Spontaneous Oscillations and Modal Resonance in Indian Grid: A Case Study

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***Abstract*— Inter area oscillation in large grid is inherent to a large system. However, it is desirable that these oscillations are adequately damped for a secure and reliable transfer of power. Occurrence of Low Frequency oscillations in inter area range have been observed in the Indian grid after the synchronization of Southern grid with the rest of the Indian grid. These oscillations were generally triggered by unforeseen grid events such as unit tripping, load loss-changeover, line tripping etc. However, on one occasion, spontaneous oscillation and modal resonance was observed in the Indian system during normal operation. This paper presents the case study of that experience. The event was captured and analyzed with the help of synchrophasors units installed at various geographical locations across the grid. Possible remedial measures for further studies have also been suggested for improving the system security during such oscillation.**

***Keywords*— Eigenvalue, Interarea Oscillations, Modal resonance, Mode Shape, Power System Stabilizers, Small Signal Stability.**

I. Introduction

Indian power grid is demarcated into five regional electricity grids namely Eastern grid, Northern grid, North –Eastern grid, Southern grid and Western grid. These regional grids have been gradually interconnected synchronously to form the synchronous Indian Grid having installed capacity of around 233 GW. The recent milestone in this journey has been the synchronization of the Southern Grid with the rest of India Grid through 765 kV Raichur (in Southern Region) to Solapur (in Western Region) on the 31st December 2013. Figure 1 shows the various Interconnections in the Indian grid after the synchronization of SR grid.

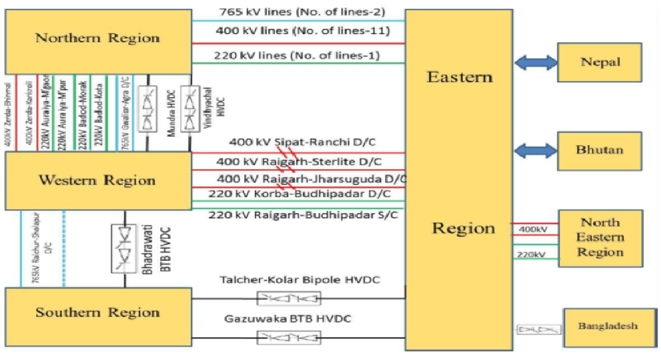

Fig. 1. Indian Grid Schematic Diagram showing all the Inter-regional and transnational links

For better visualization and understanding of the dynamic behavior of the large synchronous system Phasor Measurement Units have been installed at several critical locations in the grid [1]. Analysis of grid events consequent to synchronization of the Southern Grid on 31st December 2013 has revealed presence of an Inter-area mode of 0.2 Hz magnitude the in the Grid. The frequency of this mode varies in the range 0.18-0.22 Hz depending on the operating condition. It is generally well damped, however on 28th January 2014 spontaneous oscillations were observed in the system through synchrophasors. These oscillations were analyzed for the identification of mode frequency, its damping and other characteristics. This paper analyses the event based on the various data available to give a detailed overview of the event.

The paper is organized as follows. Section II is the brief overview of Inter area modes based on the literature survey. Section III illustrates the case of the spontaneous oscillation while Section IV describes the Fast Fourier Transform (FFT)

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and Matrix pencil analysis of the event and its results. Correlation between the currents as observed from various Synchrophasor Units across the grid is discussed in section V. Section VI brief out the inferences and remedial actions based on that. At the end, the paper has been concluded with the future prospects.

II. Interarea Oscillation

The oscillation which involves a large group of generators in one area swinging against a group of generators in another area is called as inter area mode oscillations. A large interconnected system usually has two distinct forms of inter area mode out of which the first is a low frequency mode wherein one coherent group of generators swing against the other in the frequency range of 0.1-0.3 Hz. While the second is higher frequency mode wherein a subgroup of generators swinging against another one in frequency band of 0.4 Hz - 0.7 Hz [2].

Inter area oscillations of 0.36 Hz and 0.76 Hz have been reported in Central China [3] while in South China interconnected system Inter area modes of 0.53 Hz and 0.66 Hz is studied in [4]. The UCTE network is having 0.21 Hz and 0.31 Hz as their major inter area modes that have been explained in [5]-[6]. In small grid like Thailand grid, the modal frequency of inter area nodes as measured from synchrophasor units are 0.4 and 0.55 Hz [7]. Inter area and other oscillation in Indian Grid have been explained in details in [8]-[9]. These inter area modes are very essential to be kept in view, as they have resulted in various major blackouts in the world [10]-[11].

Various simulation and measurement based study for identifying the root cause of inter area oscillation has been explained in [12]–[15]. The fundamental reason for the inter area oscillation is the weak tie line between the areas which can further get aggravated by high power flow on the link and poorly tuned PSS of the generators in the system as in [16].

III. Case Study

In India, the Southern Regional Grid (57 GW) is connected to the NEW Grid (176 GW) through the 765 kV Sholapur-Raichur AC link, Bhadrawati and Gajuwaka HVDC Back to back and Talcher-Kolar HVDC bipole link. Several other transmission elements upstream and downstream of the interconnection are expected to be commissioned in near future. System Protection Schemes have also been implemented to automatically shed load (in SR) and/or back down generation (in WR) in the event of tripping or overloading of critical lines for safe and reliable operation under contingencies.

As has been observed in various synchronization of large grid across the world, inter-Area oscillations are inherent. In case of Indian grid also after southern grid synchronization 0.2 Hz inter-area oscillation were observed. The power flow on AC tie line is sensitive to the load/generation changes in either of the grid. Oscillations have been observed in the system in the event of tripping of units or during load changeover in the grid. These oscillations often have a large magnitude but are generally damped within 20–40 seconds with damping in range of 8-30 %. However at 20:03 Hrs. on 28th January 2014, spontaneous oscillations of large amplitude were observed. In the antecedent, the flow on 765 kV Solapur-Raichur circuit 1 was 264 MW from NEW to SR grid. No switching/tripping of transmission lines or generating unit was recorded in the system that could have triggered the oscillations. The power flow on the tie line is shown in figure 2.

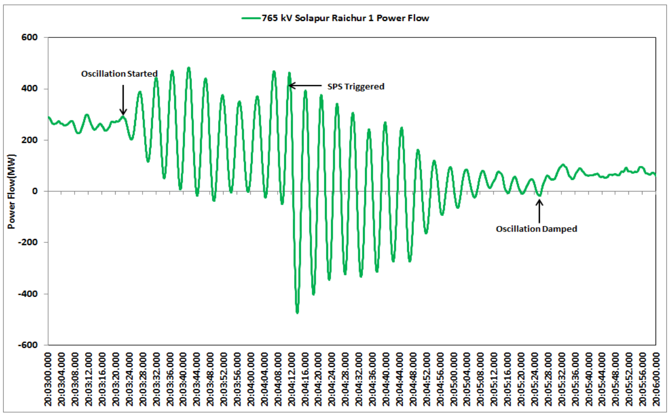

Fig. 2. Active Power flow in 765kV Solapur-Raichur ckt I

It is observed from figure 2 that the oscillation started at 20:03:25 hrs. After 45 seconds of initiation of oscillation, i.e. at 20:04:10.859 Hrs, SPS provided for restricting high rate of change of power flow on this link was triggered. This resulted in generation reduction in NEW grid and load reduction in Southern grid. To analyze the event, synchrophasor measurements from various locations in the synchronous system were collected for analysis.

The oscillation was observed in various parameters like current, voltage and power flow on transmission and generation across the grid. The oscillation in frequency across various PMUs in Indian grid is shown in figure 3. The Solapur frequency is in phase opposition with rest of the PMU. Figure 4 shows the oscillation observed in the R phase voltage as observed across the grid. The oscillation is more prominent near the tie line as compared to the other location in the grid. The Power flow on various lines has also observed the oscillation out of which maximum oscillation were observed near to the tie line.

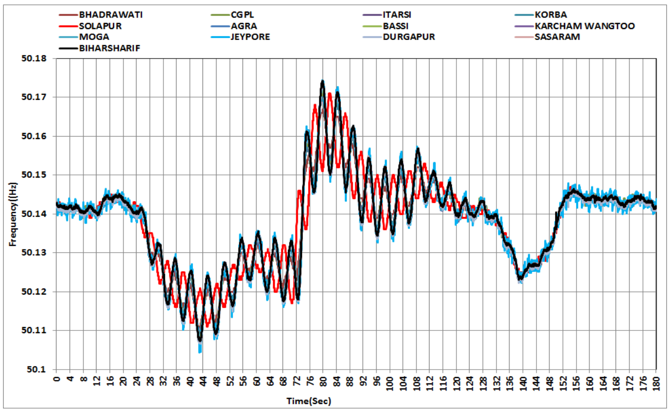

Fig. 3. Frequnecy of important nodes in the grid

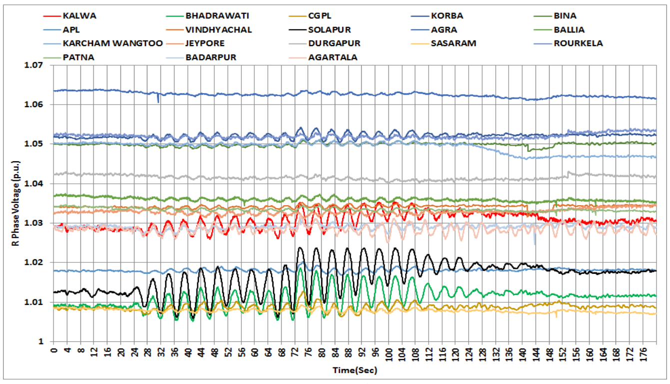

Fig. 4. Single phase volatge of important nodes in the grid

The duration of 130 seconds for which oscillations persisted could be divided into two parts one prior to SPS operation while the other after SPS operation which has been named as duration A (45 seconds) and duration B (75 seconds) for analysis purpose. Section IV summarises the inferences drawn from FFT analysis (for oscillatory modes). While section V summarises the inferences from Matrix pencil (for mode shape, damping and other characteristic features).

IV. Fast Fourier Transform

Results of FFT done on the power flow of 765 kV Solapur Raichur for duration-A and duration-B is shown in figure 5 and figure 6. From figure-5 it may be inferred that the major dominant mode during the duration A (prior to SPS operation) were 0.19 Hz and 0.207 Hz. Presence of two Inter area modes having high amplitude and nearby frequency suggest of mode coupling or modal resonance [19].

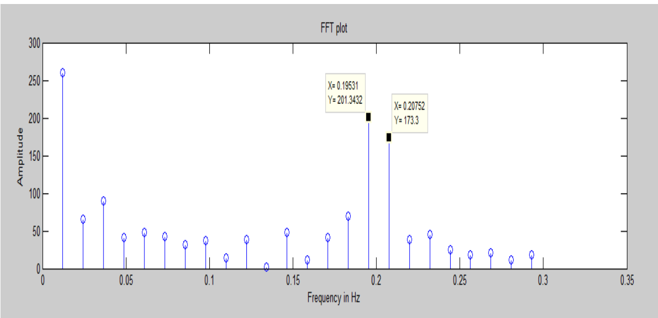

Fig. 5. FFT of Duration A showing various modes and their amplitude.

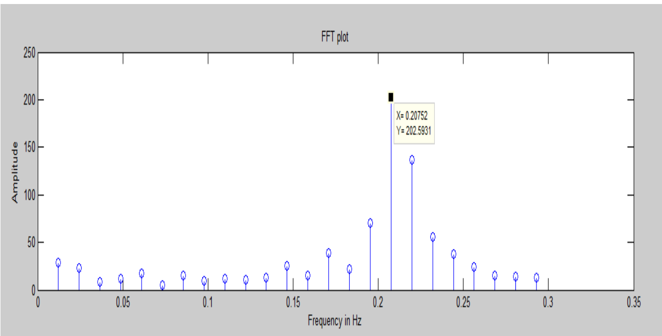

Fig. 6. FFT of Duration B showing various modes and their amplitude.

From figure 6, it may be inferred that only one mode i.e. 0.207 Hz is present during duration B. This suggests that one of the inter area modes has got damped out effectively. To confirm the modal resonance in the system modal analysis using linear technique was carried out and the results are summarized in next section.

V. Matrix Pencil Analysis

To evaluate the observability of different modes in the oscillations across different PMU signals, modal analysis using Matrix Pencil method was carried out. Matrix Pencil (MP) method is one of signal processing techniques which assumes signal as linear combination of system modes [17]. The input signal used for analysis were frequency, voltage and active power recorded in synchrophasor. 25 samples/sec is used for analysis with a time window of 10 seconds. Main parameter for MP is selection of number of modes existing in the signal.The number of modes for which maximum SNR is achieved is chosen as number of modes existing in the signal [17].

A. MP Analysis on frequency

Frequencies from various PMU's were analyzed together for both the durations. Analysis from duration A shows two modes i.e. 0.235 Hz and 0.19 Hz out of which the first having positive damping while other is having zero damping whose mode shape is given in figure 7 and 8 respectively.

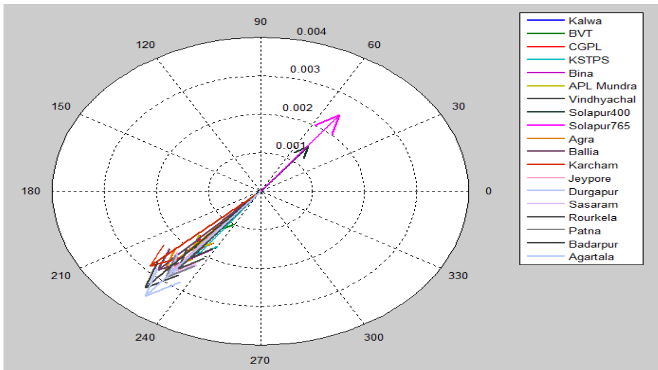

Fig. 7. Mode shape of 0.235 Hz having 4 % damping observed during duration A.

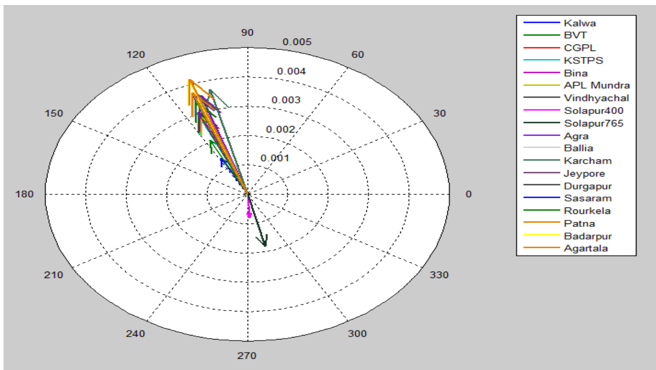

Fig. 8. Mode shape of 0.19 Hz having zero damping observed during duration A.

During duration B, only one dominant mode with frequency 0.205 Hz was observed with positive damping whose mode shape is plotted in figure 9.

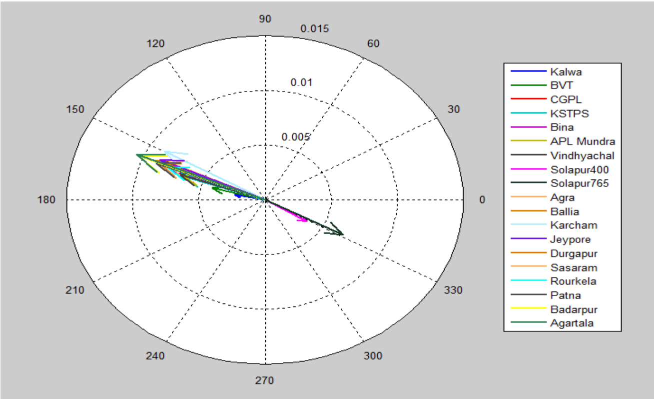

Fig. 9. Mode shape of 0.205 Hz having 3.4 % damping observed during duration B.

In duration A, modal resonance is observed and to confirm the phenomenon moving window Matrix Pencil method was adopted. It was observed from the modes shape of both modes as shown in figure 7 and 8 that both the modes approaches each other and move out in orthogonal direction after interaction. This resulted in zero damping for 0.19 Hz while positive damping for 0.235 Hz. With this, the oscillation started growing and resulted in SPS operation. With change in system state, the negatively damped mode damping improved and oscillation damped out. In addition, it can be observed from figure 7, 8, 9 that the frequency at Solapur is swinging against the frequency at rest of the PMU locations. This indicates that SR machines were swinging against the machines in the rest of NEW grid.

B. MP Analysis on Voltage

R phase voltage of various PMUs widespread across Indian grid was analyzed using the MP method for both durations separately. Similar to observation in frequency, here also during duration A two modes are observed whose mode shape are orthogonal as shown in figure 10 and 11. One of them is having positive damping while the other has zero damping. After SPS, operation only one mode with positive damping is present.

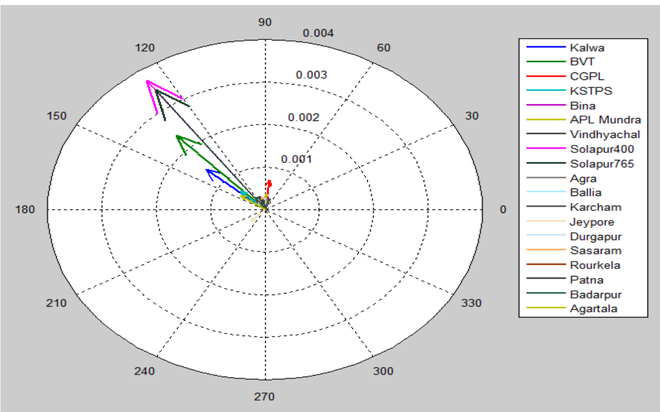

Fig. 10. Mode shape of 0.225 Hz having 3.53% damping observed during duration A.

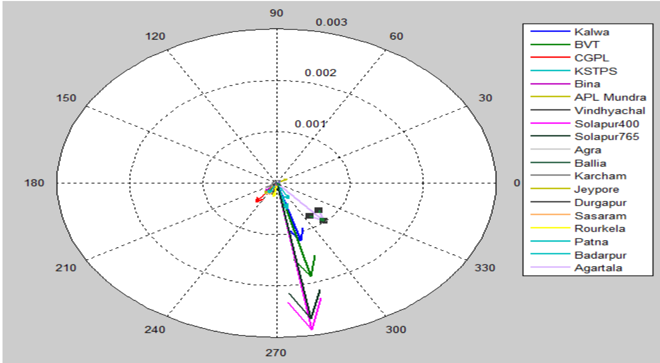

Fig. 11. Mode shape of 0.19 Hz having zero damping observed during duration A.

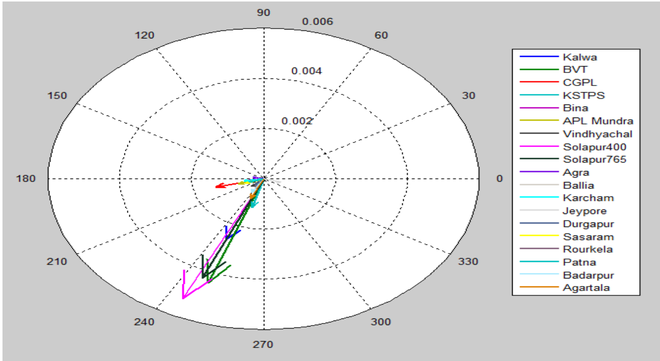

Fig. 12. Mode shape of 0.207 Hz having 3.7 % damping observed during duration B.

C. MP Analysis on Power

The most observable signal in which the oscillations were seen was the power flow. From figure 4, it was observed that the oscillations in voltage were low. Therefore, the large oscillations in power were mainly due to changes in current. Few of the significant line power flows were considered for modal analysis based on visibility of oscillations. Here also similar to observation of frequency and voltage, two modes coexist during duration A and resonance was observed in the movig window with orthogonal departure of the modes. Figure 13,14 and 15 shows the modeshape of dominant mode observed. The mode shape of Power flows however depends on the sign convention used for the direction of flow of Power.

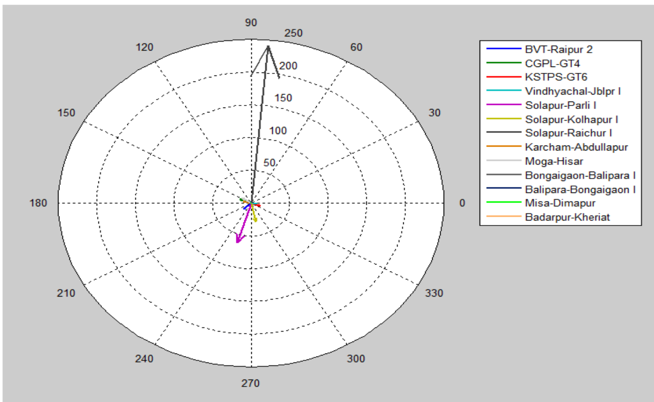

Fig. 13. Mode shape of 0.218 Hz having 5.7% damping observed during duration A.

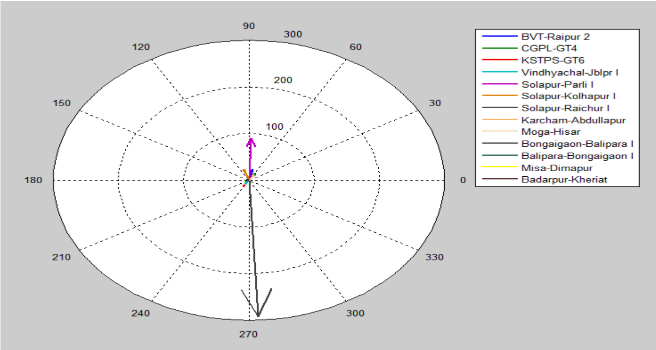

Fig. 14. Mode shape of 0.197 Hz having 6.7 % observed during duration A.

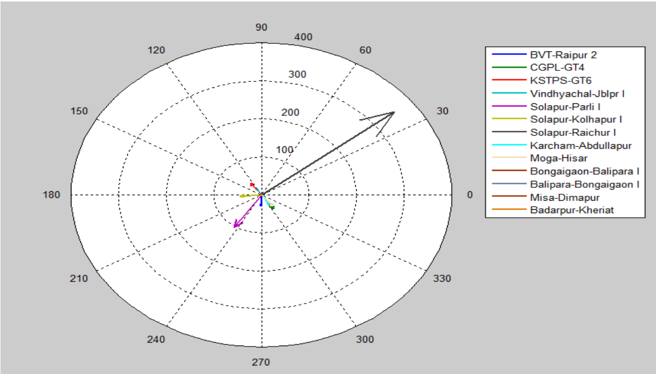

Fig. 15. Mode shape of 0.212 Hz having 5% damping observed during duration B.

Therefore, MP analysis has confirmed the modal resonance observed between the two modes, which have resulted in instability of one of the modes. Such phenomena are very rare and their analysis is difficult from simulation. Next section discusses the mode propagation path.

VI. Mode Propagation Path

Based on the analysis of real time data acquired through different PMUs installed across the Indian Grid, oscillations were observed in certain line flows. A correlation matrix was obtained on the PMUs Data between all the lines with Solapur-Raichur line power flow [19]. Since the oscillations in current signal were higher as compared to voltage, the correlation between currents of various feeders was studied and the observations are illustrated in figure 16.

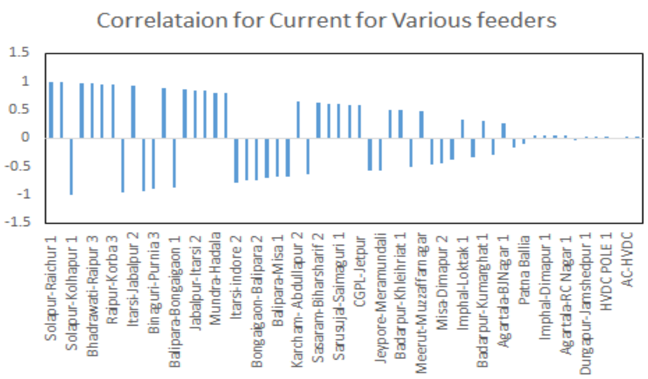

Fig. 16. Correlation of R phase current of various feeders as observed by Synchrophasor units

It can be observed that few correlations are positive while few are negative which is due to the change in the normal direction of the current. The negative correlations would come if the direction of the current flow were taken in opposite direction for getting the mode propagation path. Based on correlation, the lines were arranged in descending order and a certain pattern was observed which was plotted in figure 17. It is observed from figure 17 that the oscillations propagated from Solapur-Parli-Bhadrawati-Raipur-Rourkela-Durgapur-Binaguri-Bongaigaon-Balipara. The Northern grid nodes did not participate much in the oscillations observed in the current. This would mean that any oscillations in Solapur-Raichur power flow are likely to propagate through this path. This may be because of the high availability of the generators in the eastern part of WR region and ER region.

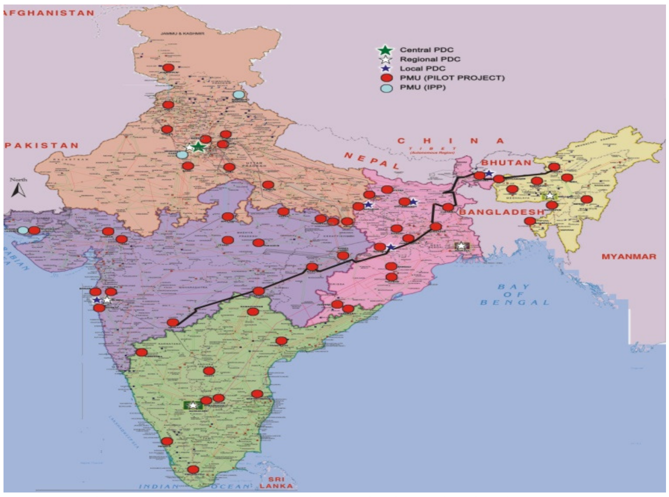

Fig. 17. Mode propagation path along the dominant route

VII. Observation and Suggestion

Based on the analysis carried out in section IV,V and VI it is observed that 0.2 Hz mode inter-area oscillation are present in the system. It was earlier experienced that this mode arises during the transient changes in the system. But the oscillation observed on 28th January 2014 gave the indication that such oscillation can be observed in system during normal condition. The oscillation became more dangerous with the mode coupling resulting in instablization of one the modes. The system cam back to stable state on operation of the system protection scheme operation which changed the system state. Such phenonmon in power system are very rare and may lead to large system disturbance in case failure of system protection scheme. There is a need to take immediate preventive action for safe and relaible system operation.

The suggested measures for damping the oscillations that may be taken up for further studies are as under:

- Oscillation in frequency is more observable in North-eastern grid and eastern grid. So it is desirable to have feedback signal for PSS from frequency/speed for controllability of this mode in the generators located in these areas.

- In Western regional grid the generator nearby Solapur, Bina, Vindhyachal, Korba, APL, CGPL, Mundra, may be tuned with speed signal as feedback if necessary as oscillation in frequnecy is also dominant..
- Fine tuning of generator AVR/Exciter is suggested for generators nearby Solapur, Bhadrawati, Kalwa, Agartala, Korba, CGPL and Badarpur. As at these location oscillation I voltage is quite significant.
- The observability in Power flow is maximum in 765 kV Solapur-Raichur and generators located nearby i.e. Solpaur, Raichur, Parli, Kolhapur nearby generators may require power related feedback signal in PSS.
- NEW grid and SR grid is connected by an AC line of 765 kV Solapur-Raichur and an HVDC link at Bhadrawati in parallel which is a typical case studied in literature for power oscillation damping in ac line using Power oscillation damping (POD) mode in HVDC. This can be achieved by the WAMS based input to HVDC control.

This is not being the first case of modal resonance as earlier also it has been observed in Indian grid as given in [9]. It is observed that the availability of literature in this area is limited and need more attention from the academician and industry [20]-[21]. The analysis of modal resonance need proper offline simulation with a model which correctly represent the actual system. The oscillation resulting from modal resonance may result in a severe disturbance.

VIII. Conclusion

This paper has put forward a case of modal resonance of inter area modes and its measurement based analysis. This shows how modal analysis and mode propagation method have helped in giving a good insight into the grid dynamic during small signal instabilities. This paper necessitates the need of further research in area of modal resonance and strong tools in real time using WAMS for sensing these phenomena to alert operator for corrective action.

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