Modal Resonance in Power System-A Case study

P.Pentayya
Ex General Manager
WRLDC
Mumbai, India
ppentayya@gmail.com

Rajkumar A
Engineer
WRLDC
Mumbai, India
anumasula@gmail.com

Chandan Kumar
Engineer
WRLDC
Mumbai, India
chandan.wrldc@yahoo.com

Rahul Chakrabarty
Engineer
NERLDC
Shillong, India
rahuletxv@yahoo.com

Sunil patil
Engineer
WRLDC
Mumbai, India
skpatil.posoco@gmail.com

Srinivas Chitturi
Engineer
WRLDC
Mumbai, India
srinivas.chitturi@hotmail.com

Abstract—**Modal resonance occurring in the power system is a rare phenomenon, which has come into existence due to increasing complexity of the system. The power system is nonlinear in nature. Eigenvalue analysis is done for understanding the behavior of the system. Modal resonance is observed in power system when two eigenvalues of frequencies move very near to each other and collide. This results in either weak or strong resonance. In resonance condition, one of the modes exhibit a negative damping while the other exhibit positive damping. The negatively damped mode may result in system instability. This paper presents a practical case of modal resonance observed in Indian Power system. This phenomenon was analyzed with the help of synchronized measurements from the PMUs installed in the grid. The synchrophasor data was analyzed using Matrix Pencil Method for finding the eigenvalues corresponding to low frequency oscillation, and their damping during the observed frame.**

Index Terms—**Low Frequency Oscillations, Matrix Pencil Method, Modal resonance, Phasor Measurement Units. Strong resonance, Weak resonance,**

I. INTRODUCTION

North Eastern Regional Load Despatch Centre (NERLDC) is the apex body to ensure integrated operation of the North-East regional grid of India as mandated by the Electricity Act 2003. NERLDC supervises the activities of seven states and eight Inter–state generating stations (ISGS) of North-Eastern grid. The real time operator at the Regional load Despatch Centre (RLDC) has to respond to the contingencies in real time in quickest possible way to minimize the adverse effects on the grid.

Earlier the information available to the load dispatcher (grid operator) in real time was restricted to data obtained from SCADA/EMS systems, which have an update rate of more than 10 seconds. This has limited the visualization of intrinsic properties of the power system. Operators were only able to detect the steady state problems in real time. Introduction of Phasor measurement Units (PMUs) has given the operator a platform to observe the grid dynamics in real time.

LFOs are categorized under small signal stability, which occur due to insufficient damping torque.. If there are N generators in a system, then total number of such LFO modes would be N-1. Most of these oscillatory modes are well damped in normal conditions. However, some of the modes get excited due to any small disturbance or spontaneously with load/generation change in the system resulting in negative /close to zero damping and is observed in power system parameters like rotor velocity, rotor angle, voltage, currents, power flow, frequency etc.

LFOs in power system can be analyzed either with eigenvalue analysis with real time measurement of some parameters using signal processing techniques or through offline simulation with complete modelling of power system elements. These eigenvalues are associated with various states in power system and with the small change in any system parameter, these eigenvalues change. They sometimes come very close to each other and lead to resonance, which in turn results in instability.

This paper describes the modal resonance concept and a case study where actual modal resonance was observed in NER Grid. Section II of the paper describes the concept of Low frequency oscillation and Modal resonance. Section III gives an overview of the Case study while Section IV discusses the analysis and results. In section V the resonance and effect in view of the case study is discussed. The remedial actions and suggestions to improve the power system stability have been given in Section VI. Section VII concludes the paper.

II. LOW FREQUENCY OSCILLATIONS AND MODAL RESONANCE

Small signal instability in power system is observed due to insufficient damping torque, which results in growing low frequency electromechanical oscillations in the system [1]. During Low Frequency oscillations, kinetic energy is exchanged between synchronous generators of the inter-connected system through tie lines. Most of these oscillatory modes are well damped during normal conditions. However, they get excited due to any small disturbance in the system.

Eigenvalues play an important role in power system stability analysis and can be used to determine the small signal stability of the power systems [2]. Each state has some participation factor in all the oscillatory modes in power system. With the change in parameter, the eigenvalue will change resulting in change in the oscillatory mode and its damping. The change in the oscillatory mode characteristic is reflected in its mode shape [3].

During normal conditions, these low frequency oscillatory modes are well damped. When these damped modes move closer to each other with gradual changes in important system parameters like generator redispatch or bulk power transactions, it may lead to interaction or coupling between two oscillatory modes [4]. The mode coupling arises from the similarity between eigenvectors. The modes that are far from each other initially move close to each other and collide in such a way that one of the modes may subsequently become unstable. If the system matrix is not diagonalizable at the point of collision of eigenvalues, the phenomenon is known as strong resonance and weak resonance if it is diagonalizable [4]. At a strong resonance, the dynamic model of the system has two conjugate complex pairs of eigenvalues that coincide in both frequency and damping. The weak interaction is characterized by coincidence of eigenvalues only [5-6].

In practice, the power system will not experience such strong resonance. In real power system modes will pass close to such a resonance and the qualitative effects will be similar i.e. the eigenvalues will move quickly at right angle from their original direction as they interact and this can lead to oscillatory instability[4]. Figure 1 shows the ideal strong resonance while figure 2 describes a practical strong resonance.

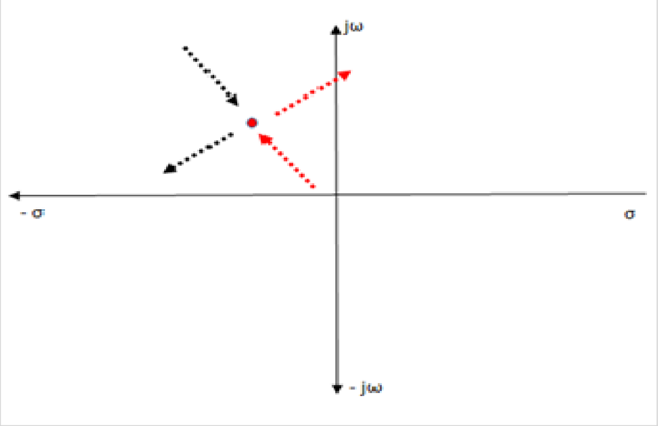

Figure 1. Modal interaction during ideal strong resonance

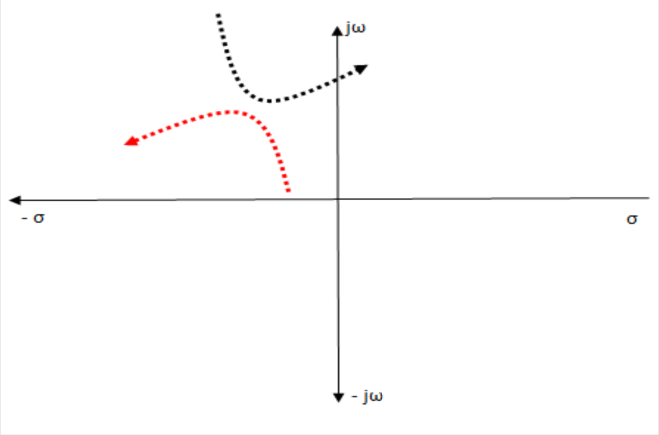

Figure 2. Modal interaction during in practically observed strong resonance in real power system.

From Fig. 1 and Fig. 2 it can be observed that the strong resonance in power system will result in instability in power system with one of the modes moving to right half plane. Such cases in power system need specialized research and analysis. One of such strong resonance phenomenon was observed in the Indian power system in the North Eastern grid. The next section introduces the case study of the North Eastern grid in India during which the oscillations were observed in resonance resulting in instability.

III. CASE STUDY

Indian electrical grid comprises of five regional grids which are connected via AC/DC tie lines. Out of these, North Eastern grid is connected via Eastern grid to the rest of Indian Grid. North Eastern grid is the smallest regional grid having a large number of small hydro and gas generators. The Phasor measurement units have been installed at strategic locations to observe dynamic changes in power system. Figure 3 shows the location of PMUs installed in the NER grid.

On 11th August 2013, NER Grid which is synchronously connected to the rest of NEW Grid, was exporting around 74 MW through tie-lines to Eastern Region. Most of the hydro plants were online as this was the Peak Hydro season. NER Grid is having typically skewed hydro-thermal (gas) generation mix of around 1:1.

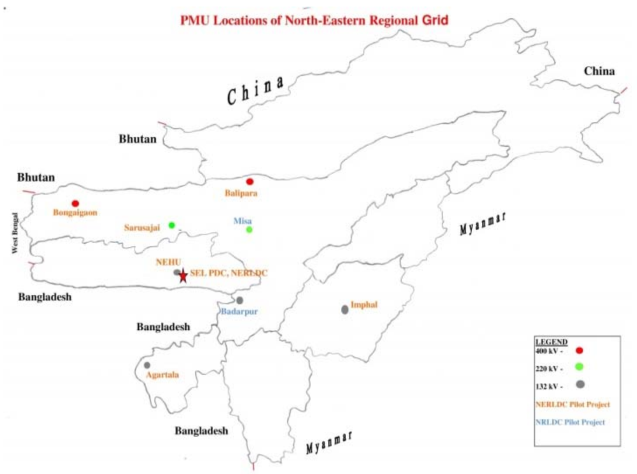

Figure 3. Location of PMUs and PDC in North-Eastern Regional Grid of India

At 23:35:07 Hrs, one 63 MVAR Bus-Reactor at 400 kV Silchar substation was taken into service to improve the local voltage profile following which low frequency oscillations were observed from PMU data of few nodes in NER upto 23:37:47 Hrs, a duration of 2 mins 40 secs.

Following this incident of reactor switching, heavy oscillations (hunting) were observed in active and reactive power and current of outgoing feeders from Doyang Hydro power plant. Similar oscillations were also observed at Loktak Hydro power plant of NHPC, in active and reactive power and also in current of outgoing feeders from Loktak.

With the oscillation observed in the system, one of the constituent decreased its load while one of the generating station immediately reduced its generation. At the same time Doyang hydro power plant, Unit-2 of Doyang HEP (Generation = 23 MW) tripped along with 132 kV Doyang – Dimapur II line following which the oscillations subsided. Snapshot of NER grid showing location of Doyang power plant, Silchar and the generating plants output in which severe oscillations were observed are shown in Figure 4.

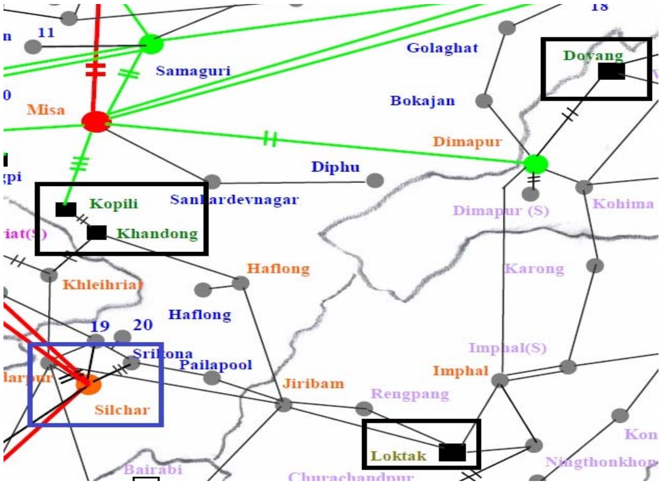

Figure 4. Snapshot of NER Grid (Blue rectangle indicates the place where the 63 MVAr Bus reactor was switched on which excited the LFOs. Black rectangles show generators that participated in LFOs.)

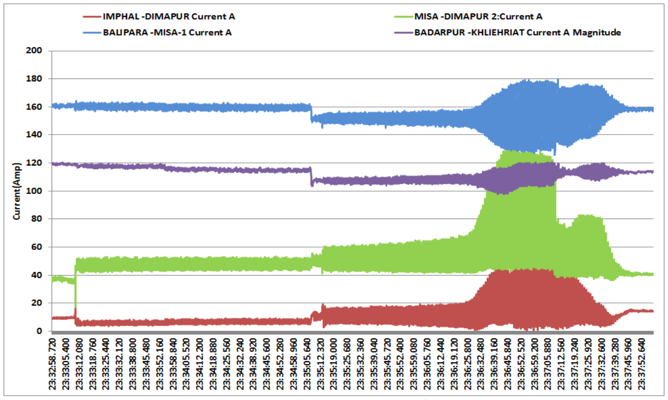

Figure 5. R-phase currents of Major lines of NER Grid from PMUs

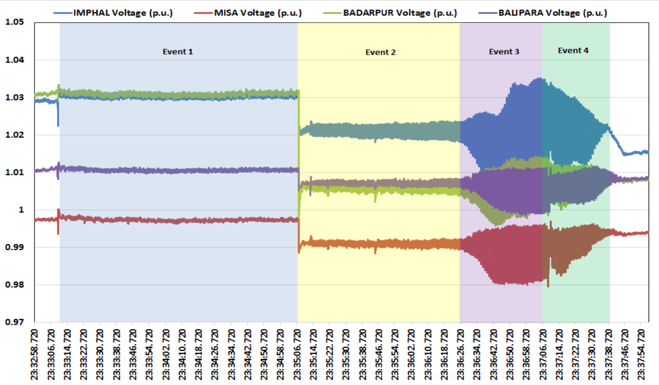

Figure 6. Positive seuqnece volatge of Major Nodes in NER and the event categorisation for analysis

Figure 5 and 6 depicts plots of synchrophasor data which indicate that three events had occurred which are as follows:

1. 23:33:10:740 : Small perturbation in system
2. 23:35:07.920: 63 MVAr Bus Reactor at Silchar was switched on.
3. 23:37:09.440: Doyang Unit 2 tripped along with 132 kV Doyang-Dimapur II.

These oscillations were found to be concentrated in NER region only. PMUs in other region did not show any oscillations during the period. Neither is there any report of hunting in any generators in the rest of the grid. This suggests the oscillation is of local mode category. The next section describes the analysis carried out for identifying low frequency oscillation and modal resonance during the event.

IV. LOW FREQUENCY OSCILLATIIONS ANALYSIS

The voltage data was used for the analysis of low frequency oscillation and modal resonance in the system. The data was subdivided into four parts for analysis as shown in figure 6 which are as follows:

1. Event 1: Prior to 63 MVAr Reactor switching
2. Event 2 : After Rector switching till the oscillation started growing
3. Event 3: Growing oscillation resulted in tripping of generator and a 132kV line.
4. Event 4: Generation tripping till damping of oscillation

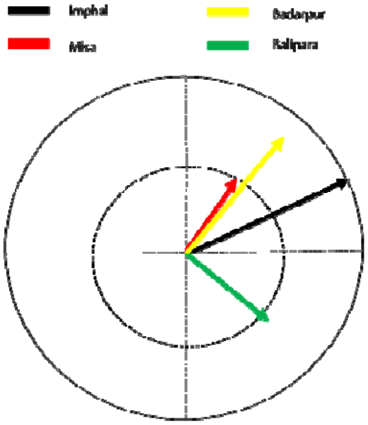

Figure 7. Mode shape of 1.0058 Hz observed during event1

With the analysis of Event 1 using the moving window matrix pencil (MP) [2], it was found that interplant mode with frequency 1.0058 Hz with low residual and 0.18 % damping was excited in the system. The mode shape of this mode is shown in Figure 7 indicating three set of coherent generators out of which Imphal and Badarpur are having high participation factor.

After the switching of 63 MVAr reactor at Silchar i.e. event 2, oscillation amplitude had increased as observed from figure 5 and 6.With change is system condition the mode of 1.0058 Hz got modified to 1.0074 Hz with high residual and negative damping of -0.09 %. The mode shape is as shown in figure 8. Now the oscillation between generator located in Balipara and Imphal has increased and are swinging in phase opposition. Apart from this 2.0156 Hz mode which a second harmonic of the inter plant mode observed was also detected having low energy and negative damping.

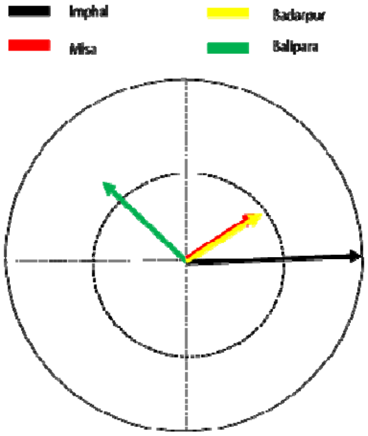

Figure 8. Mode shape of 1.0074 Hz observed during event 2

After event 2, modal resonance had occurred which was also verified from the results of the MP analysis carried out for the event 3. Here it was found that 0.99 and 0.97 Hz modes interacted and resulted in high positive damping of 0.99 Hz and high negative damping for 0.97 Hz. Both of these modes were having high residues. The poorly damped mode of 0.97 Hz resulted in oscillatory instability, which can be observed, from the exponential increase in oscillation amplitude thus driving the system to instability. This has eventually resulted in tripping of few generators and transmission lines in the region. This mode was previously present in the system with good damping.

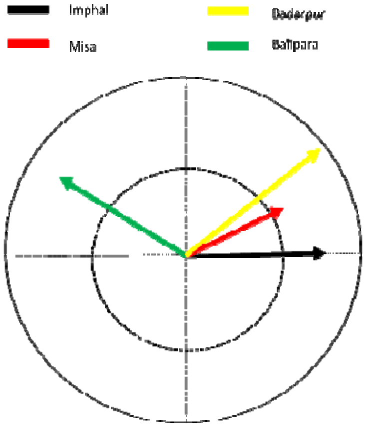

Figure 9. Mode shape of 0.99 Hz observed during event 3

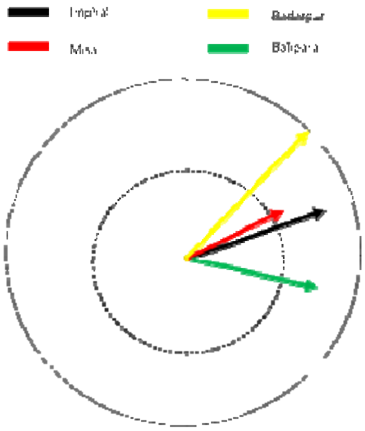

Figure 10. Mode shape of 0.97 Hz observed during event 3

Along with these two inter-plant modes their second harmonics(1.94 and 1.97 Hz) were also observed in the system out of which one was having positive and other negative damping. The participation factors were maximum at Balipara.

After the loss of generation in the grid and tripping of lines, the network configuration changed resulting in the damping of the modes. Even though there does exists mode of 0.9964 with negative damping during event 4 the relative energy is very small and may not influence the system behavior larger. The damping of other modes and their harmonics improved and finally all the oscillations were damped.

Table 1 shows the various modes observed during the four events. It can be observed clearly how the mode shape of 1.0058 Hz changed during the four events. During event 3, the resonance was observed in system, which was subsided in the event 4. From the table it can be observed that initially the energy of 1.0058 Hz mode was less during event 1. With the switching of reactor, the energy of this mode increased and damping degraded. During event 2 and event 3 another mode of similar frequency came close to this mode and resulted in moving away of one of the mode to the right half plane. It can be observed from the table I that 0.99 Hz and 0.97 Hz modes were present in the system. Out of these two, one is having positive while other is having negative damping and their relative energy has increased considerably. With the tripping of lines and generators in the area, the damping of the modes improved and their mode energy got reduced drastically..

TABLE I. MODES OBSERVED DURING THE FOUR EVENTS FROM MATRIX PENCIL ANALYSIS

Event No	Mode Frequency (Hz)	Mode Damping (%)	Relative Energy
1	1.0058	0.0171	0.1033
2	1.0074	-0.1038	0.2455
	2.0156	-0.0929	0.0214
3	0.9958	1.4589	0.6203
	0.9729	-0.1670	0.2851
	1.9470	-0.1909	0.0685
	1.9774	0.4950	0.2826
4	0.9627	0.9109	0.6157
	0.9964	-0.1357	0.0373
	1.9637	0.1785	0.1578
	1.9164	0.9092	1.0167

Further it can be observed that not only the resonance has occurred between the inter-plant modes, it also appeared in the intra-plant modes.

To verify the Matrix pencil results, FFT analysis was performed on the Imphal positive sequence voltage signal.

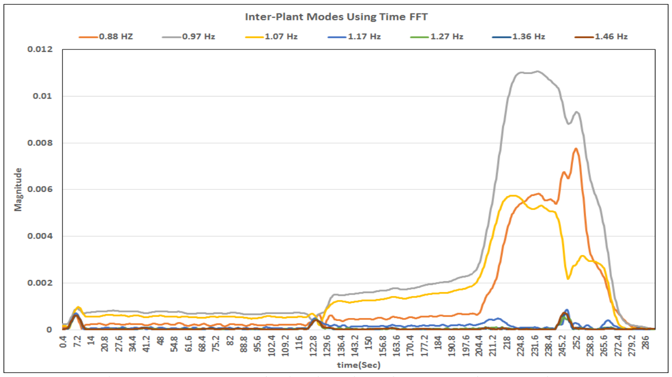

Figure 11. FFT analysis showing the Inter-plant modes

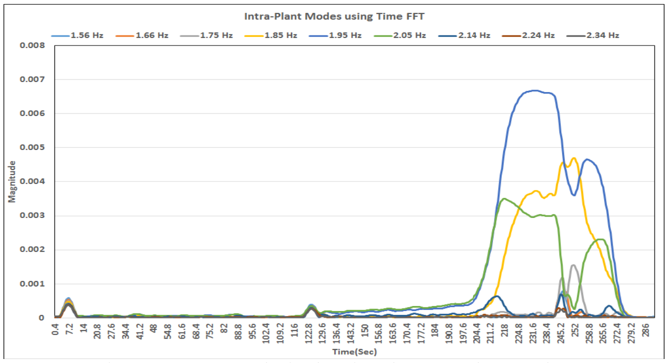

Figure 12. FFT analysis showing the Intra-plant modes

From the figure 11, it can be observed that how the 0.9 Hz and 1.0 Hz signals amplitude are varying and increasing exponentially at the starting of event 3. Similarly the 1.9 Hz and 2.0 Hz signals are there in the system as observed in figure 12 which verifies the presence of the two modes.

V. RESONANCE AND ITS EFFECT

Prior to oscillation, the system was in stable condition. The 63 MVAr reactor was switched on to improve the system voltage profile and to reduce the losses in the system. This small change in the system has resulted in resonance of two modes resulting in oscillatory instability. This can be explained in terms of Eigenvalues Resonance that when the two Eigenvalues approached very close to each other it results in rapid movement of the two modes in orthogonal direction after the resonance. This has led to movement of one of the Eigenvalue towards right half plane which in terms of bifurcation theory can be said as system modes have crossed through the Hopf bifurcation point [7]. With Eigenvalue in right half plane, the corresponding oscillatory mode has negative damping resulting in growing oscillation in various parameters. This resulted in tripping of generators and lines and thus subsiding the oscillation.

In terms of Eigenvalue and oscillatory modes sensitivity, the critical modes in power system have sensitivity towards various parametric change in power system like load change, generation change, control actions by AVR etc [8] . At a certain state of power system, such modes are very highly sensitive towards the parametric change and can drive the modes towards the Hopf bifurcation point and result in oscillatory instability. In this case study it is observed that two modes which were initially local to their areas (one was highly damped and was not observed in the modal analysis while other having lesser damping) have moved closer with the switching of reactor (a small disturbance in the system). The modes were initially decoupled so that a disturbance in one area has not affected the mode in other area [9-10]. With the parametric change (reactor switching) these two modes interacted by passing near a strong resonance. As the strong resonance approached, the mode eigenvectors experienced resonance and the eigenvalues moved in the complex plane quickly by right angle.

VI. REMEDIAL ACTION

The North Eastern grid in India is having a large numbers of small hydro and gas thermal power plants. From the Generator and Control Centre's SCADA data, it was observed that for various units within a plant there was exchange of real and reactive power. Also the large fluctuations were recorded in real and reactive power between different generating plants in the system. The oscillations were not observed outside the North Eastern grid due to inter-plant and intra plant modes of oscillation. This suggests that, there is a need of tuning of the PSS and AVR of these stations in a coordinated manner to improve the damping of various interplant and intra plant modes in the system. In addition, SVC may be added in the system, which will improve the voltage profile as well as dynamic performance in the system and will add to increased damping in the system.

VII. CONCLUSION

In this paper, a practical case of modal resonance of interplant and intra plant modes was discussed. In addition, the case study emphasized the severe impact of modal resonance on any power system and the instability arising out of it. The dynamic reactive power support has also come out as a possible solution to reduce incidences of such a catastrophic effect as just a small switching incident gave rise to growing oscillations.

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