Low Frequency Local mode oscillations in NER Grid, Validation using model based analysis, & Mitigation

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***Abstract*—Bulk power systems are collection of large number of generators intricately connected by a network of transmission and distribution over large geographical distances. Oscillatory instability in large power systems can cause wide spread blackouts, and are matters of concern to system operators. Rotor angle stability is an electro-mechanical stability phenomenon, which arises as rotors of generating units change their angles in response to changing demand in the power system to maintain frequency stability[1]. In cases of weakly interconnected generators, system damping may be low enough such that oscillations tend to grow. As the oscillations spread, their operating conditions deteriorate and may lead to instability [2]. A practical case of Inter-Plant oscillations observed in North-Eastern Regional Grid of India is presented. This phenomenon was observed using measurements from Phasor Measurement Units (PMUs). Further analysis in MATLAB and NEVA was done to corroborate the observations. PSS of the participating generators were tuned for damping these oscillations.**

***Index Terms*—Weak interconnection, Low Frequency Oscillations, Modal analysis, Phasor Measurement Units (PMUs) , NEVA, Model based analysis, Indian Power System**

I. Introduction

Indian power system is one of the largest bulk power systems in the world and has the fastest growth rate. North-Eastern region is the smallest of the 5 operational regions of Indian Power system with about 2 percent share of the Peak Demand Met of India. North Eastern Regional Load Despatch Centre (NERLDC) is the apex body to ensure integrated operation of the North-Eastern regional grid of India as mandated by the Electricity Act, 2003. NERLDC supervises the activities of Seven state control areas and Ten Inter–state generating stations (ISGS).

India, a country having low per capita electricity consumption and the world's youngest population, is witnessing high levels of growth ever since restructuring of power system & introduction of Open Access in Electricity transactions since 2003. The restructured power markets operate closer to their operating limits at dynamically changing operating points [3].

North-Eastern Grid is weakly interconnected to rest of the Indian grid through AC links from one node of NER (Bongaigaon- Salakati) and 1 high capacity Multi-terminal HVDC link from BiswanathChariali in North-Eastern to Agra in Northern Region. Most of the strong interconnections through high capacity corridors exist in Northern part of NER Grid.

The Southern part of the Grid comprises of state control areas of Manipur, Mizoram, Tripura, South Assam, part of Bangladesh load & the ISGS stations Palatana CCGT, AGTPP-CC, Loktak HEP. This part of Grid is weakly connected with the Northern part of NER Grid, and has about 36 % of installed generation capacity of the Grid. The important tie lines from Southern part to Northern part of NER Grid are 400 kV Double Circuit lines – 400 kV Silchar – Byrnihat – Bongaigaon and 400 kV Silchar – Azara – Bongaigaon.Being a mountainous terrain with densely forested areas, tripping of the 400 kV tie-lines between Southern and Northern part of NER Grid are common on transient faults. This further increases the vulnerability of Southern part of NER Grid to oscillatory instability.

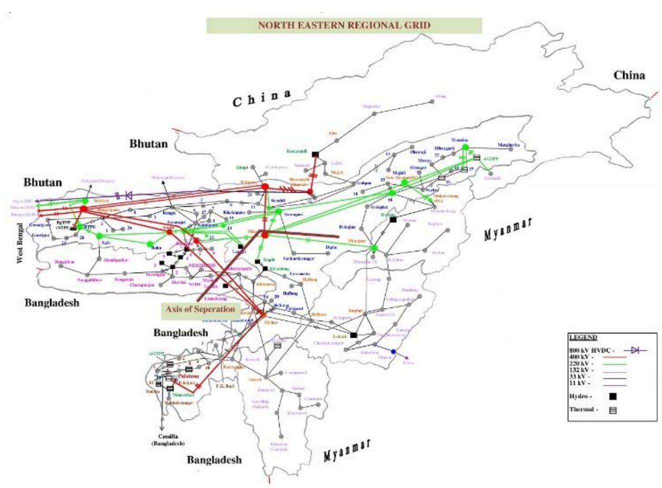

Figure 1: NER Grid & Axis of Seperation

As part of adoption of synchrophasor technology in Control Center operations, 8 number Phasor Measurement Units had been installed in NER Grid at strategic buses as part of Pilot Project, in 2013.

Ever since installation of PMUs, operational visibility to real-time power system operators have improved. Several cases of Low Frequency Oscillations (LFOs) have been observed in North-Eastern Region since.

II. Low Frequency oscillations

The Bulk power systems are complex non-linear dynamic systems [2] operating in a state of equilibrium. Power transfers over large geographical distances lead to the power systems operating close to their stability limits with wide angular differences. Any oscillatory instability in a stressed power system may cause outages and further reduce the strength of the system. Basic oscillatory instability of interest to the power system operator are – rotor angle stability and voltage stability, while the frequency stability is usually maintained. Rotor angle stability is concerned with electromechanical oscillations arising out of generator's response to changing load-generation balance, and lack of sufficient synchronization torque. Electromechanical oscillations appear in the power system on account of dynamically changing operating point, and inherent difference in response times between electrical power output of generator and mechanical power input from the turbine. [4]

Weakly damped electromechanical modes of oscillation normally exist in the power system. Power system controls can get excited on account of changes in the grid like faults or sudden changes in load or generation, and behave in a fashion as to produce negative damping effect. This, in turn, causes increase of growth of particular oscillatory mode(s). Oscillations can be observed in power system parameters like rotor velocity, rotor angle, voltage, currents, power flow, frequency etc.

Growth of oscillations may occur due to one of the following reasons – Spontaneous: Gradual change in power system's equilibrium cause one of the modes to become poorly or negatively damped ; Due to an event: A fault in the power system, or tripping of major loads or generation may cause poor or negative damping of some modes ; Forced oscillations: due to incomplete islanding or throbbing loads. [3]

III. CLASSIFICATION OF LFOs

Low Frequency Oscillations in power systems of frequency range 0.05 Hz to 2.0 Hz are considered for purpose of monitoring.

Based on literature survey as per [7] to [13], LFOs have been broadly classified as follows on basis of root cause of oscillation:

1. Inter-area modes: 0.05 Hz to 0.3 Hz.
   - These oscillations typically involve generators in one control area of the power system swinging against generators of another control area across long tie lines. Coherent groups of generators across the tie-lines exchange energy over large interconnections.
   - LFOs in Inter-area mode have been observed in All India grid ever since installation of PMUs. The mode of oscillation has also reduced after synchronization of all the regional grids of India.
2. Intra-area mode: 0.4 Hz to 1.0 Hz
   - These oscillations typically involve one part of a synchronously connected power system oscillating against another. An axis of separation typically develops along highly loaded transmission lines, leading to grouping of generators.
   - In Indian power system, several cases of separation have been observed within the Regional Grids across tie lines, where a part of generation rich portion oscillated against generators in load centers.
3. Inter-plant mode: 1.0 Hz to 2.0 Hz
   - These oscillations typically involve units of one generating station oscillating against another group of generating station or units.
   - This type of oscillation has been observed in several cases in North-Eastern Regional Grid of India, due to cases of bus reactor switching, transient faults, among others.
4. Intra-plant mode: 1.5 to 3.0 Hz
   - These oscillations typically involve units within a generating plant oscillating against each other.
   - Trigger of these oscillations, as observed from cases in Indian Power system, indicate one unit oscillating against the other(s) while their AVRs race against each other to control the generator terminal voltage. Hitting of excitation limiter constraints are also suspected. [5] [6]

IV. Analysis Methods Of LFOs Used At NERLDC

LFOs (Low Frequency Oscillations) in power system are a Small signal stability problem, and can be analyzed using mainly 2 techniques in Frequency domain – Measurement based analysis: eigenvalue analysis of real-time data using signal processing techniques, or, Model based analysis: offline simulation of a power system model. Eigenvalues characterize states in a power system and they change with changes of system parameters.

At NERLDC, in the PMU visualization provided by vendor, a provision exists for monitoring the real-time modes colored as per their quality of damping. The modes are computed in a 15 second long window using Prony's method. The observation from this Modal Analysis window together with actual power system signals like voltage, frequency, active & reactive power flow, enable the operator to observe whether the modes are decaying or not. Any growing oscillations are monitored by the grid operator for suitable actions.

In major cases of oscillations in the Grid, to arrive at the root cause of oscillations, offline simulation is also used. This serves the purpose of identification of oscillatory modes as well as validation of the offline power system model. At NERLDC, Siemens PTI PSS/E package along with NEVA is used for Eigen-value analysis of power system states to observe the mode characteristics.

The real-time data as capture by PMUs are also further analysed in MATLAB's using spectral density analysis to find the relative strength of modes and capture the modes with reduced damping.

At NERLDC, the real-time switching grid operator continuously monitors the network conditions of angle spread, voltage profile, and frequency using PMU visualization. In addition to the front line switching operators, a Real-Time Security Desk (RTSD) is operational at NERLDC post the blackout of July 2012. The RTSD operator checks for possible cases of instability in the system including Low Frequency Oscillations.

V. Case Study

On 14th July'2016 during 13:16:28.440 Hrs to 13:20:05.840 Hrs, Low Frequency oscillations were observed by the RTSD operator. The oscillation was observed in both Positive Sequence Voltage and Frequency, and lasted for a total duration of nearly 4 minutes.

The relative magnitude of oscillations was compared for all 8 buses of NER Grid where PMUs are installed, and across various monitored parameters.

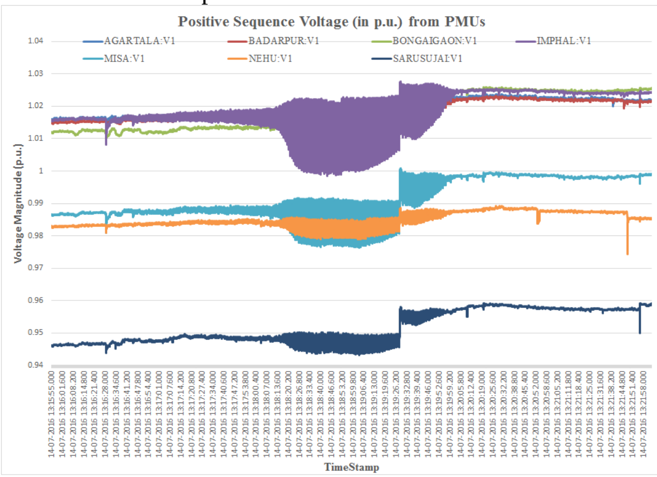

Figure 2: Oscillation in Positive Sequence Voltage on 14th July 2016 in NER

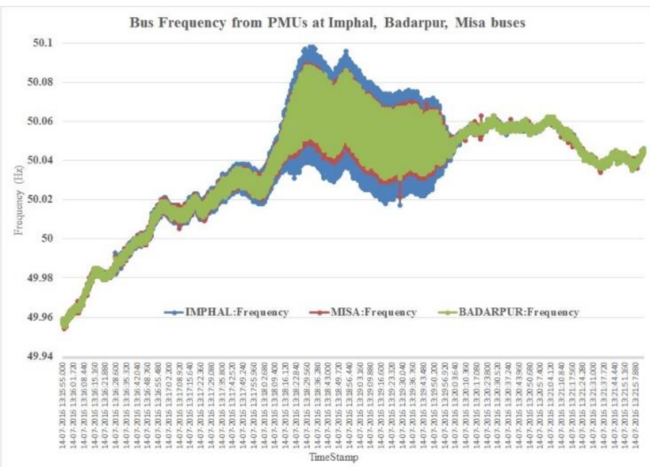

Figure 3: Oscillation in Bus Frequency on 14th July 2016 in NER

As can be seen from plots above, maximum oscillation was observed in 132 kV Imphal bus, followed by that in 220 kV Misa and 132 kV Badarpur buses. All these buses are located in the Southern part of NER grid and are in close proximity of several small hydro generators.

The Imphal bus is nearby to Loktak HEP (3x35 MW) and Doyang HEP (3x25 MW), Misa bus nearby to Kopili HEP (4x50 MW), Khandong HEP (2x25 MW), Kopili Stg-II HEP (1x25 MW) & Doyang HEP, and Badarpur bus nearby to Kopili HEP, Khandong HEP & Myndtu Leshka HEP (3x42 MW). Oscillation was not observed in PMUs located at other regions of Indian Grid, indicating a localized phenomenon.

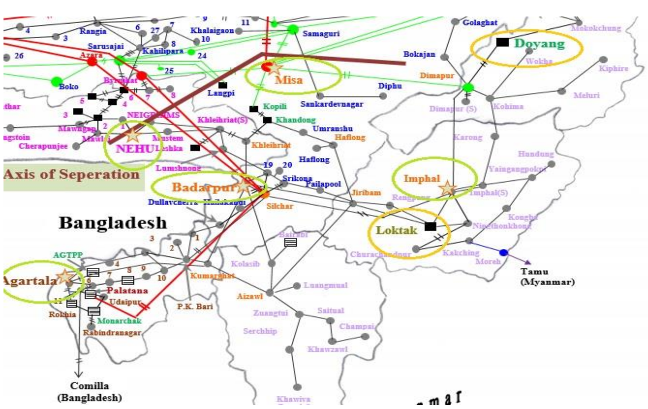

Figure 4: PMU locations and participating generators

The mode of oscillations was checked using the OMS (Oscillation Monitoring System) engine at NELRDC. Oscillatory modes with negative damping was found near 0.98 Hz and 1.96 Hz (2nd Harmonic of the 1st mode). This mode in negative damping or poor damping (<5 percent damping) was observed during the entire duration of oscillation.

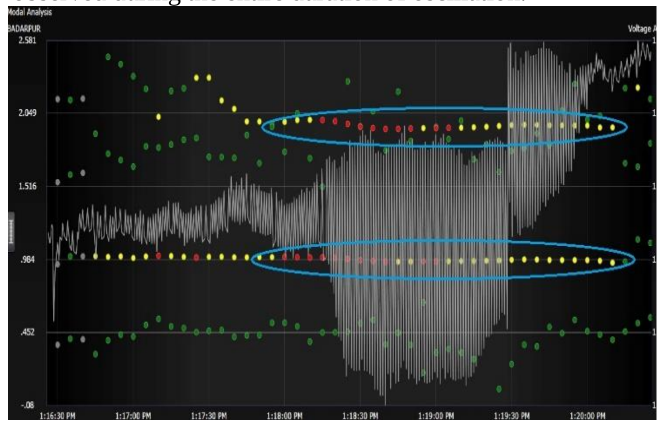

Figure 5: LFO Modes from OMS engine at NERLDC

For verification of the oscillation modes, Power Spectral Density (PSD) estimate of the Voltage Magnitude signal at 132 kV Imphal was done using MATLAB. The PSD estimate shows peaks at 0.976 Hz and 1.965 Hz, which corroborates the estimate of Prony analysis.

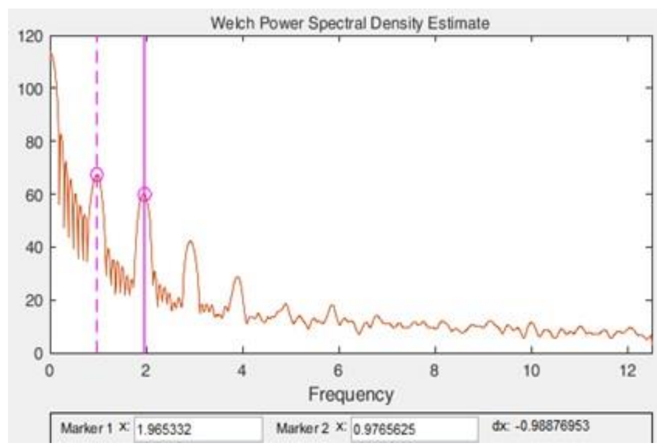

Figure 6: LFO Modes from OMS engine at NERLDC

VI. IDENTIFICATION OF CAUSE OF LFO

Comparison of relative amplitude of oscillations in all eight(8) PMUs of North-Eastern Regional Grid in the above instances of LFOs, 132 kV Imphal(PG) and 220 kV Misa(PG) was found to be the most prominent. No instance of element switching was observed in the Sequence of Events log in NERLDC SCADA systems.

The units at Loktak HEP and Doyang HEP were suspected to have participated in oscillations based on their close proximity to 132 kV Imphal(PG) and 220 kV Misa(PG), respectively.

Loktak HEP also reported oscillation in their outgoing 132 kV feeders during 14th July 2016 in the period of oscillation, but no hunting of machines was intimated.

On enquiry by NERLDC to Doyang HEP, it was found that their units had undergone hunting during this period of LFOs in the Grid. The operator at Doyang HEP had manually reduced generation upon seeing hunting of the units to prevent unwanted tripping.

Also, Nagaland State Load Dispatch Center (SLDC) reported tripping of 132/66 kV, 100 MVA transformer at

Dimapur(DoP, Nagaland) bus and load loss in Dimapur area of Nagaland. This indicated maximum magnitude of oscillation near Dimapur and pointed to Doyang HEP as the candidate for investigation.

Further investigation regarding the possible causes of triggering of LFOs in the Grid on multiple occasions led to the following observations:

- 220 kV Mokokchung – Mariani D/C line was out of service since 12th July 2016, viz. before the start of oscillations, which have reduced the inertia of the power system around Doyang HEP
- Doyang HEP was scheduled to generate to its maximum value of 72.6 MW in these periods of oscillations

Further studies was felt necessary to identify the exact cause of oscillation to mitigate, and also to prevent similar cases of oscillations in future.

VII. MODEL BASED ANALYSIS IN PSS/E+NEVA

Model based analysis in PSS/E + NEVA was conducted at NERLDC. The studies were conducted on 3 different scenarios:

- **Case A:** With Grid network as on 14th July'16 during period of LFO, with Load-generation balance as actual on 14th July with Doyang generation = 72 MW
- **Case B:** With Grid network as on 14th July'16 during period of LFO, and with less generation at Doyang (44 MW instead of 70 MW , viz. 1 unit kept out of service)
- **Case C:** With Grid network as on 14th July'16 during period of LFO, with Load-generation balance as actual, but with 220 kV Mariani(PG) – 220 kV Mokokchung(PG) – 132 kV Mokokchung (PG) – 132 kV Mokokchung (Nagaland) – 132 kV Doyang HEP closed

From the study results in NEVA, about 70 oscillatory modes were found in each of the above cases. After filtering of the oscillatory modes to between 0.8 Hz and 2.2 Hz, several oscillatory modes around 1.1 Hz, 1.4 Hz, and 1.9 Hz were observed with negative damping.

In Case-A, oscillation was found to occur within the in-service units of Doyang HEP, viz. Intra-plant oscillation was observed. The damping observed in this mode was found to be -5.2 percent.

Figure 7: Mode Shape of Intra-plant oscillations at Doyang HEP

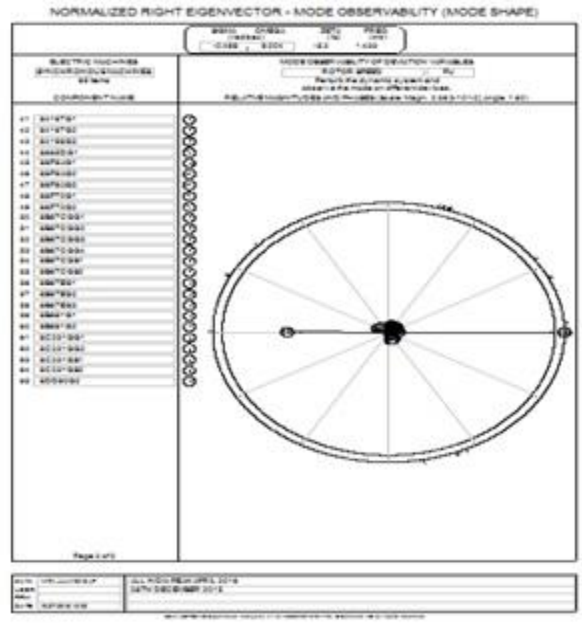

Figure 8: Mode Shape of Intra-plant oscillations at Doyang HEP

Close to 1.19 Hz, oscillation was observed amongst Leshka HEP (Close to 132 kV NEHU PMU), Doyang HEP (Close to 220 kV Misa PMU), and Loktak HEP (Close to 132 kV Imphal PMU). The damping observed in this oscillatory mode was -7.7 percent.

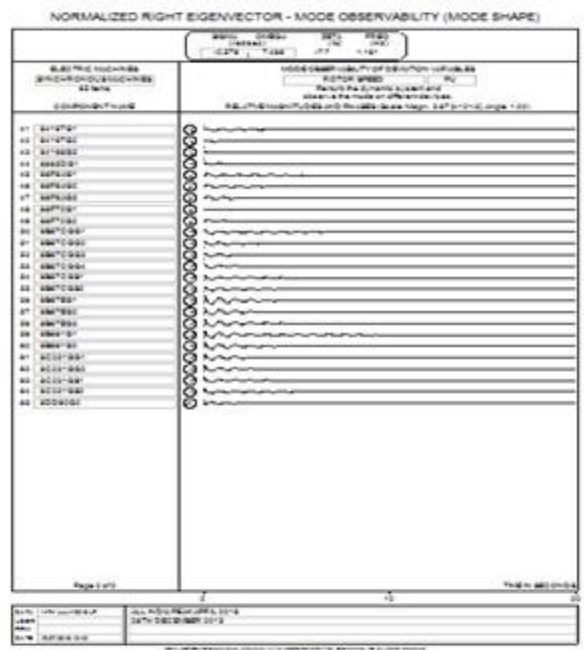

Figure 8: Inter-plant oscillations at Doyang HEP, Loktak HEP and Leshka HEP

In Case-B, upon switching on the 220 kV Mariani(PG) – 220 kV Mokokchung(PG) – 132 kV Mokokchung(PG) – 132 kV Mokokchung (Nagaland) – 132 kV Doyang HEP corridor, the oscillatory modes remained but damping had improved.

Also, in Case-C, with reduction in quantum of generation at Doyang HEP, the number of oscillatory modes were found to reduce, and no oscillation was observed in the 1.19 Hz mode. The 1.19 Hz mode is Inter-plant oscillation mode, close to the 0.96 Hz mode observed from measurement based analysis of PMU data.

This indicated that on account of maximization of generation at Doyang HEP to match with it's injection schedule, oscillations could have occurred in the Grid. The ill-tuned AVR of the small hydro generators together with low inertia of the Southern Part of NER Grid led to growth of these oscillations.

VIII. CORRECTIVE ACTION AND MITIGATION

The hunting of generators is an expected phenomenon arising out of parallel operation of generators, and interaction between the Power-Angle curve and rotary inertia of generator. Without sufficient damping, as in case of hydro generators, the oscillations tend to grow. In cases of hydro generators, the main source of negative damping has been the turbine-governor and fast acting Automatic Voltage Regulators, with action of AVR being larger. Wherever the generator is subjected to large angle swings, the tendency of oscillation growth is higher. As in the Southern part of NER, the hydro generators Loktak, Doyang, Leshka are subject to large variation in angles. Small oscillations in generators may then add up to produce a significant effect on tie-line power flows. [18]

Considering that low frequency oscillatory instability could result in loss of synchronism of generators or mal-operation of protective systems, it was decided to restrict the scheduled injection of Doyang HEP.

Local mode oscillations have been commonly found in case of AVR of generating units acting with high output and feeding into a weak network. In such cases, damping can be improved by using supplementary controls to AVRs through Power System Stabilizers. [15]

Same was the case with Doyang HEP in case of maximized generation and outage of important corridors, where Doyang HEP was feeding its generation to the NER Grid primarily through 132 kV Doyang – Dimapur I & II lines and feeding radial load of Mokokchung area of Nagaland through 132 kV Doyang – Mokokchung line.

Investigation by Doyang HEP led to the observation that PSS (Power System Stabilizer) on the units had been kept out of service since last 2-3 years after installation of Digital AVR.

The PSS in all 3 DAVR of the units of Doyang HEP was checked, tested and tuned before putting into service on 13.08.2016. Test results of Doyang HEP with PSS in service with DAVR in Auto Channel, and at rated injection showed no oscillations.

The 220 kV Mariani(PG) – 220 kV Mokokchung(PG) – 132 kV Mokokchung(PG) – 132 kV Mokokchung (Nagaland) – 132 kV Doyang HEP corridor was also put into service to add to the stability of the interconnected system.

In case of Doyang HEP, with outage of the link as above from 220 kV Mariani(PG) to 132 kV Doyang HEP, the overall impedance to the system seen by Doyang HEP would increase, and may cause the voltage regulators to act, especially when Doyang HEP is at the limits of its capability curve.

IX. CONCLUSION

A practical case of Inter-plant and Intra-plant oscillation as observed in North-Eastern Regional Grid of India was presented in this paper. The study indicates that proper tuning of AVR, PSS and other generator controls are essential in the operation of interconnected power systems.

The study also indicates that proper modelling and model based analysis in conjunction with measurement information from WAMS help in identifying and mitigating power system oscillations. Availability of proper modelling information is necessary to perform the mode validations.

In rapidly growing power systems of developing countries like India with ambitious target of Renewable Integration, periodic testing and tuning of generator controls are essential to keep in sync with the changing grid conditions.

X. ACKNOWLEDGMENTS

The authors acknowledge the guidance and support given by management of POSOCO as well as POWERGRID and for permitting the publication of this paper. The authors are also thankful to NERLDC personnel for their support. The views expressed in this paper are of authors and not necessarily that of the organizations they represent.

REFERENCES

[1] P. Kundur, "Power System Stability and Control", (McGraw-Hill: New York, 1994).

[2] Jan Machowski, Janusz Bialek, James Richard," Power System Dynamics and Stability, 2nd Edition", Wiley, 2009

[3] I. Dobson, F.L. Alvarado, C.L. DeMarco, P. Sauer, S. Greene, H. Engdahl, J. Zhang, "Avoiding and Suppressing Oscillations", Power Systems Engineering Research Center, Publication 00-01, December 1999

[4] Michael J. Basler, Richard C. Schaefer, "Understanding Power System Stability" IEEE Trans. on Industrial Applications, Vol. 44, Issue 2, PP. 463–474, Year 2008.

[5] K. Prasertwong, N. Mithulananthan and D. Thakur, "Understanding low frequency oscillation in power systems", International Journal of Electrical Engineering Education, 47 3: 248-262

[6] S. Avdakovic, A. Nuhanovic, M. Kusljugic, E. Becirovic, & M. Music, "Identification Of Low Frequency Oscillations In Power System"

[7]. F. Alvarado, C. DeMarco, I. Dobson, P. Sauer, S. Greene, H. Engdahl, and J. Zhang, "Avoiding and suppressing oscillations," PSERC ProjectFinal Report, 1999.

[8]. EPRI Power Systems Dynamics Tutorial. EPRI, Palo Alto, CA: 2009. 1016042.

[9]. Xi-Fan Wang, Yonghua Song, Malcolm Irving,"Modern Power Systems Analysis",Springer Science & Business Media, 07-Jun-2010.

[10]. Leonard L. Grigsby, "Power System Stability and Control",CRC Press, 25-Apr-2012.

[11]. Bijaya Ketan Panigrahi, Ajith Abraham, SwagatamDas,"Computational Intelligence in Power Engineering",Springer Science & Business Media, 20-Sep-2010

[12]. Debasish Mondal, Abhijit Chakrabarti, Aparajita Sengupta,"Power System Small Signal stability Analysis and Control", Academic Press, 28-Apr-2014.

[13]. Analysis And Control Of Power System Oscillations, CIGRE, Final report by the Task force 07 of Advisory Group 01 of Study Committee 38 , December 1996.

[15] "The Electric Power Handbook", CRC Press, IEEE Press