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Coordinated Tuning of AVRs and PSSs for Local and Inter-Area Modes of Oscillation in Eastern Regional Grid of India

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***Abstract*—A wide range of events can cause oscillations in power systems. Most oscillations are dampened by the system, but a few oscillations may remain undamped, causing the system to collapse. As a result, in the history of modern power system operation and control, low frequency oscillations (LFOs) investigation is necessary. This paper explains the small signal stability analysis of eastern regional (ER) grid neglecting the impact of other regional grids of India. The modal analysis is performed to know the LFO modes in ER grid system. The coordinated tuning of automatic voltage regulators (AVRs) and power system stabilizers (PSSs) have been carried out to damp out these LFO modes and provide required stability margin. The modes those are excited during the disturbance having less damping and high amplitude have been studied and discussed. The truncated 102-bus ER grid system of India is considered for this analytical study.**

***Index Terms*— Low frequency oscillation, Eastern regional grid, Automatic voltage regulator, Power system stabilizer, Modal analysis**

I. Introduction

THERE are five regional power grids in India viz. Northern, Eastern, Western, North Eastern and Southern grids, which were interconnected to form the National Grid. In recent years, the Indian power system has undergone colossal growth in system size, load/generation, transmission/distribution and voltage levels which is widely monitored by phasor measurement unit based synchrophasor systems [1]. The challenges that the Indian electricity grid operator is facing have also been increased in many folds. Among these challenges, small signal stability is one of the most serious issues in the Indian grid. The small signal stability is the ability of the power system to damp out the LFOs with a frequency range of 0.2 to 3 Hz. When generators of one coherent area swing against those of another area at a frequency range of 0.2 to 1 Hz, then it is known as inter-area oscillation. However, when one generator oscillates against the rest of the system at a frequency range of 1 to 3 Hz, this is referred to as local mode [2]–[7].

In Indian power system, several cases of oscillations starting from local to inter-area has been observed. Presently synchrophasor technology is used to monitor and analyse these LFOs [8] [9]. In order to damp these oscillations, several initiatives have been taken by the Indian power system operator as well as the planner. There are different techniques that has been used to analyse these oscillations to take correctives actions . Many available literatures illustrate that the present Indian power system is providing improved damping to local and inter area modes of oscillations [2], [5], [10]–[13].

It is known that local PSS, where input signals are the local signals are effectively utilized to damp out low frequency oscillations if they are tuned properly for local modes [11]. However, because local feedback signals are used, the effects are limited in damping out inter-area oscillations. Inter-area oscillations develop across the large interconnected power grids which impacts the interconnected power system stability and reducing tie-line power flow. Major inter area oscillation damping is improved by system strengthening or utilized POD devices on HVDC, FACTS devices which are sometimes not economic. Another way is to use the PSS of generating units and ensure local oscillations tuning and providing aided benefit as improvement in inter area damping to some extent. Howver to ensure the same, it is necessary to tune the AVR along with PSS tuning to provide proper adequate damping to mitigate LFOs [14].

The paper is based on the some of the objectives defined under Science and Engineering Research Board (SERB) funded project CRG/2018/002915 and associated studies carried out to achieve those objectives. This paper analyses the low frequency oscillation and their damping in the eastern region grid in Indian power system. The study is being carried out to analyze past cases of forced oscillation, impact of AVR and PSS tuning in the system and improvement of the damping. The paper highlights the various characteristics of LFOs observed in the system with detailed analysis using various case studies ways systematic approach.

This paper is organised in five sections. Section II describes the system description of eastern regional grid. Section III describes small signal stability issue in ER grid system. Section IV explains objective and methodology. Further section V includes the simulation result and analysis of different cases. Finally, Section V concludes the findings from the above study.

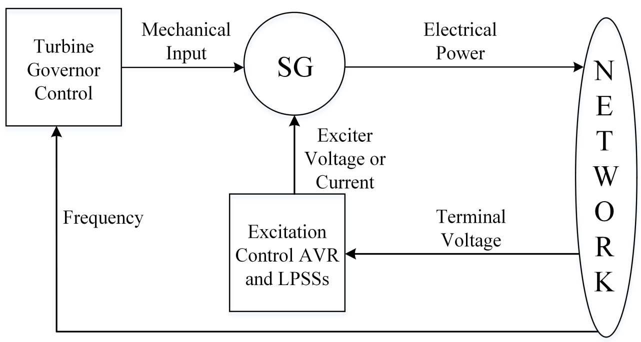

Fig. 1: Structure of a power system

II. Brief Overview of ER grid System and Dynamic Modeling

The eastern regional (ER) grid comprises different voltage levels and is interconnected to other regional grids of India. This is the only regional grid in India that is connected to all other regional grids and has interconnection with three neighboring countries (Bangladesh, Bhutan and Nepal). It consists of five states viz. Bihar, Odisha, West-Bengal, Jharkhand and Sikkim.

The truncated model of ER grid system have been taken and its dynamic model has been developed as a part of this project based on available input. ER grid system taken is truncated at 400 kV and above voltage level. Lower voltage levels have been truncated using equivalent generation or load and they are not reflected in the model. Thus the entire analysis has been performed on the voltage levels of 765 kV and 400 kV. The ER grid can be classified upon voltage level as shown in Table I. There are inter-regional HVDC line, however those are not considered for analysis carried in this paper. The network elements composition of ER grid system for this analysis is shown in Table II. The summary of models utilized for ER grid system is shown in Table III. The 25 generating plants of eastern regional grid considered connected at EHV system at 400 kV and above voltage level is shown in Table IV. In view of the confidential nature of data the plant name has been kept like this.

Power system of ER grid system is dominated by synchronous generators there for proper modelling of its components e.g. generator, excitation, turbine, governor, power system stabilizer etc. are required for simulation analysis. The overall structure of the ER grid system power system is shown in Fig.1. During this simulation analysis, being thermal generation domination in ER grid truncated system, for simplicity all generators have been treated as thermal generator in simulation analysis. However the modelling data is as per the actual details available for each unit. The detailed model of synchronous generators (type GENROU) with saturation are used for generating unit modelling. The AC1A type AC exciters are used in this model along with IEEEST type local power system stabilizer for small signal stability improvement. The TGOV1 type turbine-governor model is considered for the analysis. The TGOV1 turbine-governor is considered for both thermal and hydro for this analysis. The developed model will be subsequently utilized for further studies and analysis as explained in next section.

TABLE I: Node Details

Voltage Rating (in KV)	Number of Nodes	Length (in Km)
765	6	1177
400	96	23560

TABLE II: Network Composition of ER grid

S.No.	Components	No. of Components
1	Buses	102
2	Synchronous machines	60
3	Current loads	72
4	Impedance loads	73
5	Transmission lines	230
6	Fixed shunts	34
7	Two-winding transformers	16
8	Three-winding transformers	0
9	HVDC lines	0
10	FACTS devices	0
11	Switched shunt	47

TABLE III: Summary of Models

S.No.	Models	Type	No. of Models
1	Synchronous Generator	GENROU	60
2	Excitation System	AC1A	60
3	Stabilizer	IEEEST	30
4	Turbine Governor	TGOV1	60

TABLE IV: ER grid Generating Plant Description

Plant Name	Power Generation (MW)	Type	Installed Capacity (MW)
T1	1309	Thermal	1500
T2	300.4	Thermal	390
T3	623.8	Thermal	840
T4	686.1	Thermal	1050
T5	473.4	Thermal	540
T6	399.1	Thermal	500
T7	747.8	Thermal	1000
T8	747.8	Thermal	1000
T9	373.9	Thermal	500
T10	747.8	Thermal	1200
T11	611.9	Thermal	700
T12	349.5	Thermal	1000
T13	932.6	Thermal	1000
T14	81.5	Thermal	110
T15	521.1	Thermal	1200
T16	1891.6	Thermal	2000
T17	279.6	Thermal	600
T18	430.6	Thermal	1050
T19	1064.5	Thermal	1600
T20	360.5	Thermal	500
T21	1672	Thermal	2100
T22	540.8	Thermal	1260
H1	510	Hydro	510
H2	111.6	Hydro	96
H3	1200.1	Hydro	1200

III. Overview of Small Signal Stability Issues in ER grid System

The ER grid system in the past has faced several case of low frequency oscillation. These oscillation were either local modes due to forced oscillation caused by any controlling system malfunction in generating unit. Such forced oscillation have also led to excitation of inter area oscillation. There were cases of low frequency oscillation of inter plant nature due to weaker transmission network also in the past. In addition, the eastern region being connected to all other regional grid has also participated in inter area oscillation. With the massive integration of phasor measurement units in the Indian power system, real time monitoring of low frequency oscillation are observable to grid operator [2] [8] [9] [15].

Due to this, a massive exercise in terms of PSS tuning has been carried out in ER grid system since 2018-2021 and so far, more than 50 number of generating units have been tuned [16]. In order to validate the ER grid system damping improvement with AVR and PSS tuning, one study has been performed under the funded project and the some of the relevant outcomes of the study has been published in this paper.

IV. Objective and Methodology

The objective of this paper is to analyze the ER grid system model to identify the various LFOs. In order to study the LFOs characteristics, forced oscillation cases of LFOs and impact of PSS tuning on local and global modes in ER grid system, the developed power system model has been utilized. This study shows, how forced oscillation can result in local mode as well introduction of inter area mode excitation and lower damping. Furthermore the purpose of this study is to verify the tuning of the AVR as well PSS to improve the system damping as observed in real system over the years.

In order to analyze LFOs in ER grid system, a brief overview of small signal stability and modal analysis as described in [6] is adopted in this paper.

A. Excitation System and Power System Stabilizer Tuning

The excitation system is an important part of SGs and it provide control over voltage and reactive power of SGs. For tuning of excitation system, excitation response test is performed in PSSE v35.2, by varying the controller parameter of exciter with keeping the range as mentioned in IEEE Std 421.5™-2016 [17] [18]. However, it is known that fast acting excitation system improved synchronizing torque however reduces the damping torque. To ensure that such fast acting digital AVR do not provide negative damping, a supplementary control in form of power system stabilizer is added in loop with AVR control.

Power system stabilizer is used for damping the low frequency oscillations which appear due to low damping of the system when any perturbation in form of small disturbance (line trip, fault, switching of elements) or any forced oscillation due to controller/equipment malfunction occur in the power system. The system design and equipment's control should ensure that these LFOs should always have sufficient damping in the system. Being one of the most effective way to damp LFOs is power system stabilizer it is necessary to properly tune them [11]. An ill tuned PSS can is not desired as it can cause further reduced damping by introducing the negative impact. Further, AVR if not properly tuned can add very large negative damping and make generating plant less stable. Therefore proper precaution has to be taken while devising tuning of the VAR and PSS in the system.

Objectives defined above can be achieved by performing the modal analysis on the linear state space model of ER grid system. In order to carry out a systematic analysis, various scenarios has to be prepared as provided below :

(i) All AVR and PSS tuned : Present ER grid system scenario where most of the AVR and PSS are properly tuned.

(ii) All AVR tuned , PSS OFF : Scenario where all AVRs are tuned in ER grid however PSS of the four units at different plants which have shown forced oscillation in the past are not tuned and kept out of service. This is to check how system LFOs damping changes associated with these four units and their impact on damping of inter area oscillations.

(iii) AVR untuned and PSS OFF : Scenario where all AVR and PSS are tuned in ER grid system except the four units. The PSS of these units are kept out as observed when the forced oscillation occurred in the past. In order to analyze the forced oscillation from these units, their AVR are untuned to generate forced oscillation. This will provide how the forced oscillation of these plants causes local oscillation and their excitation as well impact on inter area oscillation.

(iv) AVR untuned and PSS tuned : Scenario where all AVR and PSS are tuned in ER grid system except the four units. In these four units, their AVR are in untuned state to excite forced oscillations however their PSS are tuned. This study will show how tuned PSS helps during forced oscillation cases in the system.

B. Steps of Proposed Method for LFOs Analysis and Tuning

For performing modal analysis on above case studies to meet the defined objective scope, following step wise methodology has been adopted : (i) Preparation of detailed dynamic model in PSS/E (As completed in section II).

(ii) Utilizing load flow and dynamic model for generating linear state space model of power system at selected operating point by using network eigen value analysis.

(iii) Modal analysis is done to find the local modes and critical inter-area modes.

(iv) Identification of units suitable for tuning using geometric measure of controllability and observability.

(v) Tuning of units with high participation factor to mitigate the oscillation in the system.

The next section describes the overall all simulation for various case studies and summary of the output.

V. SIMULATION RESULT AND DISCUSSION

The truncated ER grid system is considered to demonstrate the assessment and enhancement of small signal stability. For this purpose four case studies are created with and without proper tuning of AVR and PSS. The Plants T1, T7, T9 and T16 have already experienced the low frequency oscillation within the ER grid in the past, and that analysis has been recreated in these case studies. A three-phase fault for 100ms is considered to see the dynamic behaviour of the system with and without proper tuning. The PSSE v35.2 simulation software is used for this analysis.

TABLE V: Electromechanical modes of ER grid system

Mode	Frequency [Hz]	Type	Damping ratio [%]
M1	1.018	Inter-area	5.067
M2	0.877	Inter-area	5.925
M3	1.359	Local-mode	6.005
M4	1.335	Local-mode	6.548
M5	1.19	Local-mode	7.394

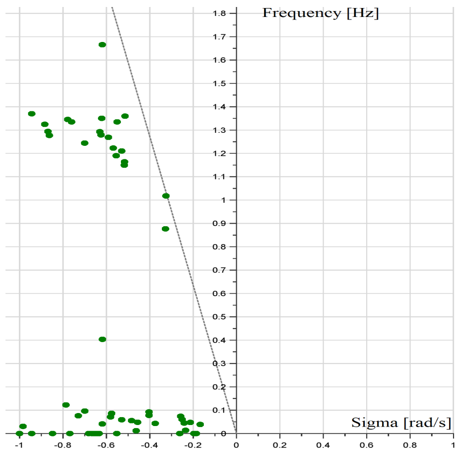

Fig. 2: Eigen value plot

A. *Case I: Both AVR and PSS tuned*

In present scenario, the ER grid system is well tuned. After linearizing the system about an stable equilibrium point, modal analysis is conducted to find low frequency modes of oscillation. The mode distribution on complex S-plane after tuning of AVR and LPSSs for all modes with a 5% damping line is shown in Fig. 2. it can be observed that oscillations are existing with damping ratio of more than 5%. The electromechanical modes of ER grid system are shown in Table V. In this table, modes M1, M2 are inter-area modes and M3, M4, M5 are local modes of oscillations. However, the damping ratio of these modes should be increased, because these modes are at boundary condition. The participation factor analysis method is performed to tuning of the system. The mode shape for modes M1 and M2 are shown in Fig. 3. The machines participated in M1 and M2 modes can be represented by their plant name. In one area, generator of plant T1, T2, T3, T4, T5, T7, T8, T9, T10, T18, T19, T20, T21, T22 and in other area, generator of plant T11, T12, T13, T14, T15, T16, T17, H1, H2, H3 are oscillating against each other for mode M1. On the other hand, the generator of plant T1, T2, T9, T21, H1, H2, H3 and generator of plant T3, T4, T6, T8, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T22 are oscillating against each other for mode M2. The left eigen vectors give the control location where the units need to be tuned. Now by varying the parameters of excitation system and LPSSs, corresponding responses are checked for that unit. After performing proper tuning it can be observed that there is no undamped modes in the right half of S-plane and all critical modes of oscillations are damped out.

The dynamic simulation is performed on PSSE software. At t = 5 sec, three phase fault on bus 11 is enabled for 100ms then it is removed and simulation results are obtained for 30 sec. The system responses is stable initially before disturbance. After proper tuning of excitation system and LPSSs, the LFO modes are damped. The time domain responses for all rotor angles and speed deviation are shown in Fig. 4 and Fig. 5 respectively. It can be observed from these responses that the stability of the system has been enhanced. In order to analyse the past LFOs in ER grid system, further analysis has been carried out by exciting the forced oscillation through controller malfunction of AVRs and PSSs.

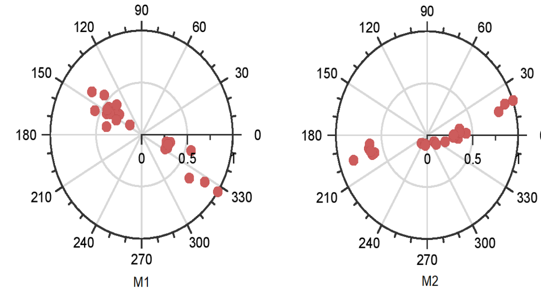

Fig. 3: Mode Shape for modes M1 and M2

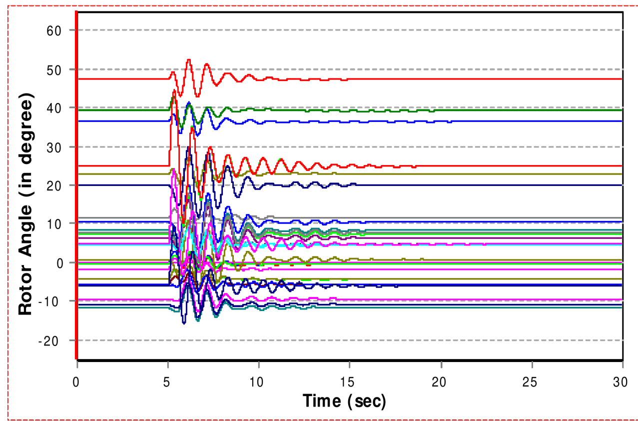

Fig. 4: Rotor angle (in degree) vs time for case I

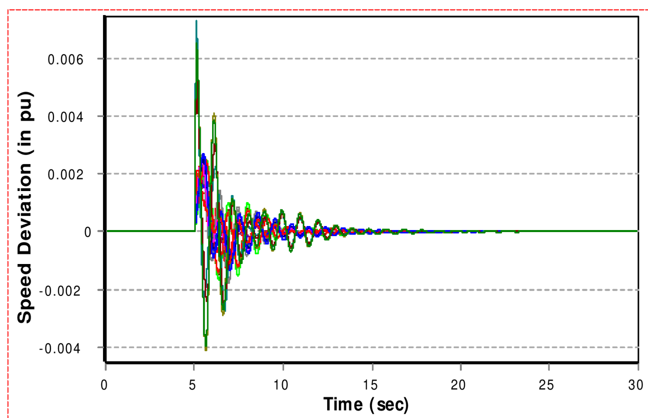

Fig. 5: Speed Deviation (in pu) vs time for case I

B. *Case II: AVR tuned and PSS OFF*

In this case, the AVRs are tuned, but power system stabilizers are bypassed for 4 plants namely T1, T7, T9 and T16,

TABLE VI: Electromechanical modes of ER grid system

Mode	Frequency [Hz]	Type	Damping ratio [%]
M1	1.024	Inter-area	4.385
M2	0.88	Inter-area	6.967
M3	1.385	Local-mode	4.278
M4	1.31	Local-mode	8.289
M5	1.226	Local-mode	7.741

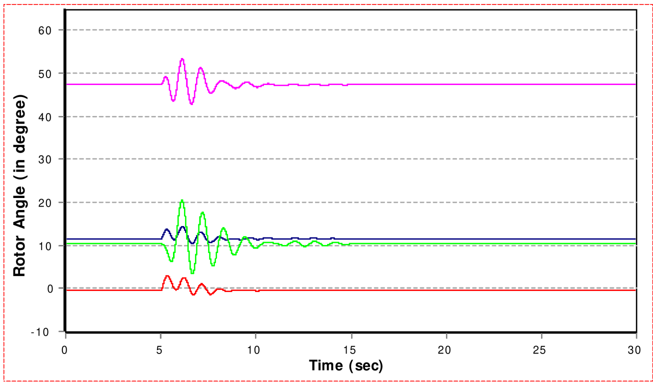

Fig. 6: Rotor angle (in degree) vs time for case II

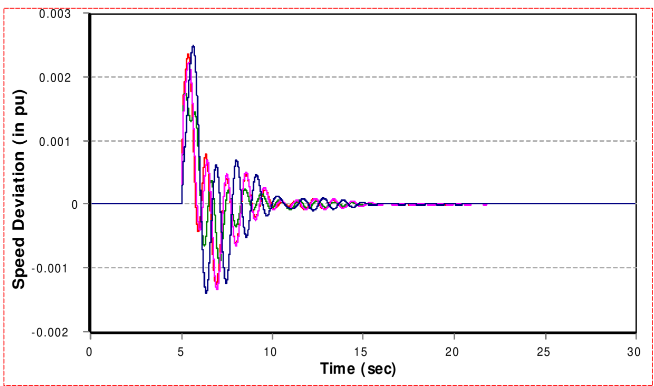

Fig. 7: Speed Deviation (in pu) vs time for case II

Out of 25 Plants. The electromechanical modes of ER grid system are shown in Table VI. These modes are tracked by using participation factor method. Due to bypassing of PSS the damping ratio of modes M1, M2 are reduced and that of modes M2, M4, M5 are increased. Similar dynamic analysis has been performed as carried out in case-1. For those plants which PSS kept OFF the dynamic response of rotor angle, speed deviation are shown in Figs. 6 and 7 respectively. It can be observed that the system is stable because the damping ratio of two modes are decreasing and at the same time damping ratio of other three modes are increasing. So, there is enough damping to damp out the oscillation in the system.

C. Case III: AVR untuned and PSS OFF

In this case, the AVRs are untuned and PSS kept OFF in same plant as considered in case-II namely T1, T7, T9 and T16. The electromechanical modes of ER grid system is shown in Table VII for this case. The damping ratio of M1, M3, M5 are reduced and damping ratio of M2, M4 are increased. Based on the above discussion and using detailed model, simulation is performed on PSSE platform. At t = 5 sec, three phase

TABLE VII: Electromechanical modes of ER grid system

Mode	Frequency [Hz]	Type	Damping ratio [%]
M1	1.023	Inter-area	4.883
M2	0.879	Inter-area	8.002
M3	1.385	Local-mode	4.279
M4	1.308	Local-mode	8.298
M5	1.216	Local-mode	3.617

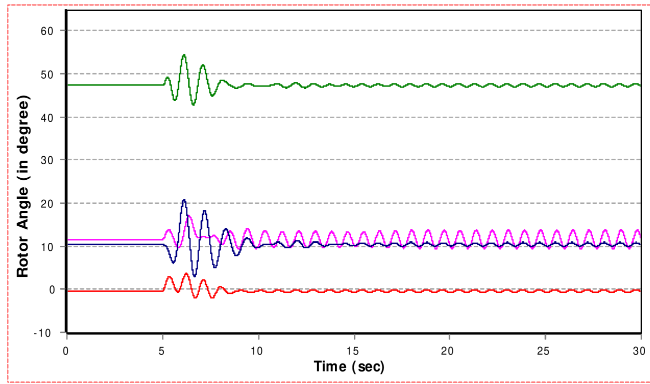

Fig. 8: Rotor angle (in degree) vs time for case III

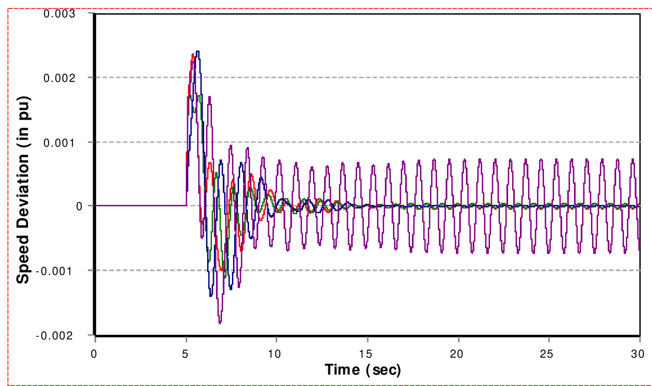

Fig. 9: Speed Deviation (in pu) vs time for case III

fault on bus 11 is enable for 100ms then it removed and simulation is carried out for 30 sec. The system responses are initially stable before disturbance, but after occurrence of disturbance, the system becomes unstable because of poorly damped modes. Time domain response of rotor angle and speed deviation are shown in Figs. 8 and 9.

D. Case IV: AVR untuned and PSS tuned

In this case, the AVRs are untuned and PSSs are tuned for plant T1, T7, T9 and T16. The electromechanical modes for this case are shown in Table VIII. The damping ratio of inter-area modes M1 and M2 along with local mode M4 are improved. However, the damping ratio of local mode M3 is becoming negative and M5 is also reduced. It shows that the proper coordinated tuning of AVRs and PSSs are required for enhanced stability margin. The dynamic performance analysis similar to case III has been performed. The response of rotor angle and speed deviation are shown in Figs. 10 and 11. These responses shows that the system becomes unstable and sustained oscillation is existing in the system.

TABLE VIII: Electromechanical modes of ER grid system

Mode	Frequency [Hz]	Type	Damping ratio [%]
M1	1.029	Inter-area	6.844
M2	0.891	Inter-area	6.383
M3	1.412	Local-mode	-2.947
M4	1.333	Local-mode	6.552
M5	1.218	Local-mode	3.909

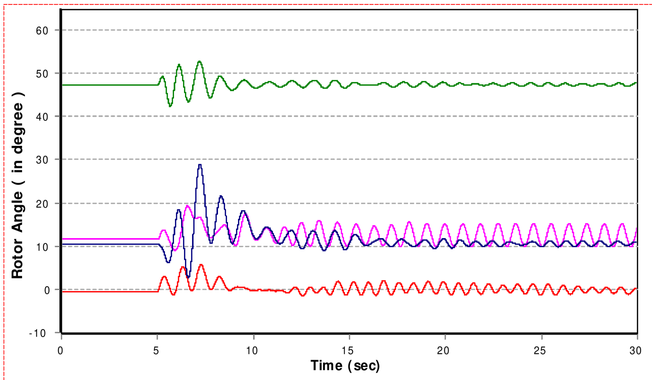

Fig. 10: Rotor angle (in degree) vs time for case IV

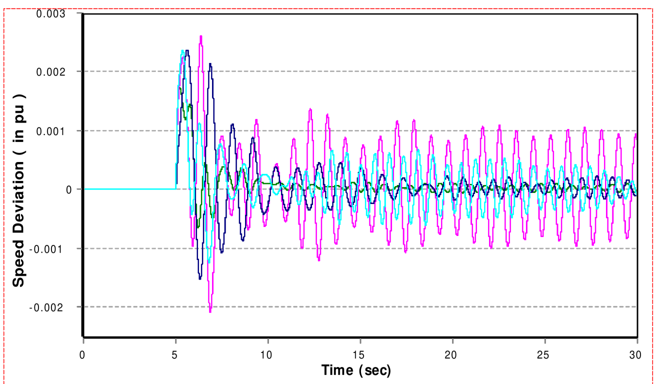

Fig. 11: Speed Deviation (in pu) vs time for case IV

This model is developed ignoring the impact of other regional grids. Local and inter-area modes of oscillation have been studies only considering the truncated model of ER grid. However, it is a well known fact that inter-area oscillations are affected by other regional grid, which will be studied in future.

VI. Conclusion

In this paper, the coordinated tuning of AVRs and PSSs have been performed to provide proper damping and mitigate LFOs in the ER grid system. For this purpose a truncated model of eastern regional grid is developed ignoring the input of other regional grids and modal analysis is performed to find low frequency modes of oscillation in the system. The geometric approach and participation factor method are considered for identifying those units, which are participating in LFO modes. The eigen value plot and the dynamic responses show that the system is able to achieve the desired damping ratio of concerned modes by properly coordinated tuning of AVRs and PSSs . Various case studies are investigated to recreate past disturbances in the eastern region grid for further analysis.

Main contributions of this paper may be highlighted as follows.

- The AVRs and local power system stabilizers (LPSSs) both are tuned through a coordinated way to damp out the low frequency modes of oscillation.
- Oscillations in the system are deliberately introduced to recreate or analyse past experiences of oscillations in ER grid.
- A geometric approach is adopted to select the units required to tune for proper damping of LFOs.
- Various case studies with and without proper tuning of AVR and LPSSs are discussed.

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