. T. NAGARAJAN

Date: SUPERVISOR

ABSTRACT

Electric Power demand in the world is increasing day by day which is forcing the world to move towards renewable energy resources. The increase in different types of generation, is responsible for increasing the complexity of power systems and the chances of blackouts. These complex power systems are exposed to atmosphere from which a different kind of disturbances can occur during the normal operating condition of power system. If the system is heavily loaded, then the disturbances in the system become more severe for the synchronism of power system. The power system have to balance these changing states of power system and operate within the suitable limit of frequency and voltage. Power system rotational inertia shall be affected by the amalgamation of converter-based renewable energy sources in the power grid, which in turn affects the protection setting of relays in the system. In this research work, phase angle data of PMU is being used for the detection of OOS condition in two area power system and the effect of inertia variations in a two area power system on the out of step condition has been studied. Phasor measurement unit based method is used for detection of out of step condition and a trip signal is generated to separate both the areas in case of OOS condition. To verify the results, time domain and modal analysis were performed in Opal-rt HYPERSIM software.

In this report we are focusing on the impact of change in power system inertia by addition of RES on the prominent inter-area oscillations due to which generators can go Out of Step (OOS) from synchronous condition. Further, this report presents an OOS detection method using PMU data on popular kundur’s two area system [5]. The study has been carried out on Opal-rt real time simulation software HYPERSIM

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Place: Delhi | Sweety Kumari Yadav

Date: | (2K20/PSY/19)

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LIST OF ABBREVIATIONS

OOS	Out Of Step
SMT	Synchrophasor Measurement Technology
PMU	Phasor Measurement Unit
WAMS	Wide Area Monitoring System
PDC	Phasor Data Concentrator
RES	Renewable Energy Sources
SCADA	Supervisory Control And Data Acquition

LIST OF SYMBOLS

Ns	Synchronous speed
F	Frequency
P	Number of poles
δ	Phase angle difference of bus voltages at bus 3 and bus7
$\angle V1PMU1$	Phase angle of positive sequence voltage at bus 3
$\angle V2PMU2$	Phase angle of positive sequence voltage at bus 7
S	Slip frequency
A	Acceleration
Δt	Sampling rate

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Indian power system have experienced a large number of disturbances in last 20 years including the largest power outage in history on 31st July 2012 which affected more than 620 million people, about 9% of the world population, or half of India's population. Further, most of northern and eastern India on 30 and 31 July 2012 got damaged because of two critical power blackouts. The 30 July 2012 blackout affected over 400 million people and was beating the January 2001 blackout in Northern India (230 million affected). Electric service was restored in the affected locations between 31 July and 1 August 2012. These disturbances caused very significant loss of power generation, transmission, distribution and loads and had an enormous impact on consumers and the wealth of the country. Predominantly, these disruptions happen when the power systems are extremely loaded and various blackouts occur within a short period, causing power oscillations between neighboring power grid systems, low bus voltages, and resulting voltage instability or angular instability.

Out of step (OOS) is a condition in generators of power system falling out of synchronism from the rest of the power system. OOS can happen due to excessive loading on the generator or more commonly due to the Power flow oscillations in the system. These oscillations in the system could be a stable oscillation or an unstable oscillation. During unstable oscillations in the generator the rotor angle exceeds the maximum angle from which it can return back to normal steady state. If any generator slips away from synchronism it has to be tripped from the rest of the system to prevent the collapse of the power system.

Phasor measurement units are relatively new power system measuring device found to be useful for prevention of blackouts in power sytem. To reduce the chances of blackout or power outages in India also, Phasor Measurement Unit is being installed at substations at various locations. For the Out Of Step detection of two area power system PMU data is used. Also for the purpose of monitoring of these large and complex power system PMU is used at the different substations. This report comprises the comprehensive summary of synchrophasor technology based PMU and it's application in Out Of Step detection of two area system.

CHAPTER 2

PHASOR MEASUREMENT UNIT

Synchronized phasor measurement is one of the most important information sources for smart transmission grid, which provides a new path for power system dynamic monitoring, analysis and control. Synchrophasors are time-synchronized electrical measurements that represent both the magnitude and phase angle of the electrical sinusoids. Synchrophasors are measured by fast time-stamped devices called phasor measurement units (PMUs) to constitute the basis of real-time monitoring and control actions in the electric grid. Therefore the PMUs which can track the status of the power system, especially under the dynamic condition, is crucial for the future of power system. Due to its enhanced situational awareness capabilities, many applications of PMUs are developed in the past decades. These applications include wide-area situational awareness and monitoring, instability prediction and control, state estimation, power system inertia estimation, power quality monitoring, fault location and protective relaying etc.

Traditional systems in power grid such as Energy Management System (EMS) and Supervisory Control and Data Acquisition system (SCADA) have the capability to provide only steady state view of power system with high data flow latency. In SCADA it was not possible to measure the phase angles of bus voltages of power system network in real time, due to technical difficulties in synchronizing measurements from distant locations. By using PMUs at different substations many problems can be solved.

2.1 CLASSIFICATION OF PMU

PMU is classified into two classes, M class PMU and P class PMU.

M class PMU : In M class PMU, M is for measurement i.e. M class PMU is used for monitoring and measuring purposes. In M class PMU very high precision is required but very fast response or minimum reporting delay is not required. This type of PMU is used for the steady state behavior.

P class PMU : In P class PMU, P is for protection i.e. P class PMU is used for protection purposes. P class PMU is intended for applications requiring fast response and mandates no explicit filtering.

2.2 SCADA VS. PMU

Before the advancement of new technology SMT-based PMU, SCADA is being used for monitoring purposes of the power system. It is efficient enough and reliable to monitor the power system in the case of a steady-state power system, but it is not efficient in the case of a dynamic power system.

Traditionally SCADA acquires sensor measurement data from a substation via a communication network in every 2-4 seconds. Since the measurement data is not received synchronously, they cannot provide the state of the power system for each instant of time. However, PMU gets 30-120 samples per second (depending upon the type and cost of PMU) from which the state of power system can be determined for each and every instant of time. SCADA is not able to calculate the phase angle of voltage and current but in case of PMU installed at substations, then the phase angle of current and bus voltage can be calculated from which the angle difference between two buses is also known.

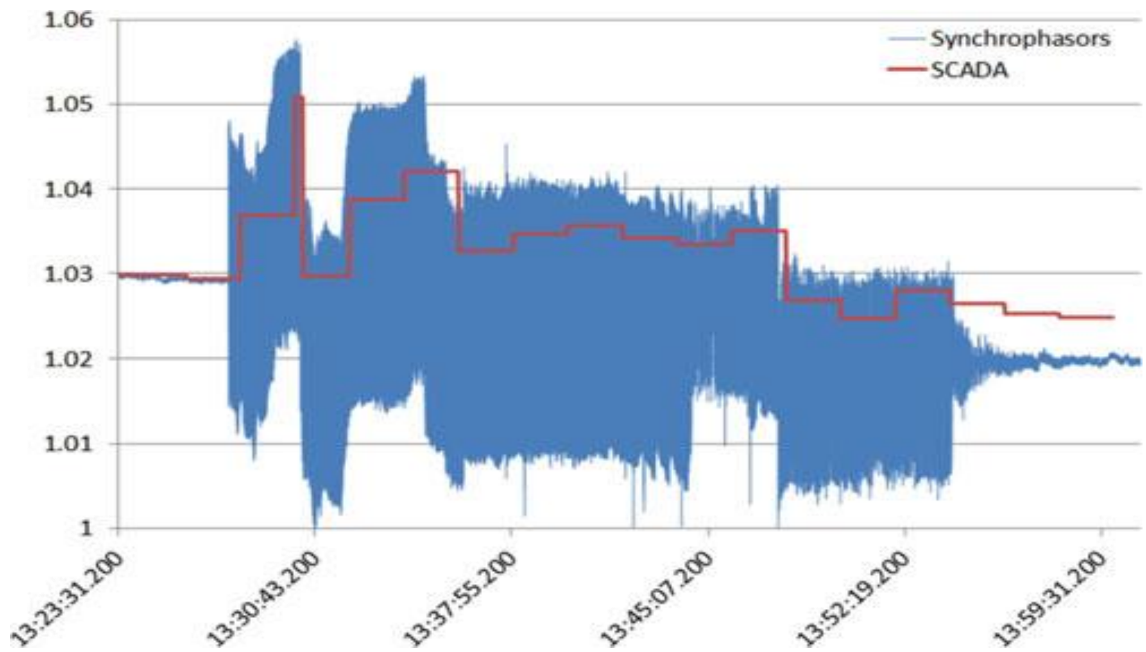

Fig. 2.1 Comparison between SCADA and PMU

CHAPTER 3

OUT OF STEP CONDITION IN POWER SYSTEM

3.1 BACKGROUND

World's electric power demand is increasing day by day, which is forcing the world to move toward renewable energy system (RES). However, renewable energies are very uncertain in nature which increases the uncertainty and complexity of power systems. It also affects the inertia of the power system as these renewable energy sources are mostly converter based inertia less systems [1]. If any disturbance occurs in power system, then power supplied by generator starts oscillating and some part of the power system can lose its synchronism which is not good for a continuous and reliable power supply. Further it could lead to catastrophic tripping of relays in power system leading to blackout of the system. Power system inertia, inherent to the rotating conventional synchronous generators offers stability to the system, by releasing the instant energy stored during the faults, offering stability to the power system. However, the converter based RES do not provide the required inertial energy during the faults leading to potential instability of the power system [2]. That's why it is very important to predict this kind of situation where the instability caused due to low inertia in the power system, before they go out of step of synchronism with the grid. Oscillations in power system can be classified into two types as local and inter-area. Oscillations associated with a single generator or single area, are called as local mode of oscillation. Frequencies of this type ranges from 0.7 Hz to 2 Hz for local mode of oscillation. Whereas, oscillations associated with sets of generators connected to different areas are called as inter-area oscillations. The frequency range for inter-area oscillation varies from 0.1 Hz to 0.8 Hz. [3] Phasor Measurement Units (PMU) are relatively new measuring instrument being widely adopted in the power systems worldwide, due to its capability of time synchronized measurements [4].

3.2 OUT OF STEP CONDITION

Out of step condition is a condition of a dynamic power system where a generator or a set of generators can lose their synchronism. At the normal operating condition of power system, all electrical parameters like system frequency, bus voltage, power through a transmission line, and power angle are kept at the desired limit. If any kind of fault or load switching occurs in this complex power system, then the power delivered by the generators starts oscillating. These oscillations result in power swings in tie lines of the system. A power swing can be of both types i.e. stable power swing and unstable power swing [6].

A. Stable Power Swing

   A power swing is called as a stable power swing when the generator does not slip poles and the power system reaches a new state of equilibrium or an acceptable operating condition. In this kind of situation, the angle difference between two areas or between two generators of single area does not go beyond 180 degrees. The angle difference oscillates for few seconds and then gets damped out in few seconds to become stable.

B. Unstable Power Swing

A power swing is called as an unstable power swing when a generator or a set of generator lose synchronism. In this kind of situation, the angle difference between two areas or between two generators of single area keeps on increasing and goes beyond 180 degrees, due to which the turbine connected to that generator and other equipment can get damaged.

CHAPTER 4

STUDY SYSTEM

4.1 INTRODUCTION

For the detection of OOS condition in power system using PMU data, a small hypothetical two area system as shown in Fig 4.1 has been developed in HYPERSIM software, is shown in Fig 4.2. For the simplicity in finding the electrical center of two area system and other parameters, the system is kept symmetrical i.e. the two area system consists of two identical areas connected through a tie line. Each area of the two area system consists of two coupled generators, each of them having the rating of 900 MVA at 20 KV and two step-up transformers, each of them having the rating of 900 MVA, 20/230 KV. Two PMUs are installed at Bus 3 and Bus 7, one PMU for each area for the collection of phasor data of line current/bus voltage. The phasor measurement unit and OOS monitor has been simulated in HYPERSIM as shown in Fig 4.4. The data of the study system is given in Appendix.

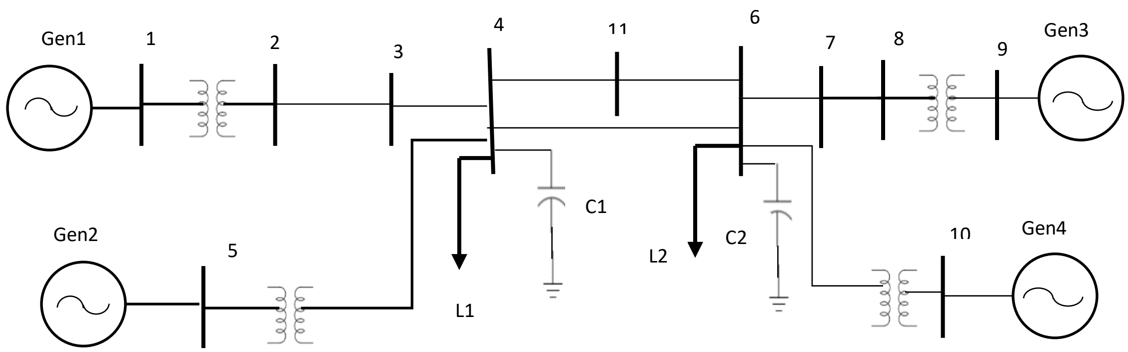

Fig. 4.1. Single line diagram of two area system

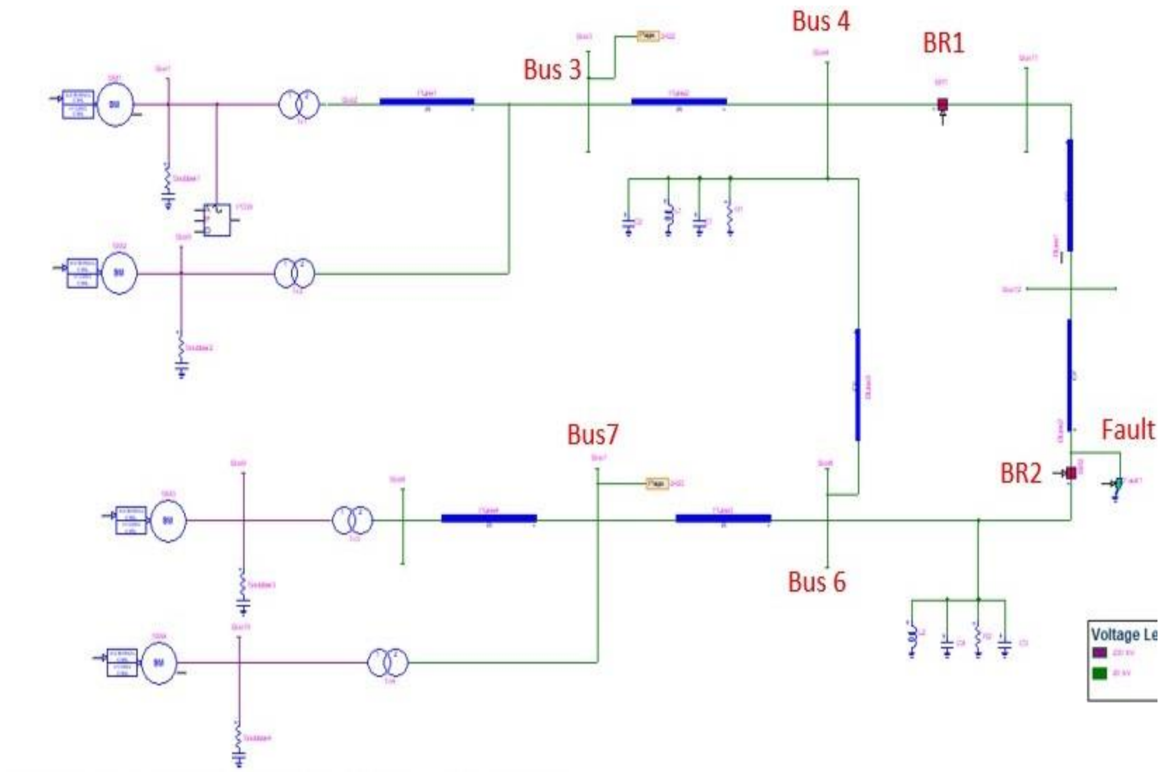

Fig 4.2. Two area system implementation in HYPERSIM

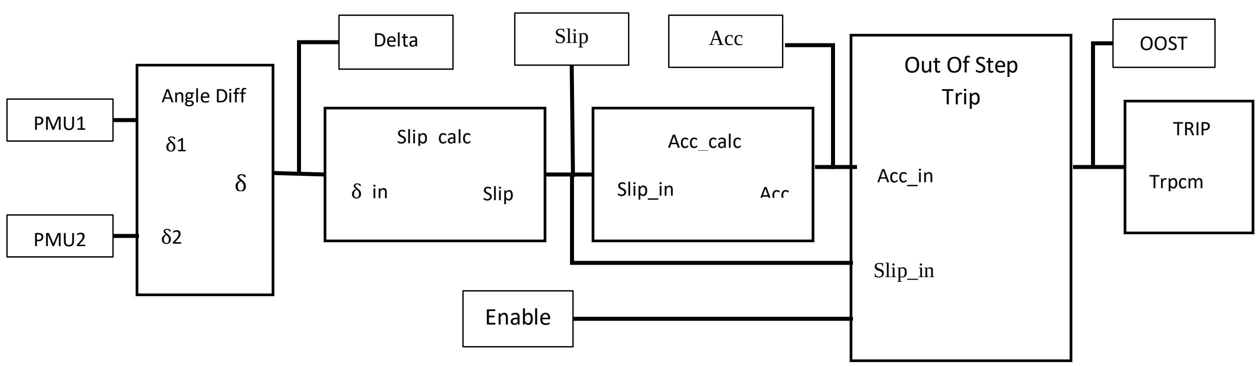

Fig.4.3 Implementation of OOS detection scheme

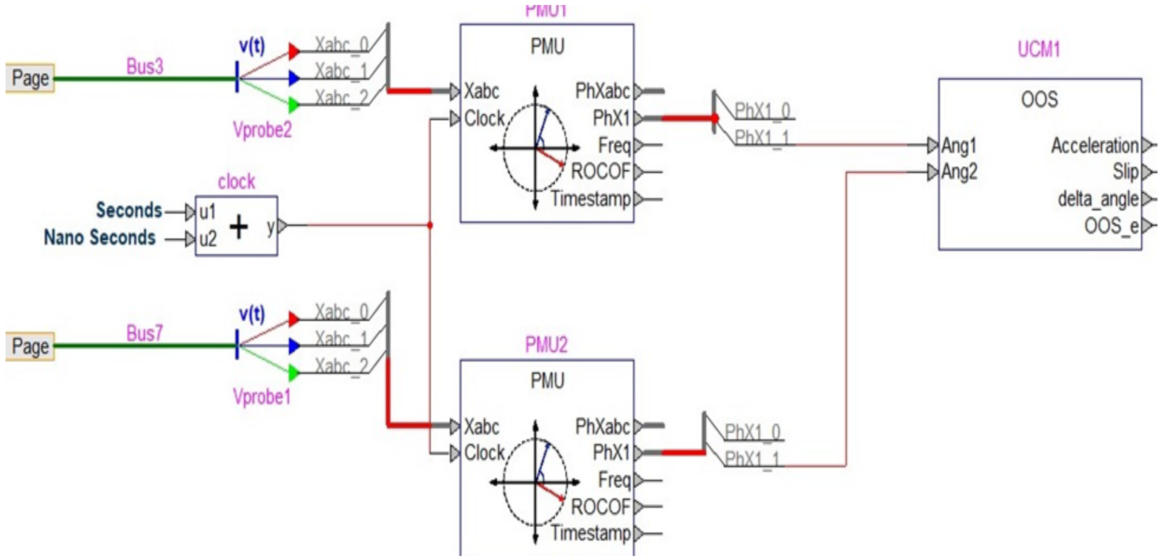

Fig 4.4. Implementation of PMU and OOS monitor in HYPERSIM

4.2 COMPONENTS OF TWO AREA SYSTEM

4.2.1 GENERATOR

Electrical generator is a dynamic device which converts mechanical energy into electrical energy. In this two area power system four synchronous generators having the rating of 900 MVA at 20 KV is connected to four different buses.

Now a days different kinds of renewable energy resources are being used for electricity generation but all these resources can not replace the synchronous generator completely. Since the inertia of power system plays a very important role in stability of power system and these resources are inertia less resources, it is important to study well the impact of inertia on power system stsbility.

Synchronous generator direct axis diagram and quadrature axis diagram is shown in below fig.

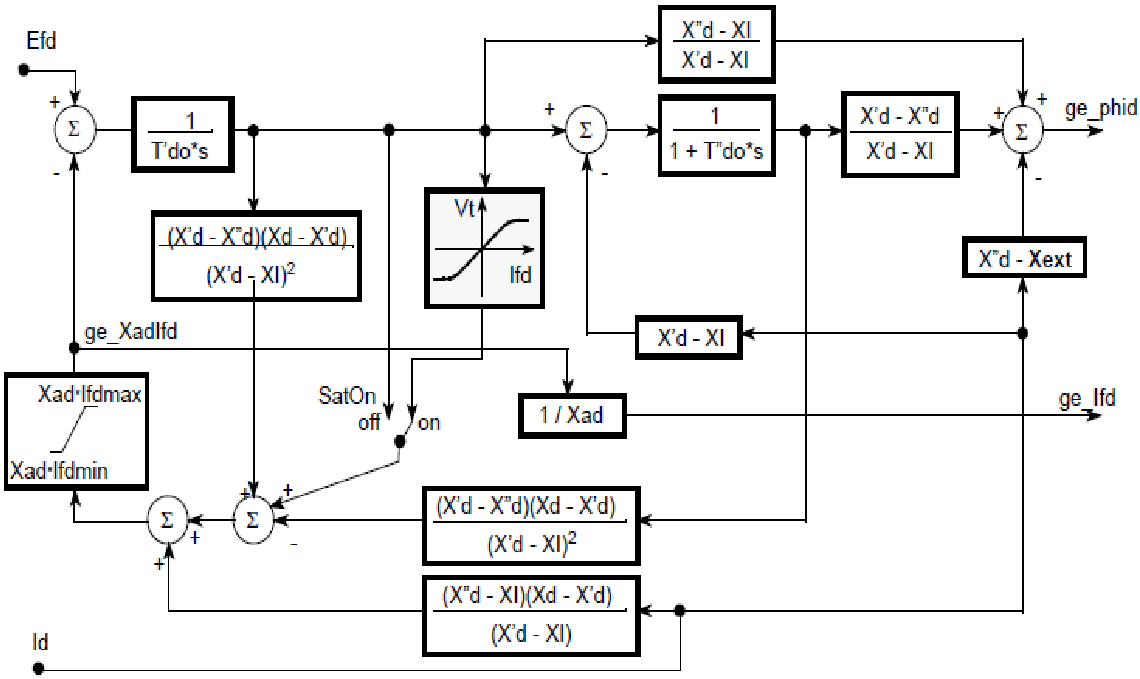

Fig. 4.5 Direct axis diagram

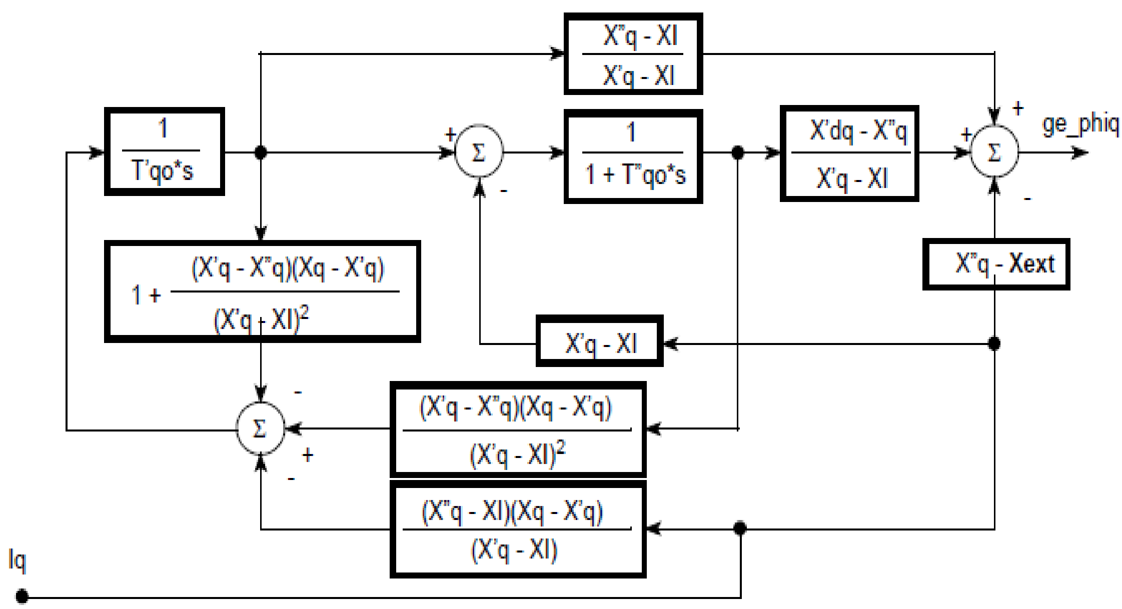

Fig. 4.6 quadrature axis diagram

EXCITATION SYSTEM

Excitation system of synchronous generator is the arrangement or system which is used to provide the field current to the rotor winding of synchronous generator. This field current is responsible for the flux generation in the field winding.

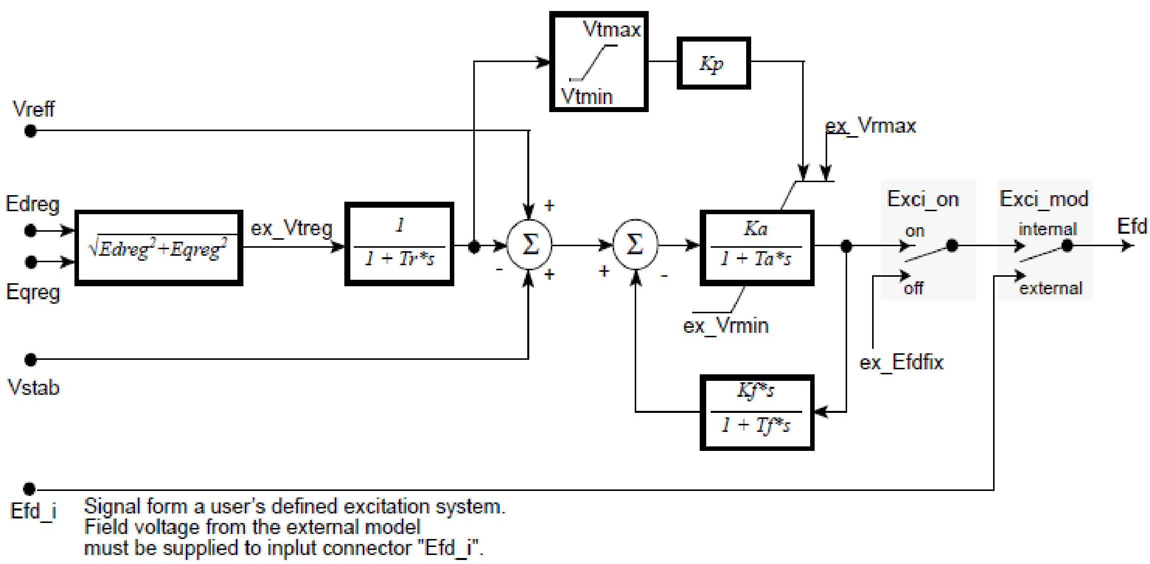

Fig. 4.7 Exciter of synchronous generator

SPEED REGULATION OF SYNCHRONOUS GENERATOR

The Voltage Regulation of a Synchronous Generator is the rise in voltage at the terminals when the load is reduced from full load rated value to zero, speed and field current remaining constant. The speed of synchronous generator depends on the frequency and number of poles of generator.

$$Ns = 120f / P \tag{4.1}$$

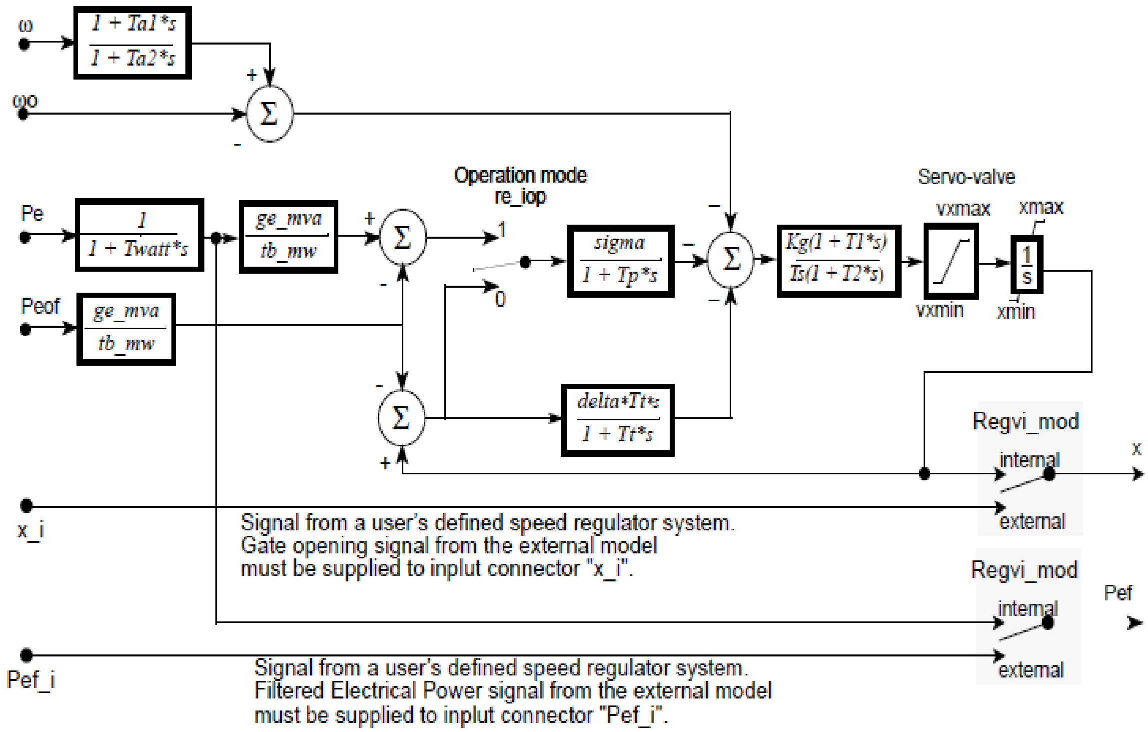

Fig. 4.8 speed regulator of synchronous generator

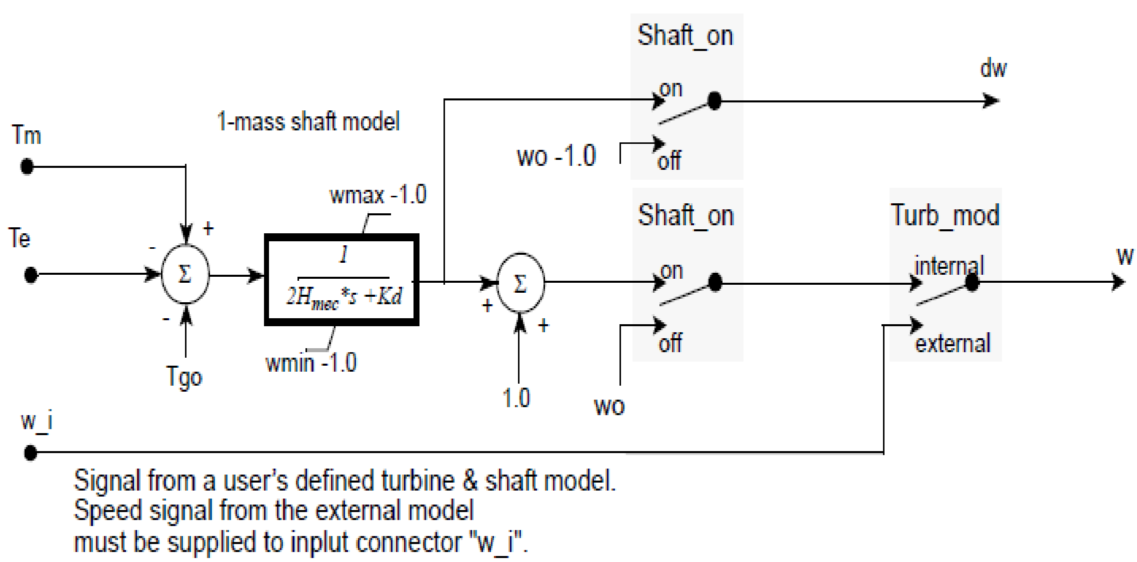

Fig. 4.9 Shaft of synchronous generator

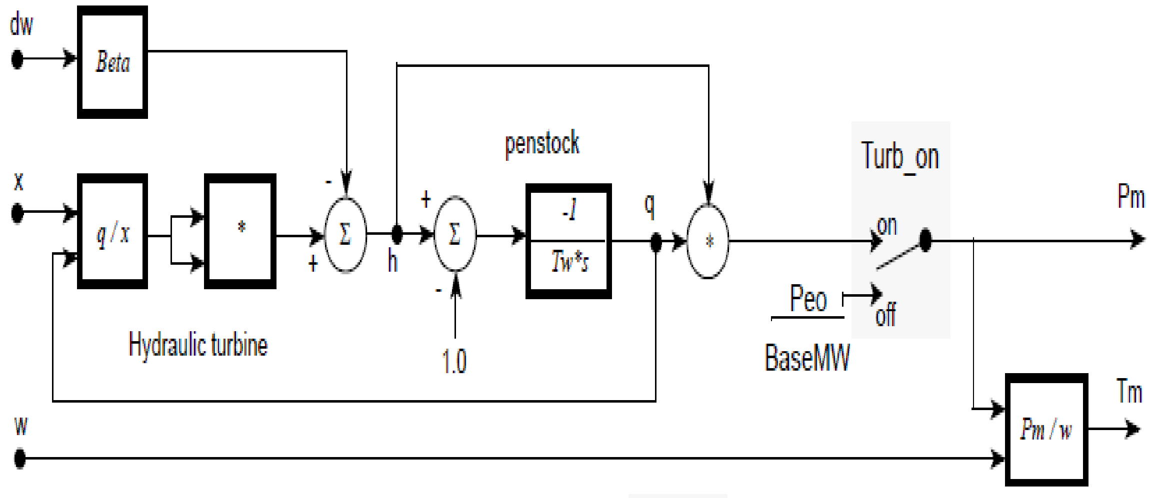

Fig. 4.10 Hydraulic turbine of synchronous generator

TRANSFORMER

Transformer is a static device which is used either for raising or lowering the voltage level of an a.c. supply. It is consist of two windings, primary winding and secondary winding. In this study system four step up transformers are used to raise the bus voltage from 20KV to 230KV.

LOAD

Load on the power system is the electrical appliances connected in household, industries, schools, hospitals, which requires electrical power to perform their work. Load is a combination of resistances, inductances and capacitances. If load is the combination of resistance and inductance then it is lagging load and it absorbs lagging reactive power. If load is the combination of resistance and capacitance then it is leading load and it delivers lagging reactive power and absorbs leading reactive power. In this study system two lagging loads are connected at bus 4 and bus 6.

SHUNT CAPACITOR

Shunt capacitors are used in power system to maintain the bus voltage level. When the load (maximum loads are lagging in nature) on power system increases then voltages at buses gets reduced, to maintain this bus voltage level at 1pu. Shunt capacitor is used. Shunt capacitor starts supplying the lagging reactive power to the lagging loads and maintain the voltage level. In this study system, two shunt capacitor are connected at bus 4 and bus 6.

CHAPTER 5

OUT OF STEP DETECTION METHOD

For the detection of out of step condition of power system different relays have been used from last several years [7]. The performance of protective relays which observe power flows, voltages, and currents may react on the variation of system voltages and currents and can be responsible for tripping of additional equipment, thus making the system weak and possibly leading to cascading power outages and the closedown of large sections of the power system. These relays can respond to stable power swings also which may lead the power system for unwanted tripping of circuit breaker. Motivated by the wide spread of Wide Area Measurement System (WAMS) with PMUs in power system, it has been proposed for using Phasor Measurement Units at two different buses which are at equal distance from the electrical center of the two area system considered in this study. In a two area system [3] shown in Fig.4.1 which is considered in this study, the electrical center corresponds to a point which is at half of the total impedance between the two sources of two different areas. In this scheme, the phase angle data provided by the PMUs for the detection of Out of Step condition has been utilized. The calculation of the OOS condition has been done as per the angle difference between two PMUs as shown below [8]:

$$\delta = \angle V1PMU1 - \angle V2PMU2 \quad (5.1)$$

$$S = (\Delta\delta)/(\Delta t) \quad (5.2)$$

$$A = (\Delta S)/(\Delta t) \quad (5.3)$$

Where

δ is the phase angle difference of bus voltages at bus 3 and bus7

$\angle V1PMU1$ is the phase angle of positive sequence voltage at bus 3

$\angle V2PMU2$ is the phase angle of positive sequence voltage at bus 7

S is the slip frequency

A is the acceleration and

Δt is the sampling rate.

The above three equations have been implemented for OOS condition detection as per the scheme shown in Fig 4.3 The OOS condition is triggered when the Acceleration Vs Slip crosses the stability boundary and remains more than 200 ms. The boundary condition of stability has been shown in Fig 5.1.

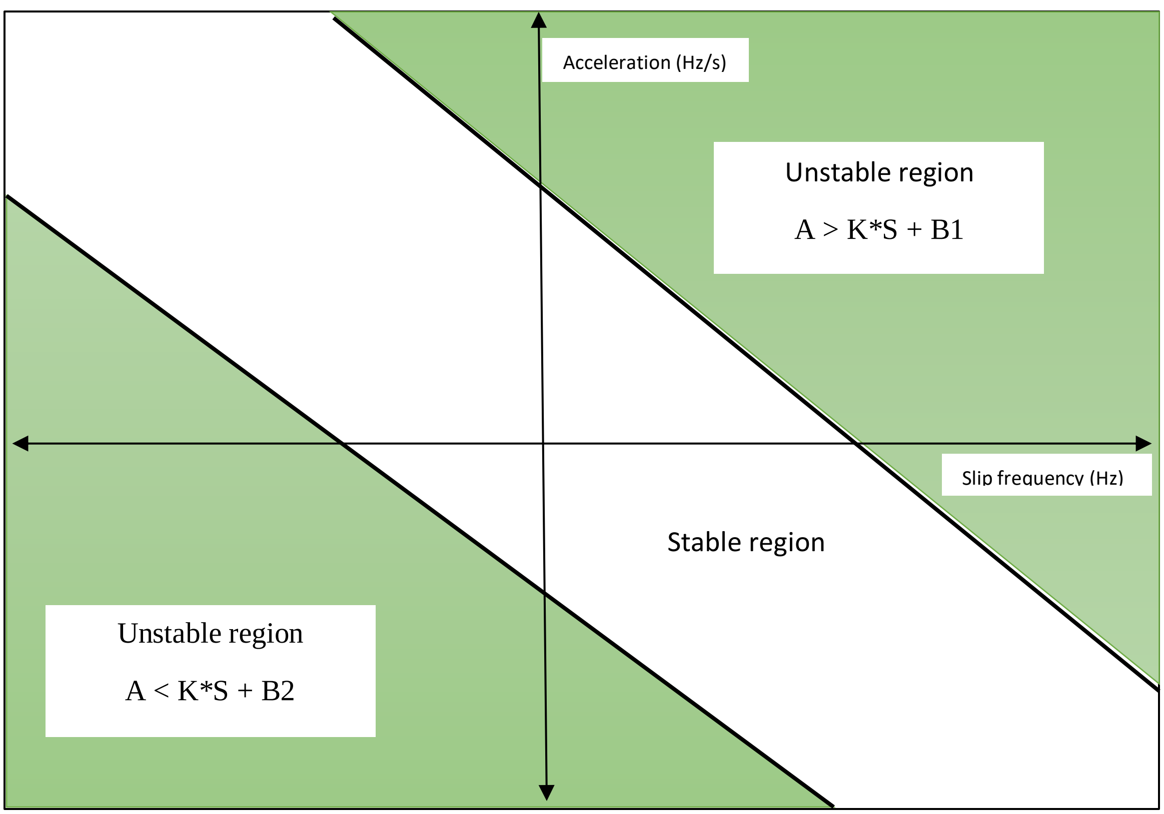

Fig 5.1 OOS stability criterion

For the above boundary condition of stability

B1 = 10

B2 = -10 and

K = -15

In this case of stability, the delay time setting is kept at 200 milliseconds. If the operating point of power system is outside of the stable region for more than 200 milliseconds, then the OOS controller will generate a trip signal and two areas will be separated.

CHAPTER 6

SIMULATION AND RESULTS

6.1 HYPERSIM TEST SCENERIO

The system simulated on HYPERSM has been initialized with Newton Raphson load flow method. The initial condition is set such that Area 1 is supplying 412 MW power through two tie lines to Area 2. A thee phase ground fault has been created on one of the tie line near Bus 6. The distance relay protection is used at Bus4 and Bus6 to protect the tie line of two area system. The distance relay protection at Bus 6 is configured to protect zone1 which is covering 80 % of the tie line with immediate tripping. The distance relay protection of zone2 which is covering 120 % of the line will operate with a time delay of 200 milliseconds. The same setting of immediate tripping and delay time of 200 milliseconds are applied to the distance relay protection on the other end of the tie line (at Bus4).

As we can see that the fault is occurring very close to the Bus6, the distance relay protection at Bus6 will pick up the three phase fault very fast and send a trip signal immediately to the circuit breaker near Bus6 (BR2). Here we assume that the distance relay protection at Bus6 will take one complete cycle which means 20 milliseconds and the circuit breaker near Bus6 will take 2.5 cycle which means 50 milliseconds to break the path. So the circuit breaker BR2 will take70 milliseconds to open the circuit which means at 1 = 1.07 seconds the BR2 will open.

The distance relay protection at Bus4 will pick up the three phase fault with a time delay of 200 milliseconds. The time taken by the circuit breaker will be same as BR2. So the circuit breaker BR1 will take 70 milliseconds to operate completely with time delay of 200 milliseconds. Which means at t = 1.27 seconds, the BR1 will open and the faulty part of the power system will get removed completely.

So, the fault occurs at 1sec, for a duration of few ms, at 1.27 sec the faulted line has been removed from service resulting in only one of the line to carry the tie line power thereby stressing the system. The simulation has been carried out for 20 secs to observe the response of the system. After removing one of the tie line, power flow from area 1 to area 2 starts oscillating. These oscillations in power flow can be stable oscillations or unstable oscillations depending upon the inertia constants of all generators.

6.2 ANALYSIS

The study has been systematically carried out with three cases of unstable, stable and variation of inertia as explained below:

6.2.1 Case Study A: With normal Inertia constant H in both areas

In this case study all the normal inertia of generators is considered as per ref [3] for response of the system. The system becomes unstable in this case and the angle between two areas keeps on increasing leading to OOS condition when the angle between two area exceeds 180˚, the frequency of the system which was common for both areas till the fault, gets separated with higher frequency in area 1 due to more power generation than demand and low frequency in area 2 due to less power generation than the demand. The Slip and Acceleration also do not settle to zero after the fault leading to OOS condition.

The Out of Step page of the ScopeView is shown in the figures below:

Fig.6.1 shows the scope View of simulation on real time simulator in which we can see that the angle difference between Bus4 and Bus6 starts increasing from 25.44˚ and go beyond 180˚. After separation of faulty power system from healthy power system, frequency at Bus4 and Bus6 deviates from 50 Hz to the opposite directions which is shown in Fig. 6.2.

Fig. 6.3 shows that after the fault occurred on the tie line and removal of faulty line, the slip frequency and acceleration do not settle at zero.

In Fig.6.4 we can see the slip frequency Vs acceleration characteristic in which we can see that the operating point is going beyond the stable region by crossing the upper boundary condition in post fault condition.

From Fig. 6.5 we can see that the trip signal is generated by the OOS controller at 4.09 seconds, which means after 3.09 seconds of the fault occurrence the two area system will get separated in two different areas.

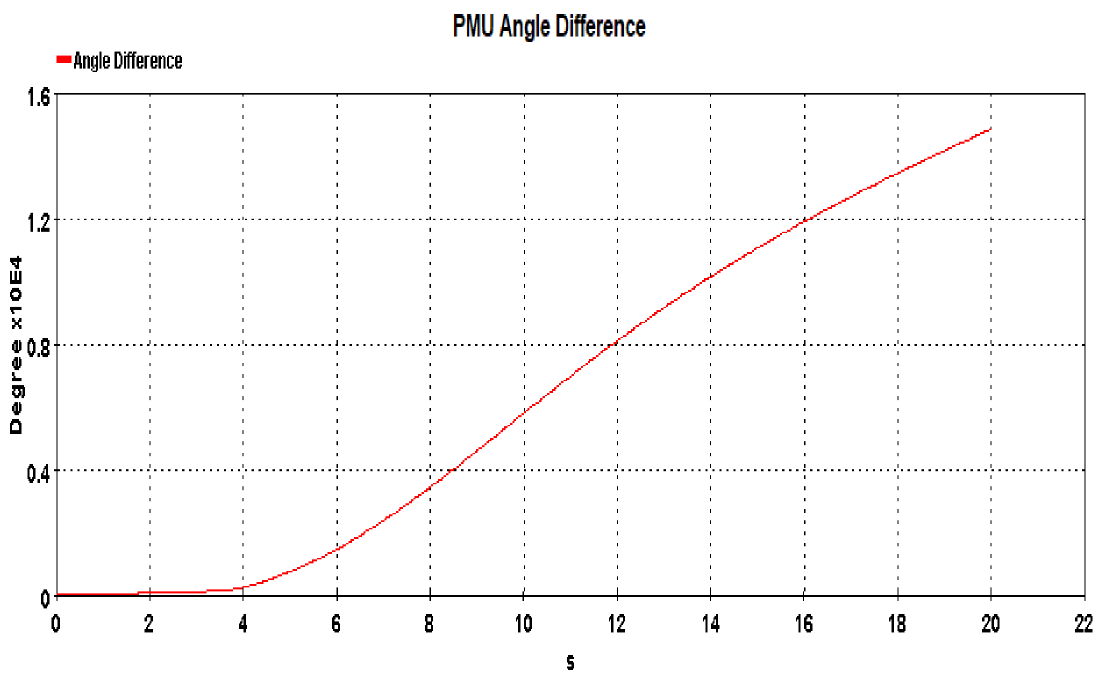

Fig 6.1 Angle difference between two areas

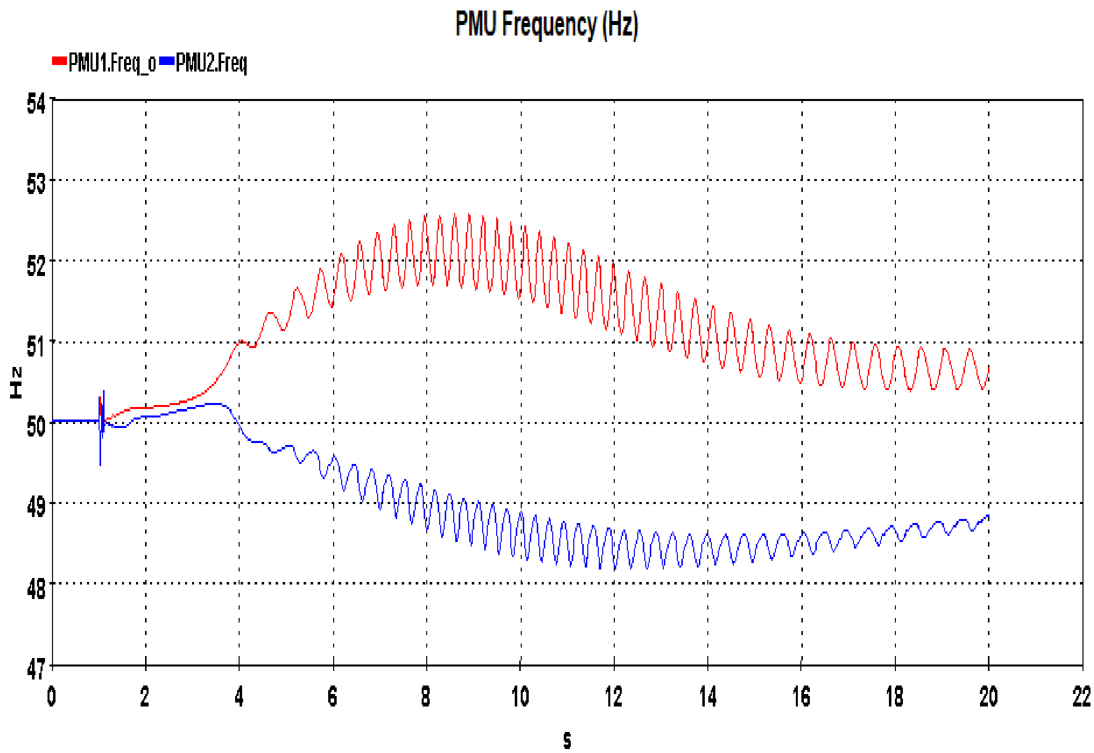

Fig 6.2 PMU frequencies of both areas

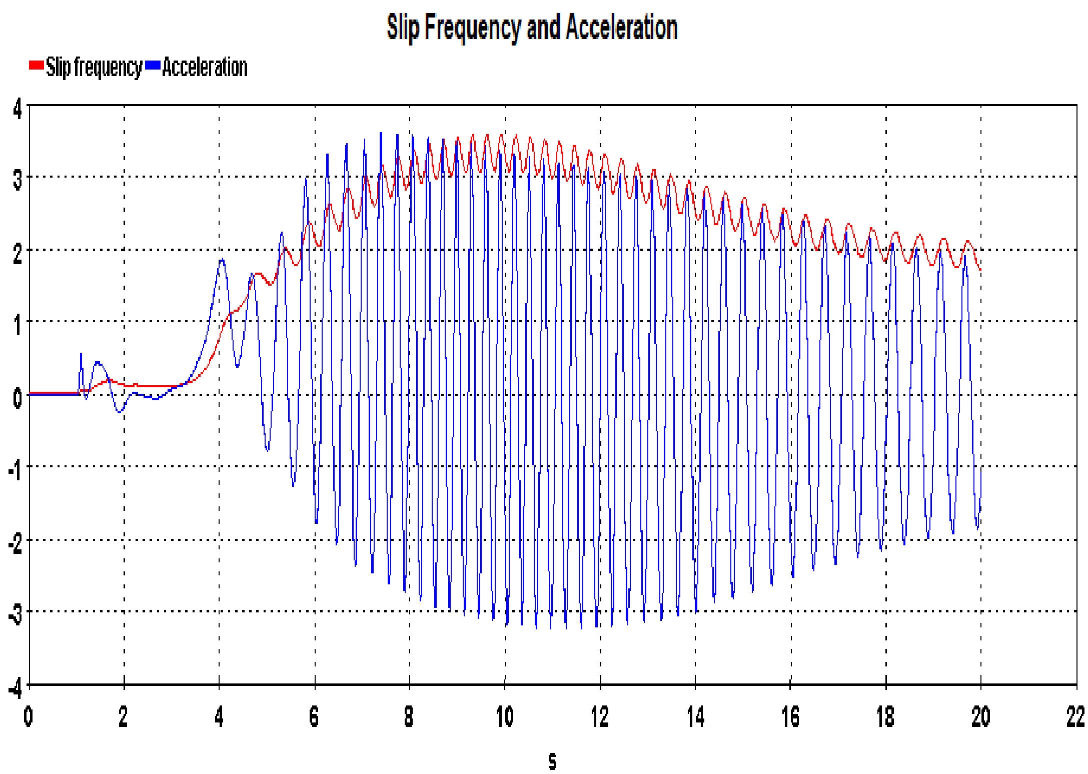

Fig 6.3 Slip Versus Acceleration of two areas

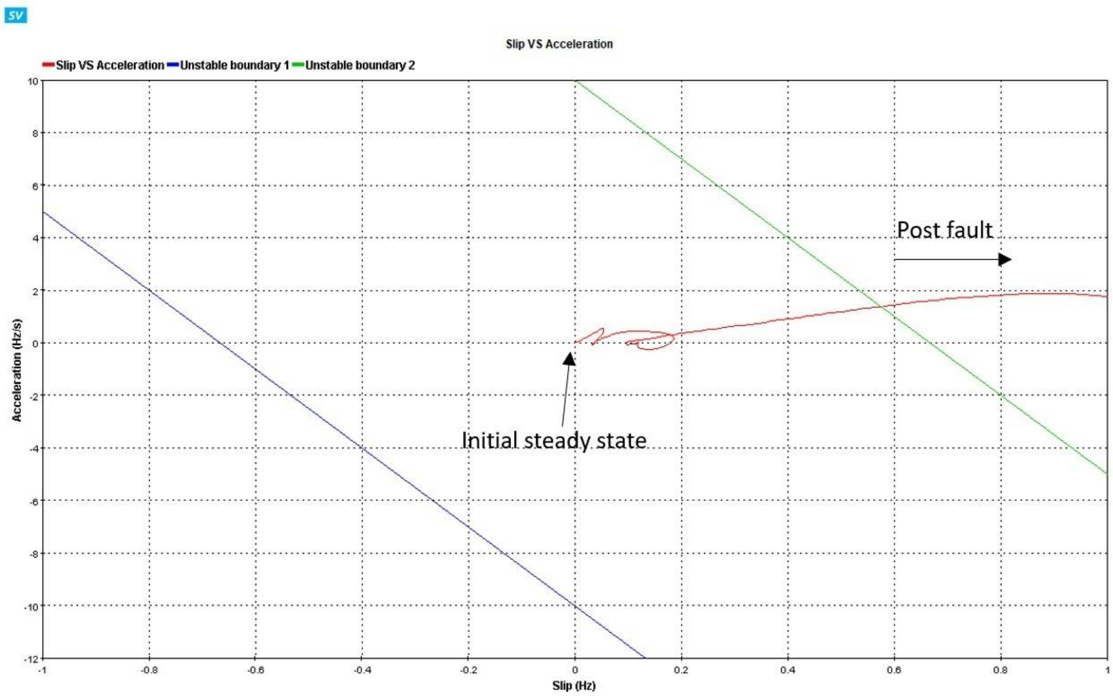

Fig.6.4 Slip frequency Versus Acceleration characteristic

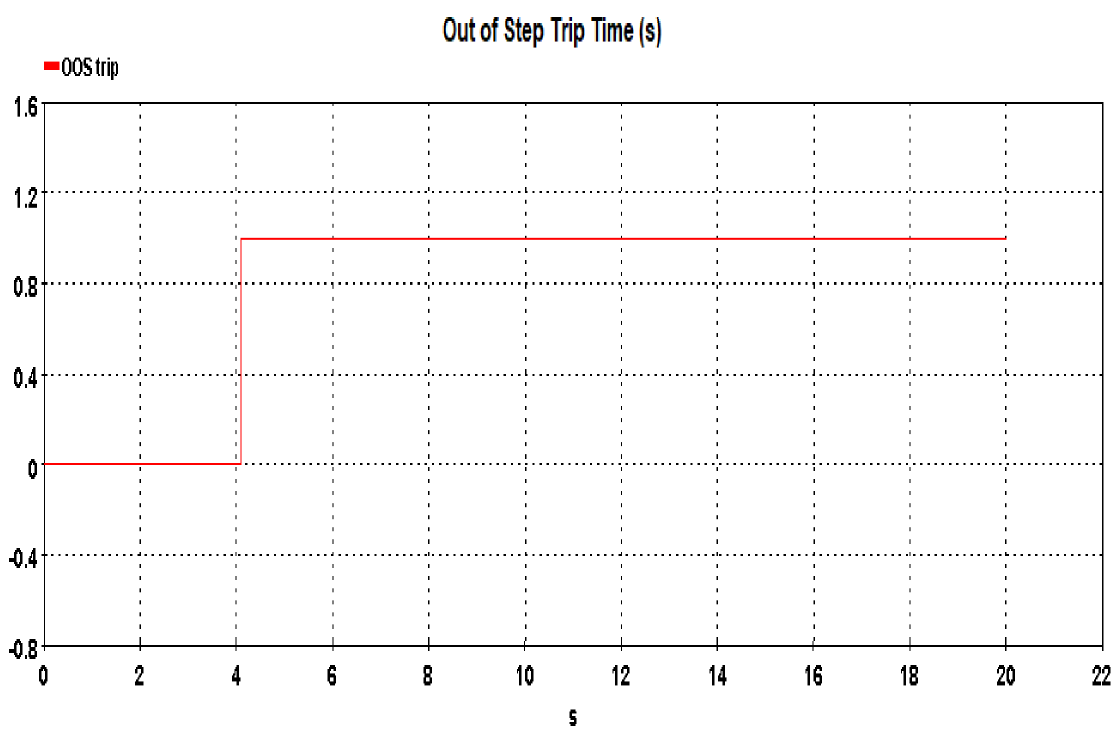

Fig 6.5 Trip signal from OOS controller

6.2.2 Case Study B: With low Inertia constant H in area2

In this case one of the generators in area 2 i.e. Gen 3 inertia has been lowered by 3s from the initial value and the fault condition has been repeated. In this case the system remains stable and no OOS condition have been observed. The angle difference between two areas oscillates for few seconds and then settles to a new higher value of approximately 58˚ which was earlier at 25.44˚. The frequency of Area1 and Area2 settles at a common value and the slip frequency and acceleration comes to the zero point again.

The Scope View of the Out of Step detection page is shown in the figures below:

Fig. 6.6 shows that the angle difference between two areas is initially was 25.44˚ and after fault it settles at 58˚.

Fig. 6.7 shows that the frequencies of both areas after oscillations settles to a common value and does not get separated by OOS condition. The Slip and Acceleration also settles to zero for this stable condition as shown in Fig. 6.8.

Fig. 6.9 shows that the operating point is within the stable region even after the fault occurred on the tie line. The trip command is not generated by the OOS controller which is shown in Fig. 6.10.

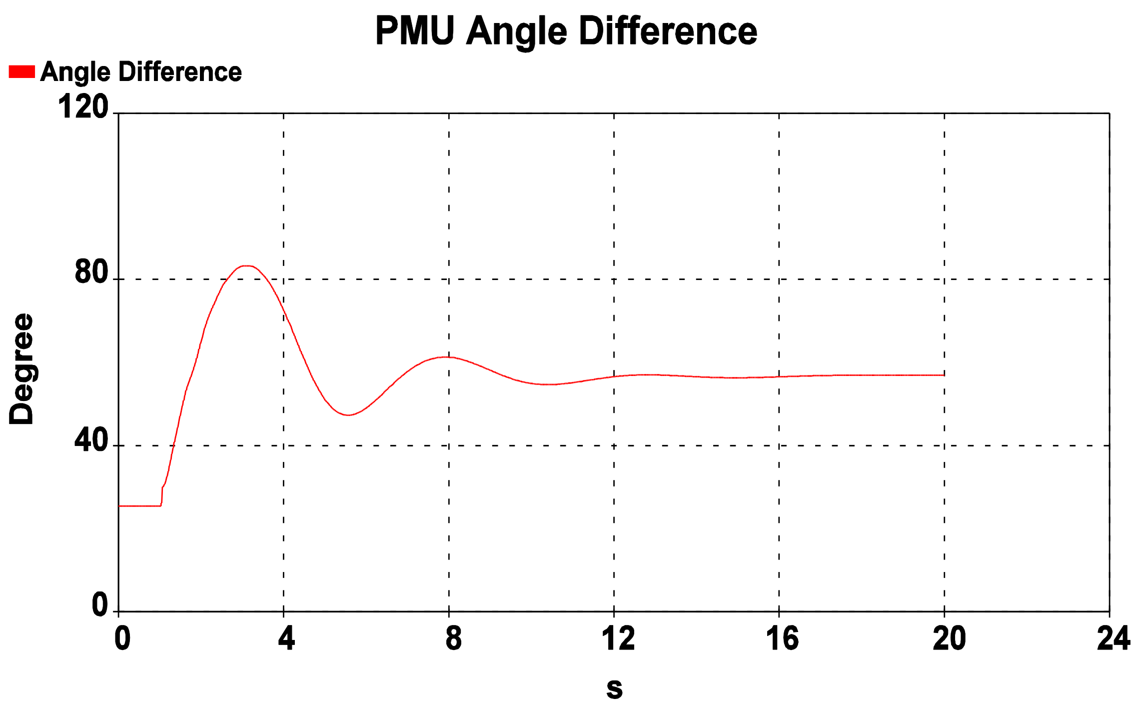

Fig. 6.6 Angle difference between bus 3 & 7

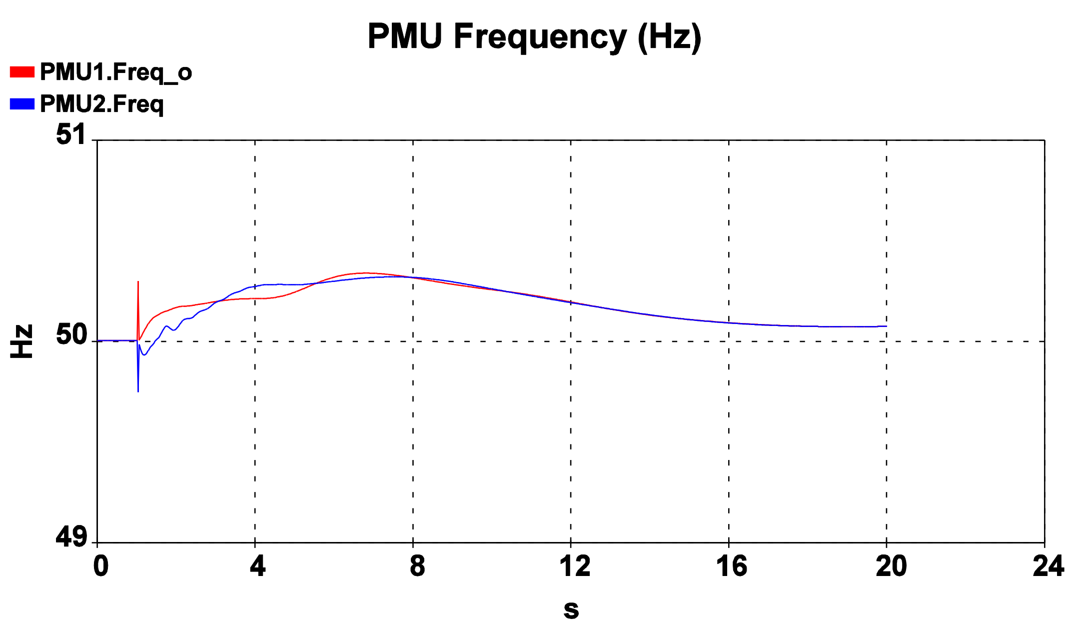

Fig.6.7 Frequency of Area1 and Area2

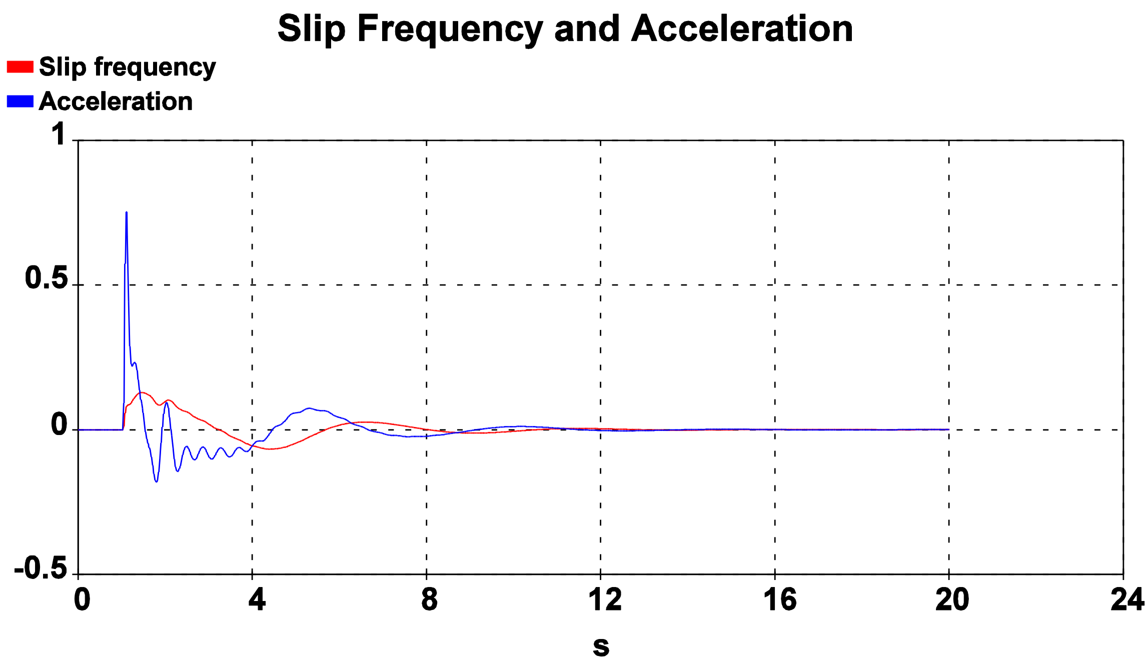

Fig. 6.8 Slip frequency and acceleration

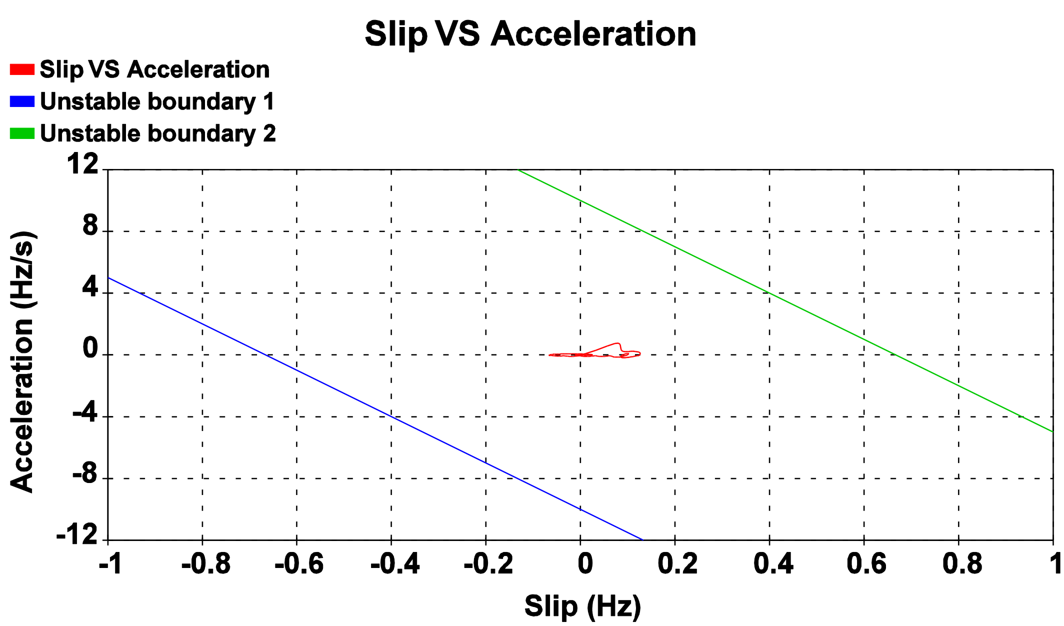

Fig. 6.9 Slip frequency Versus Acceleration characteristic

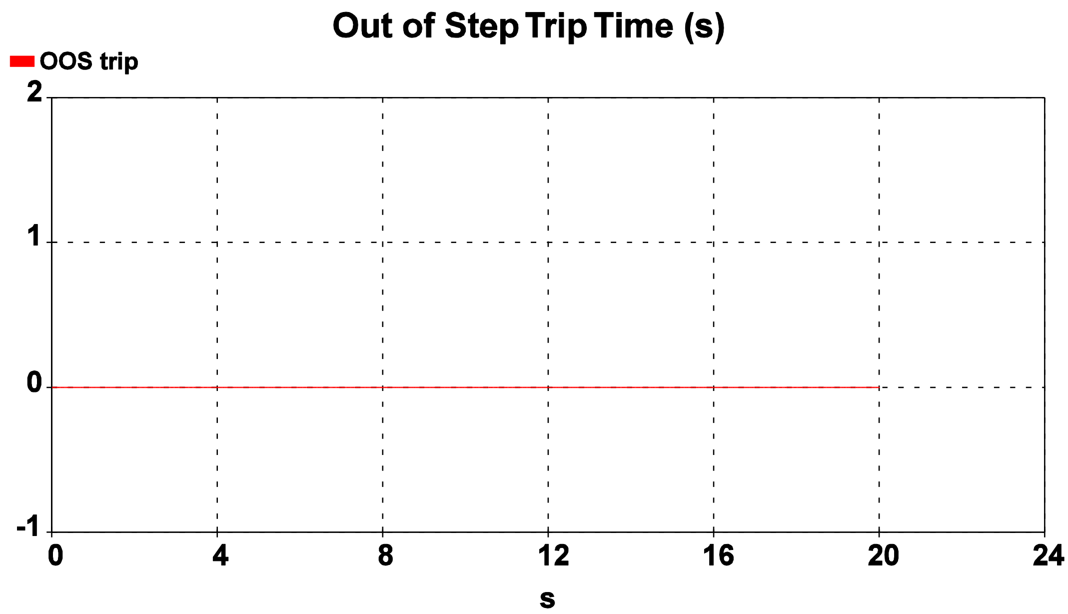

Fig. 6.10 Trip signal from OOS controller

6.2.3 Case Study C: OOS condtion with varying inertia const H in both areas

Practically, inertia of power system can be reduced by replacing some conventional synchronous generators from different types of renewable energy resources which have zero inertia. But in this case study on impact of inertia on OOS condition, for simplicity purposes we are just varying the value of inertia constants of all four generators one by one from the value of 1 to 10 to emulate the RES penetration in both areas. For a detail study of impact of inertia on OOS condition, the Inertia constants of Gen1, Gen2, Gen3 and Gen4 are varied separately from 1 to 10. In next step the inertia constants of generators of Area1 and Area2 are varied simultaneously.

i) TRIP TIME ANALYSIS

a) Trip time for OOS on varying, the inertia constants of all four generators from 1 to 10 two different types of cases are found for both areas. In case of Area1 when there is an increase in inertia of Gen1 and Gen2 the trip time (time to reach OOS condition) is increasing which is shown by plotting in Fig. 6.11 also in tables (Table 6.1 and 6.2).

b) In case of Area2, the OOS condition occurs when the inertia constant is more than 4, below which the system is stable as shown in Fig. 6.12. Also in tables (Table 6.3 and Table 6.4).

Table 6.1. Varying the inertia constant of Gen1 from 1 to 10 : Area1

H1	H2	H3	H4	TRIP TIME
1	6.5	6.5	6.5	3.17s
2	6.5	6.5	6.5	3.38s
3	6.5	6.5	6.5	3.57s
4	6.5	6.5	6.5	3.6s
5	6.5	6.5	6.5	3.95s
6	6.5	6.5	6.5	4.05s
7	6.5	6.5	6.5	4.22s
8	6.5	6.5	6.5	4.465s
9	6.5	6.5	6.5	4.6s
10	6.5	6.5	6.5	5.18s

Table 6.2. Varying the inertia constant of Gen2 from 1 to 10 : Area1

H1	H2	H3	H4	TRIP TIME
6.5	1	6.5	6.5	3.1656
6.5	2	6.5	6.5	3.3186s
6.5	3	6.5	6.5	3.4638s
6.5	4	6.5	6.5	3.6100s
6.5	5	6.5	6.5	3.7696s
6.5	6	6.5	6.5	3.9286s
6.5	7	6.5	6.5	4.0916s
6.5	8	6.5	6.5	4.2796s
6.5	9	6.5	6.5	4.5034s
6.5	10	6.5	6.5	4.7690s

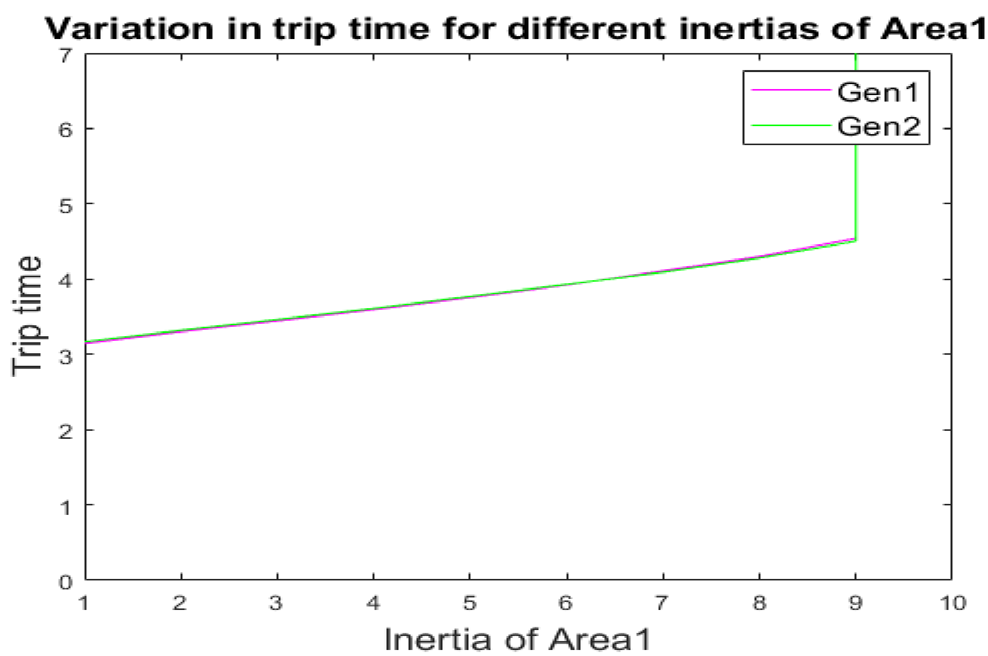

Fig. 6.11. Time taken for the OOS detection for Area1

Table 6.3. Varying the inertia constant of Gen3 from 1 to 10 : Area2

H1	H2	H3	H4	TRIP TIME
6.5	6.5	1	6.175	no trip
6.5	6.5	2	6.175	no trip
6.5	6.5	3	6.175	no trip
6.5	6.5	4	6.175	4.6500s
6.5	6.5	5	6.175	4.2216s
6.5	6.5	6	6.175	4.0666s
6.5	6.5	7	6.175	3.9570s
6.5	6.5	8	6.175	3.8994s
6.5	6.5	9	6.175	3.8398s
6.5	6.5	10	6.175	3.8054s

Table 6.4. Varying the inertia constant of Gen4 from 1 to 10 : Area2

H1	H2	H3	H4	TRIP TIME
6.5	6.5	6.175	1	no trip
6.5	6.5	6.175	2	no trip
6.5	6.5	6.175	3	no trip
6.5	6.5	6.175	4	5.0278s
6.5	6.5	6.175	5	4.3300s
6.5	6.5	6.175	6	4.0920s
6.5	6.5	6.175	7	3.9550s
6.5	6.5	6.175	8	3.8598s
6.5	6.5	6.175	9	3.8010s
6.5	6.5	6.175	10	3.7594

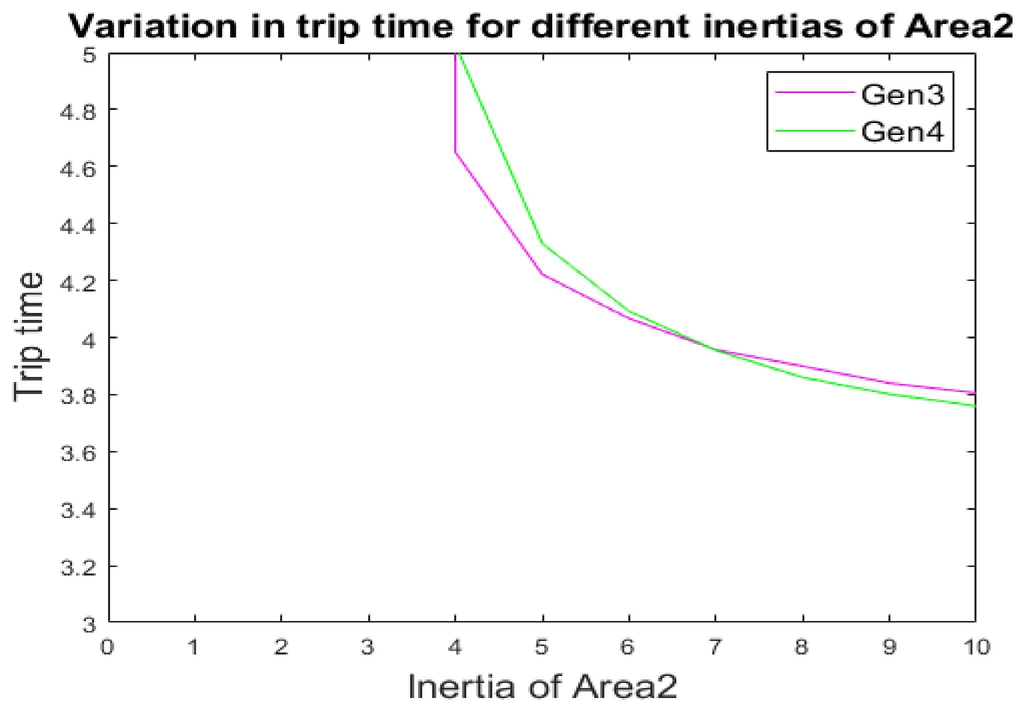

Fig. 6.12. Time taken for the OOS detection for Area2

ii) MODAL ANALYSIS

To study the effect of inertia variation on the stability of the study system modal analysis has been carried out on the angular oscillation of the system to determine the Eigen values of the inter-area mode of the system. The eigen values has been calculated by Prony method, where the eigen values are estimated from the response of the system. For a stable power system all the eigen values should be on the left side of s plane. If any one of the eigen value go to the right side of s plane then the system becomes unstable and the OOS controller generate the trip signal and separate the two area system into two different areas. Modal analysis of two area system for varying inertia constants of generators, study the impact of inertia on the eigen values of two area system.

a) Area 1 :

It can be seen from below figures and tables that when inertia constant H is increased from 1 to 10 for Gen 1 in Area 1 with other generators' inertia constant as per ref [3], the eigen values are on the right side of s-plane and the system remains unstable except for H = 10 as shown in Fig. 6.13.

A similar observation has been done for the case of Gen 2 of Area1 as shown in Fig. 6.14. However, when both generators of area 1 are varied the system remains stable above H=8 which is shown in Fig. 6.15

Table 6.5 Varying the inertia constant of Gen1 : Area1

H1 (S)	**H2 (S)**	**H3 (S)**	**H4 (S)**	**Eigen Values**	
				Real part	**Img part**
1	6.5	6.175	6.175	0.103533	0.155746
2	6.5	6.175	6.175	0.170526	0.177548
3	6.5	6.175	6.175	0.187436	0.168182
4	6.5	6.175	6.175	0.195156	0.166994
5	6.5	6.175	6.175	0.219377	0.161735
6	6.5	6.175	6.175	0.242225	0.164226
7	6.5	6.175	6.175	0.250043	0.149625
8	6.5	6.175	6.175	0.255289	0.140489
9	6.5	6.175	6.175	0.144124	0.065371
10	6.5	6.175	6.175	-0.11585	0.976601

Table 6.5 shows that when the inertia constant value of Gen1 is in the range of 1 to 9 then the real part of eigen values are positive, from which it can be considered that the system

becomes unstable after removal of faulty line. The angle difference between bus 3 & bus 7 keeps on increasing and go beyond 180˚ which was earlier at 25.44˚. When the inertia constant value of Gen1 is 10 then the real part of eigen value is negative, from which it can be considered that the system becomes stable after removal of faulty line. In this condition the angle difference between bus 3 & bus 7 oscillates for few seconds and then settle down at a new equilibrium point. Fig. 6.13 shows the plot of eigen values on varying the inertia constant of Gen1, from which we can see that eigen values are going from left to right on increasing the inertia constant of Gen1.

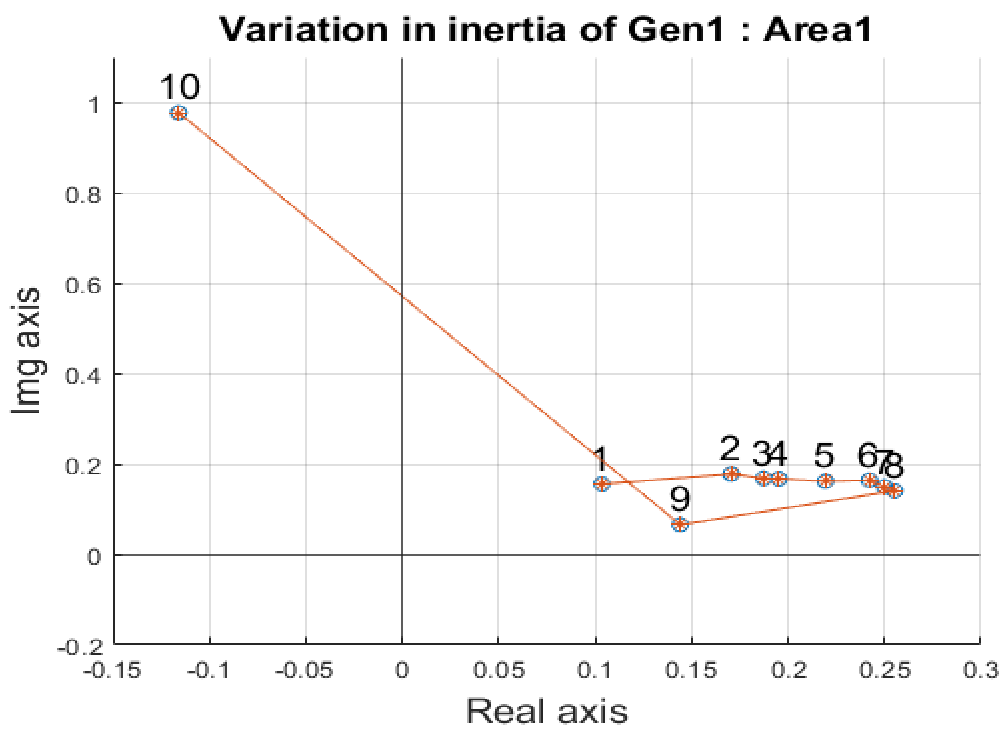

Fig. 6.13. Eigen value plot for Gen1variation of H

Similar kind of behavior is shown by the Gen2 which can be seen in Table 6.6 and Fig. 6.13.

Table 6.6 Varying the inertia constant of Gen2 : Area1

H1 (S)	H2 (S)	H3 (S)	H4 (S)	Eigen values	
				Real part	Img part
6.5	1	6.175	6.175	0.1538	0.1825
6.5	2	6.175	6.175	0.1640	0.1681
6.5	3	6.175	6.175	0.1803	0.1676
6.5	4	6.175	6.175	0.2066	0.1699
6.5	5	6.175	6.175	0.2222	0.1631
6.5	6	6.175	6.175	0.2430	0.1641
6.5	7	6.175	6.175	0.2560	0.1478
6.5	8	6.175	6.175	0.2582	0.1378
6.5	9	6.175	6.175	0.0369	0.1056
6.5	10	6.175	6.175	-0.0896	0.9472

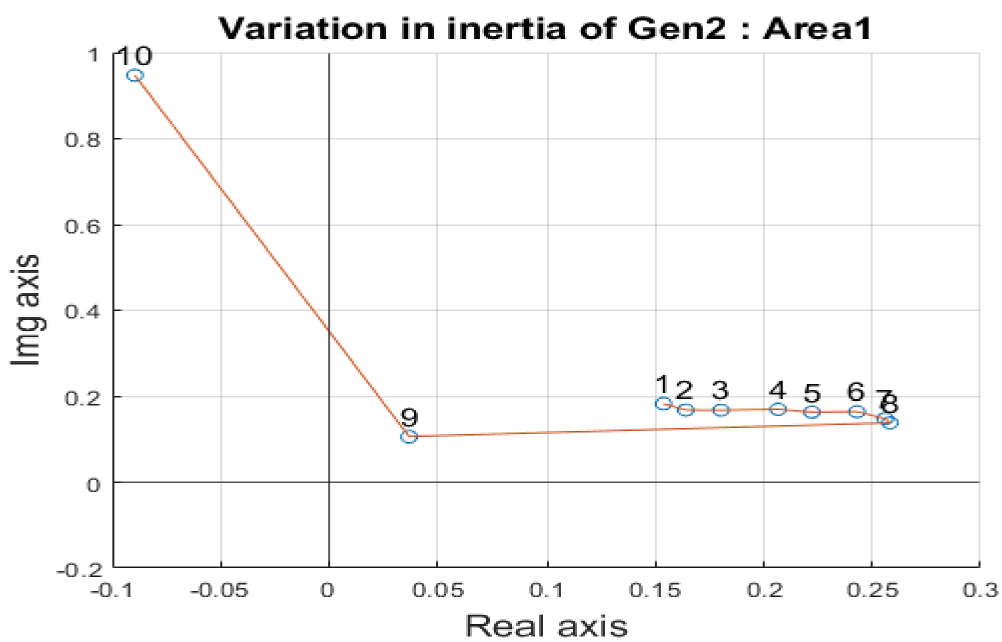

Fig. 6.14 Eigen value plot for Gen2 variation of H

When the inertia constant of Gen1 and Gen2 is varying simultaneously from 1 to 7, then eigen values are in right side and the system is unstable as shown in Table 6.7. Otherwise for inertia constant values from 8 to 10, the real part of eigen values are negative and the system is stable.

Table 6.7 Varying the inertia constant of Gen1 & Gen2 simultaneously : Area1

H1 (S)	H2 (S)	H3 (S)	H4 (S)	Eigen values	
				Real part	Img part
1	1	6.175	6.175	-0.0446	0.5074
2	2	6.175	6.175	0.0466	0.5135
3	3	6.175	6.175	0.1049	0.5195
4	4	6.175	6.175	0.1240	0.1644
5	5	6.175	6.175	0.1887	0.1705
6	6	6.175	6.175	0.2439	0.1707
7	7	6.175	6.175	0.2550	0.1437
8	8	6.175	6.175	-0.1105	0.7899
9	9	6.175	6.175	-0.1574	1.1365
10	10	6.175	6.175	-0.1632	1.1560

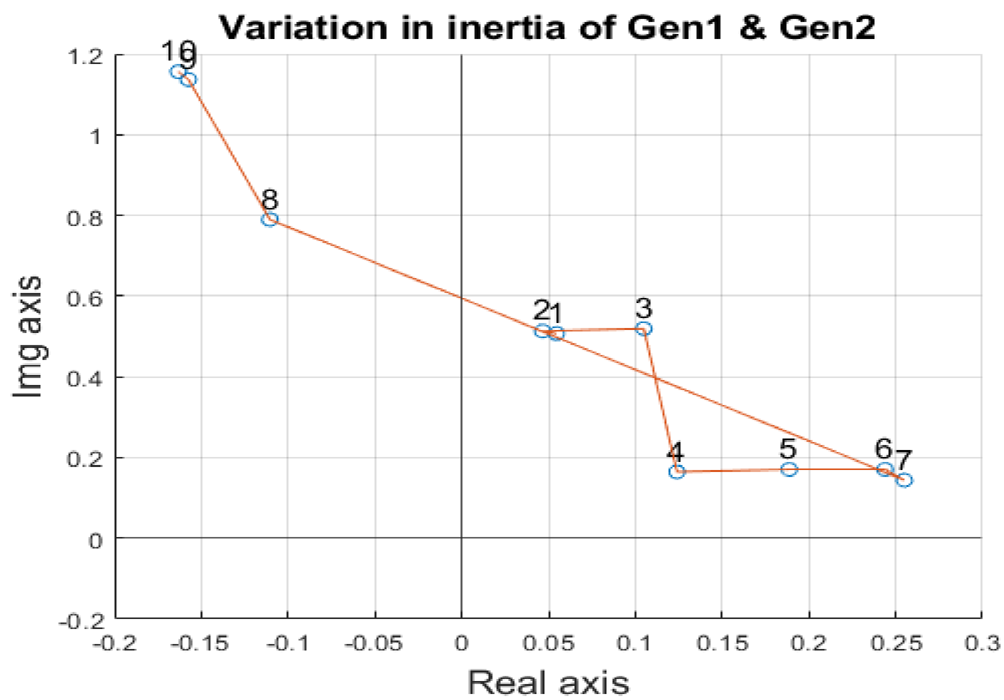

Fig. 6.15 Eigen value plot for Gen1 & Gen2 variation of H

b) Area 2 : Similar type of variation in area 2 has been performed and the eigen value has been plotted in Fig 6.16 and Fig. 6.17 for Gen 3 and Gen 4. It can be observed that the system moves towards instability for higher inertia constants. When the inertia constant of Gen3 or Gen4 is varying from 1 to 4 then the eigen values are in left side of s-plane which means the system is stable. Otherwise for higher values of inertia constant of Gen3 or Gen4, the system becomes unstable and eigen values are in right half side of s-plane.

Combined variation in Gen 3 and Gen 4 is shown in Fig. 6.18. Here also the system moves towards instability with increase in inertia constant.

Table 6.8 Varying the inertia constant of Gen3 : Area2

H1 (S)	H2 (S)	H3 (S)	H4 (S)	Eigen values	
				Real part	Img part
6.5	6.5	1	6.175	-0.2781	1.1726
6.5	6.5	2	6.175	-0.2589	1.1468
6.5	6.5	3	6.175	-0.2386	1.0709
6.5	6.5	4	6.175	-0.0284	0.6984
6.5	6.5	5	6.175	0.2354	0.1507
6.5	6.5	6	6.175	0.2063	0.1477
6.5	6.5	7	6.175	0.0584	0.0346
6.5	6.5	8	6.175	0.1713	0.1447
6.5	6.5	9	6.175	0.1902	0.1492
6.5	6.5	10	6.175	0.1950	0.1482

Table 6.8 shows that when the inertia constant value of Gen3 is in the range of 1 to 4 then the real part of eigen values are negative, from which it can be considered that the system becomes stable after removal of faulty line. In this condition the angle difference between bus 3 & bus 7 oscillates for few seconds and then settle down at a new equilibrium point. When the inertia constant value of Gen3 is in the range of 5 to 10 then the real part of eigen value is positive, from which it can be considered that the system becomes unstable after removal of faulty line. The angle difference between bus 3 & bus 7 keeps on increasing and go beyond 180˚ which was earlier at 25.44˚. Fig. 6.16 shows the plot of eigen values on varying the inertia constant of Gen1, from which we can see that eigen values are going from right to left on increasing the inertia constant of Gen1.

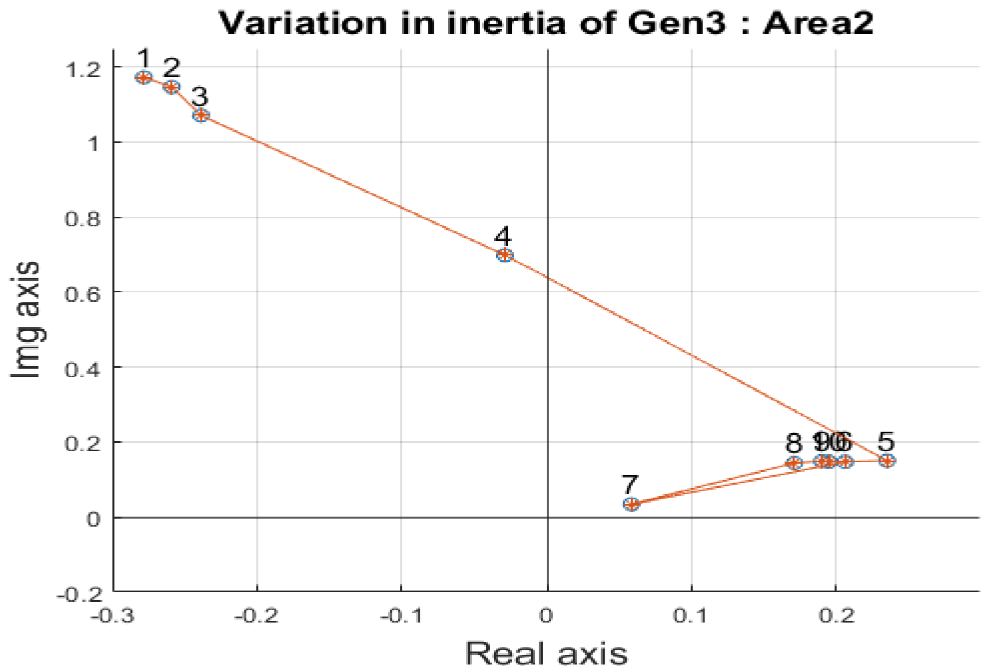

Fig. 6.16 Eigen value plot for Gen3 variation of H

Similar kind of behavior is shown by the Gen4 which can be seen in Table 6.9 and Fig. 6.17.

Table 6.9 Variation in inertia constant of Gen4 : Area2

H1 (S)	H2 (S)	H3 (S)	H4 (S)	Eigen Values	
				Real part	Img part
6.5	6.5	6.175	1	-0.4189	1.2611
6.5	6.5	6.175	2	-0.3375	1.3508
6.5	6.5	6.175	3	-0.2949	1.1892
6.5	6.5	6.175	4	-0.2387	1.1678
6.5	6.5	6.175	5	0.2259	0.1383
6.5	6.5	6.175	6	0.1936	0.1414
6.5	6.5	6.175	7	0.1883	0.1466
6.5	6.5	6.175	8	0.1619	0.1468
6.5	6.5	6.175	9	0.1751	0.1489
6.5	6.5	6.175	10	0.1758	0.1544

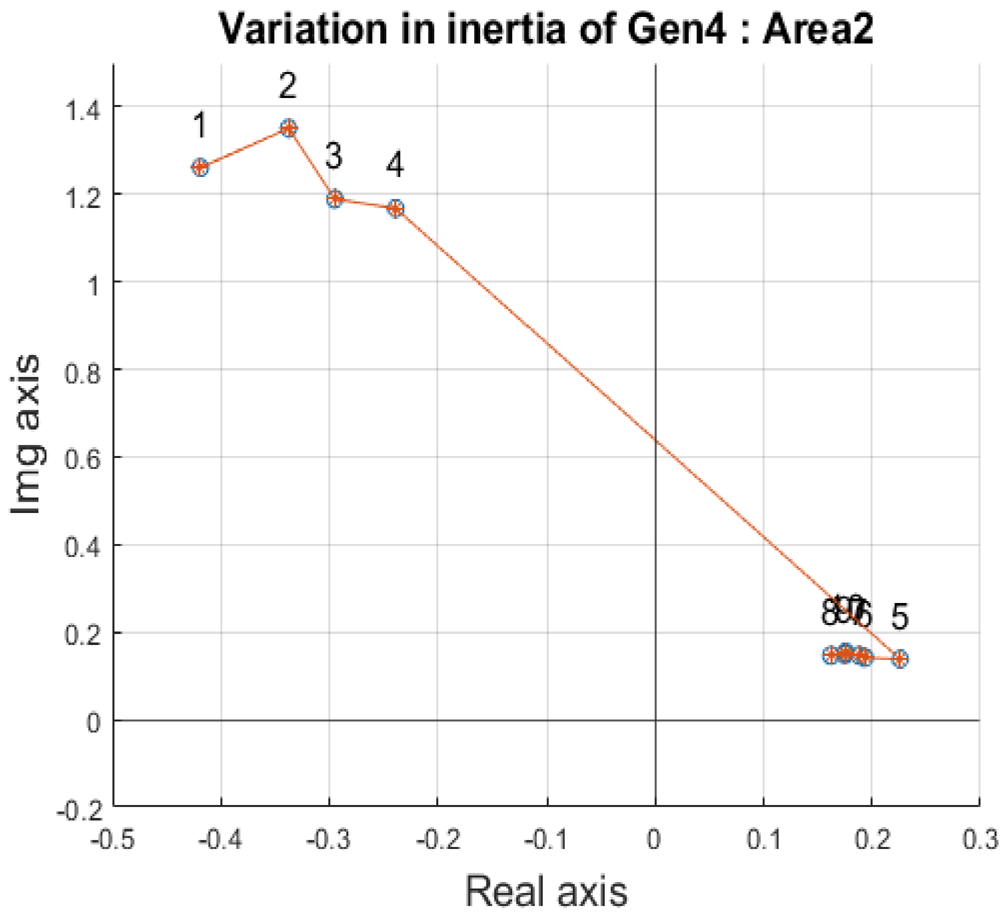

Fig. 6.17 Eigen value plot for Gen4 variation of H

When the inertia constant of Gen3 and Gen4 is varying simultaneously from 1 to 5, then the real part of eigen values are negative and the eigen values are in left side. In this condition the system is stable as shown in Table 6.10. Otherwise for inertia constant varying from 6 to 10, the real part of eigen values are positive and the eigen values are on the right side of the s plane. In this condition the system is unstable. The plot of eigen values on varying the inertia constant of Gen3 and Gen4 simultaneously is shown in Fig. 6.18.

Table 6.10 Variation in inertia constant of Gen3 & Gen4 simultaneously : Area2

H1 (S)	H2 (S)	H3 (S)	H4 (S)	Eigen values	
				Real part	Img part
6.5	6.5	1	1	-1.1155	1.5253
6.5	6.5	2	2	-0.5927	1.2813
6.5	6.5	3	3	-0.4380	1.3017
6.5	6.5	4	4	-0.3173	1.1398
6.5	6.5	5	5	-0.2181	1.1590
6.5	6.5	6	6	0.2134	0.1440
6.5	6.5	7	7	0.1744	0.1510
6.5	6.5	8	8	0.1749	0.1540
6.5	6.5	9	9	0.1737	0.1534
6.5	6.5	10	10	0.1579	0.4829

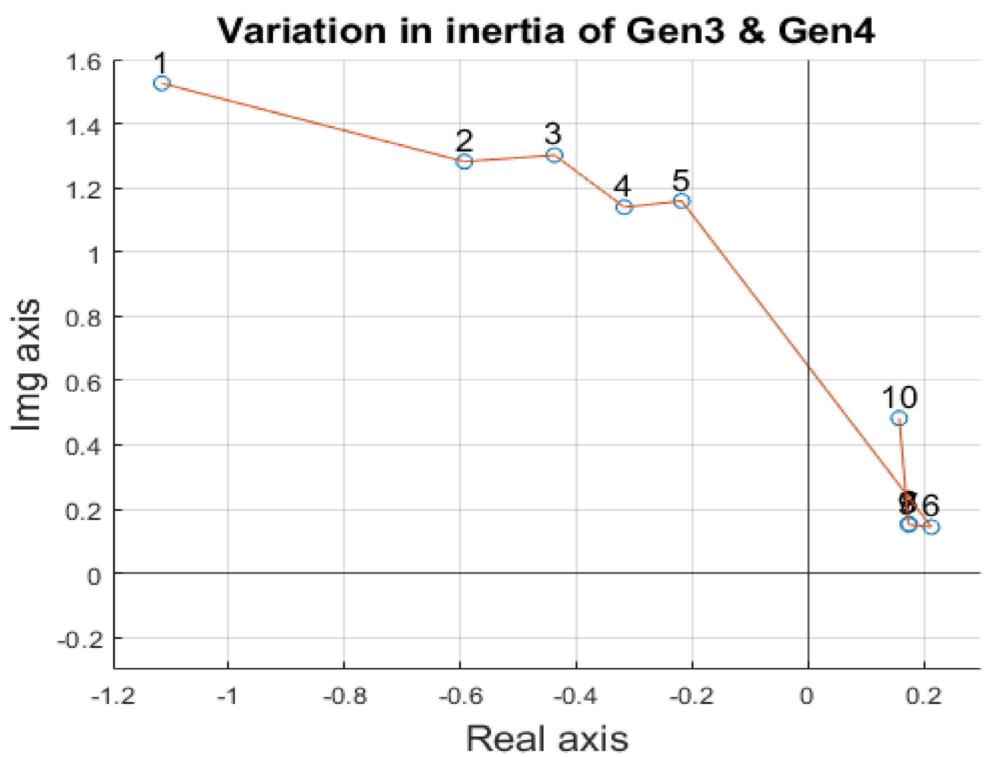

Fig. 6.18 Eigen value plot for Gen3 & Gen4 variation of H

CHAPTER 7

CONCLUSION

OOS condition has to be detected in the power system before it loses synchronism and disconnect the generators/areas to prevent the power system from collapsing. To study the effect of change in power system inertia by converter based generators on OOS condition in the power system, a two area system has been developed in a Opal-rt real time simulator HYPERSIM software. Phasor angle data at both sides of tie line has been collected from PMU, and simple logic of angle separation has been implemented to detect the OOS condition in the two area system after the occurrence of a fault on the tie line. The OOS detection using the PMU phasor data scheme is found to be successful in detecting the OOS condition and separating the system into two areas. From the simulation results, it has been found that the trip time increases with the increase of inertia in Area1. On the other hand, the trip time decreases with the addition of inertia in Area2. To verify the stability effect of RES, modal analysis of the two area system is also done for different inertias of Area 1 and Area2. From the modal analysis of two area system it is found that on increasing the inertia of Area1 Eigen values are moving from right side of s plane to left side of s plane. On the other hand, with the increase in inertia of Area-2, Eigen values are moving from left side of s plane to right side of s plane. This study thus helps in planning of a power system with RES intereation.

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Appendix

SYNCHRONOUS GENERATOR

MVA Rating = 900MVA

Voltage rating = 20 KV

Nominal power of turbine = 900 MW

Reactive power = 72.5 Mvar

Direct axis

Xd = 1.8 X’d = 0.3 X”d = 0.25 T’do = 8 T”do = 0.4

Quadrature axis

Xq = 1.7 X’q = 0.55 X”q = 0.25 T’q = 0.4 T”q = 0.05

Saturation = Off

Armature Values

Ra = 0.0025 Xl = 0.18

Exciter

Kp = 1 Ka = 200 Kf = 0 ex_Vtmin = 6.99 pu Ex_Vtmax = 7 Tr = 0.02 s

Ta = 0.0001 s Tf = 0.0001 s ex_Vrmin = 0 Ex_Vrmax = 7

Stabilizer circuit = Off

Shaft

T Start = 0 H = 6 KdStart = 10 Kd = 5 Tgo = 0.5 pu/MW.s

Wmin =0.5 pu Wmax = 1.5 pu

TRANSFORMER

Primary connection = Delta lead

Secondary connection = Y ground

Base primary winding voltage(rmsLL) = 20 KV

Base secondary winding voltage(rmsLL) = 398.372 KV

Voltage(rmsLL) = 228.386 KV Base frequency = 50 Hz

Rm = 222.222E-6 Lm = 589.463E-3 R1 = 444.444E-9 Ω

L1 = 0 H R2 = 58.778E-6 Ω L2 = 23.387E-3 H

Shunt Capacitor & Load at bus 4

C1 = 9.376E-6 F C2 = 10.028E-6 F R1 = 54.705 Ω L1 = 1.403 H

Shunt Capacitor & Load at bus 6

C3 = 17.450E-6 F C4 = 9.376E-6 F R2 = 29.937 Ω L2 = 1.403 H

Three phase pi line

Zero seq (R0) = 1.610 Ω/km L0 = 6.100E-3 H/km C0 = 5.249E-9 F/km

Positive seq (R1) = 52.900E-3 Ω/km L1 = 1.400E-3 H/km C1 = 8.775E-9 F/km

Snubber (Shunt R-C)

R = 3.960 Ω C = 66.978E-6

LIST OF PUBLICATIONS

- Accepted in IEEE ICICCSP 2022 Conference, Titled “Study On Impact Of Power System Inertial Stability By Renewable Energy Resources”