Intra-Area Mode: Measurement-Based and Model-Based Assessment in Indian Power System

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***Abstract*—Inter area and Intra area modes of low frequency oscillation are inherent to any large electrical grid. Therefore, there is a need to identify and analyze these oscillations for finding the control action required for enhancing their damping. The Inter area oscillation has been studied in detail for small as well as large power system and their mitigation measures are well known. However, there is a need for more research for the Intra area oscillations in a large power system as these modes have different characteristic and may need a different strategy. This paper describes a process for identifying Intra Area mode using measurement-based oscillation identification and its model-based validation. Further, it also discusses the methods to find its characteristics and its mitigation measures with the help of an actual case study in Indian Power System.**

***Index Terms*-- Eigenvalue, Eigenvector, Indian Grid, Low Frequency Oscillation, Small Signal Stability.**

I. INTRODUCTION

In the last few years, Indian power system has seen a tremendous growth in the system size, load/generation, transmission/distribution and voltage levels. The five regional grids in the Indian power system are synchronously interconnected with each other and thus making it one of the largest synchronous grids in the world. With this, the challenges faced by the real-time system operator have also increased many folds with the size of the grid. Among the various challenges, Small signal stability and Low frequency oscillation (LFO) is of keen interest to the system operators.

LFOs are inherently present in the power system due to the non-linear system characteristic [1,2]. However, most of them are non-observable due to high positive damping. They become a challenge for Grid Operators if their damping becomes negative leading to small variation in power system parameters and scaling to a large-scale blackout [3]. While operating the large power system closer to its stability limits, there is a high probability that the damping of such LFO may go below the safe limit even for a small disturbance [4]. LFOs also result in wear and tear of the generating units causing fatigue and reducing their life. In view of this, it is essential to analyze the LFOs and to ensure adequate remedial action to increase their damping component.

Between the types and nature of modes, the Inter area and Intra area mode affect the large-scale power system and important from the analysis viewpoint. The analysis of such LFOs needs their validation in order to ascertain the adequacy of remedial action taken. Both these modes need detailed analysis for finding the control actions for their damping. This paper presents one such method of studying the Intra-area oscillation and the required remedial action to improve their damping. The paper has been subdivided into various sections among which section 2 describes the classification of oscillation while section 3 about how the LFO can be identified. Section 4 discusses the method of analyzing the Intra-area oscillation in detail along with one case study. In section 5, the desired remedial actions required for damping such oscillation has been discussed followed by the impact of action taken.

II. CLASSIFICATION OF LOW FREQUENCY OSCILLATION

Electromechanical oscillations (Low frequency oscillations) in the power system are classified based on their observability and participation factors in the following categories [3-5]:

1. Inter-Area Mode: 0.05-0.3 Hz
2. Intra-Area Mode: 0.4-1.0 Hz
3. Inter-Plant Mode: 1.0 -2.0 Hz
4. Intra Plant mode: 1.5-3.0 Hz
5. Control Mode: Not defined and vary depending on the nature of the control system.
6. Torsional Mode: 10-46 Hz

The inter-area and intra-area mode are global modes and the inter-plant and intra-plant are local modes. This aspect of the local and global mode is explained in figure 1. The control modes and torsional mode are specific to various controls like FACTS and HVDC and their frequency range varies.

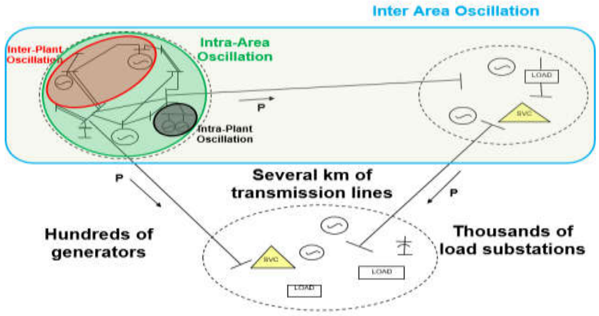

Figure 1. LFOs types and their area of observability.

Global modes are observed due to the interaction of one coherent group of generators with any other group in the electrical grid while, the local modes are due to a single plant interaction with the rest of the power system. The inter-area mode of oscillation is that mode where the whole system is subdivided into two or more coherent groups of generators. While in intra-area mode, the generators in one of the area get subdivided into two or more groups.

In a smaller power system, the distinction between the two types of global modes is not clear and they either have inter-area or local modes. However, in a large power system comprising of various control areas, the global modes are subdivided into inter-area and intra-area mode as shown in figure 1 due to their observability [3-5]. Large power grid such as the Indian Grid, having more than 1750 (200 MW and above) synchronously connected generators, the term inter-area and intra –area can be distinguished separately as per the observability. Here, the inter-area oscillations are those where one regional grid oscillates with the other while the intra-area oscillations mean two areas within a regional grid are swinging against each other [1].

The study and analysis of global modes i.e. Inter and Intra area mode are crucial and the control action required for their damping improvement need to be identified individually. The inter-area mode and the control required for their adequate damping are explicitly described in the literature [6,7]. However, the term Intra-area has not been studied in detail as seen from literature and are found clubbed with inter-area oscillation. These global modes are complex to study due to the involvement of numerous control systems. A detailed representation of the entire interconnected system is required to study them [6,7]. Further, after a detailed study, it is essential that the results must be verified and corroborated with the actual power system response so that suggested control will have the desired effect.

III. METHODS FOR OSCILLATION ANALYSIS

There are two methods to study and identify the various low frequency modes present in any power system. The first one is the model-based method and the second is measurement-based method. Model-based analysis of finding LFOs in the power system is based on the linearization of nonlinear differential equations that represent the complete power system around an operating point. After the linearization, the Eigenvectors and Eigenvalues are calculated which provide the observability and controllability of all the electromechanical modes present in the system [1]. This approach is comprehensive and based on complete modeling of the Power System. While the measurement-based identification is based on the analysis of high rate sampled data like Synchrophasor data It utilizes various techniques like prony and matrix pencil methods to identify the mode and its observability [3].

Both these methods have their own benefits and limitations. However, in the era of model validation and verification, their combined utilization is more suitable in identifying the various characteristics and controls. The next section introduces these two methods in brief based on the literature survey.

IV. MODEL-BASED AND MEASUREMENT-BASED ANALYSIS

A. Model-Based Analysis

The dynamics of the power system can be represented as coupled first order differential equations and algebraic equations together called as differential algebraic equations. The power system consists of many dynamic components such as generators, exciters, governors, power system stabilizer (PSS), FACTS devices etc. Each of these components consists of several state variables which affects their dynamics. So, the differential algebraic equations for each power system component can be represented in the form of state variables whose interaction and variation will decide its response (output variables) for any change in the input to the system (input variables). The whole system then can be represented as a state-space representation, which is a mathematical model of a physical system as a set of input, output and state variables related to first-order differential equations. The first order differential algebraic equations of the power system can be represented in a state space representation [3].

In order to start with any small signal stability analysis for the power system, its load flow and dynamic model have to be prepared. Once the mathematical model is available, different methodologies can be applied to study oscillatory behavior of the system in the low-frequency range. Researchers tend to use Eigenvalue analysis after linearization and time domain simulation with prony analysis [2,6-8]. The Eigenvalue analysis can be done by various methods and among them, the following have been used extensively [2,8]:

1. QR Method: This method provides complete solution of the system but has a limitation on the number of states depending on the computational capacity of software.
2. Sub-space Inverse Iteration Method: This method gives partial Eigenvalue solution for the system.
3. Dominant Pole Method: This method gives partial Eigenvalue solution for the system.

The Eigenvalue analysis provides the Left and Right Eigenvectors of the system at one operating point. Left Eigenvector provides details about the controllability aspect of the LFO. On the other hand, Right Eigenvector provides the observability and mode shape of the system modes, from which various characteristics of LFO can be derived.

B. *Measurement-Based Analysis*

Model-based methods are quite extensive and become difficult when being done for a large-scale system. However, they are useful in describing the controllability aspect of modes and finding the remedial measures required for damping improvement. While on the other hand, the measurement-based model is quite simple in finding the mode characteristic and its observability. Here the system dynamic measured through sensors that provide fast sampled data (like Synchrophasor data from PMU) are fit into either linear model to find the Eigenvalues or undergo Fourier transform for finding the various characteristics of LFO. Various methods of measurement-based analysis are Fast Fourier Transform, Hilbert Transform, Prony analysis, Matrix Pencil, ERA, TLS Spirit methods etc. [3]. However, they do not provide any direct information about controllability aspect of LFOs.

Both these methods of analyzing LFO have their own advantages and disadvantages. So, it is always desirable to use them simultaneously and validate and verify them with each other. In the next section, one case study on identification and characterization of Intra Area oscillation has been provided which utilises a combination of these two methods. The case study explains how both these methods complement each other in the analysis of the LFOs and helps in deciding the effective control measures to be taken for damping improvements. It involves two steps where the first step represents the model-based analysis while the second step provides the measurement based analysis followed by their comparison and tuning of the model.

V. INTRA AREA OSCILLATION IN THE INDIAN POWER SYSTEM

Indian Power system comprises five regional grids synchronized with each other. Therefore, the Indian power system is inherently having few Inter-Area modes having Inter-Regional nature and some Intra-Area modes having Intra-Regional characteristics. The details of Inter-Area modes in Indian power system have been given in the reports published by the authors [10,11]. The Intra-area modes are less studied in Indian power system. However, they have been observed on many occasions as discussed in these reports.

Among the five regional grids, Western region grid is the largest in terms of installed generation capacity. This regional grid is having major three different areas where one area is generation rich while the other two are load centric as shown in figure 2.

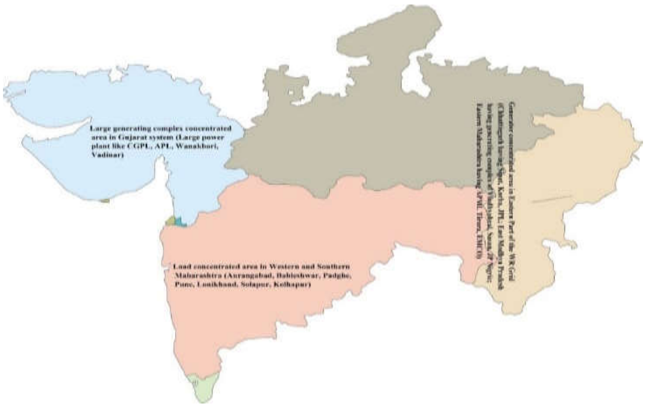

Figure 2. Three Interconnecting system in the Western Regional Grid

One of the most prominent Intra-Area modes observed in the Western Region Grid is 0.56 Hz (0.55 Hz- 0.6 Hz). This mode was identified first with the help of Synchrophasor measurement analysis. To further study it, a detailed analysis was carried out based on the combined approach of two methods as described in the previous section. The analysis of 0.56 Hz mode from Model and measurement-based methods are given below.

A. *Model-Based Analysis*

PSS/E software is being used by the system operator and planners in the Indian power system. The load flow and dynamic model of the Indian power system prepared by POSOCO were utilized for the model-based analysis for analysing the 0.56 Hz mode. However, prior to that, the Western regional grid modeling data were tuned in order to match the response near to actual system.

Small Signal Stability Study: The small signal stability analysis of Western region has been carried out using NEVA program of PSS/E which provided the Left and Right Eigenvectors [8]. Based on the analysis, it was observed that among various modes, the 0.56 Hz mode was present in the system and its mode shape seen from the model-based study is shown in figure 3. The damping of this mode was found to be 5.6 %.

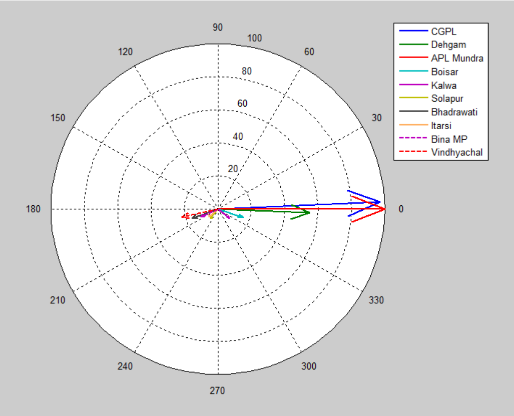

Figure 3. 0.56 Hz Mode shape from Eigenvalue obtained from the Small Signal Stability analysis of Western region Grid of India.

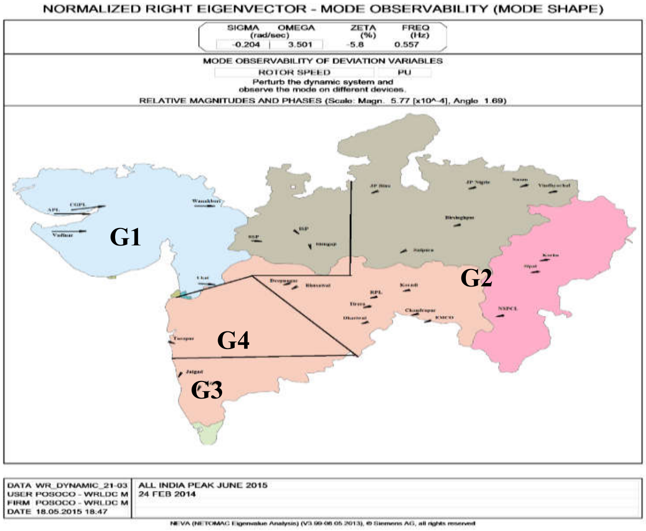

Figure 4. 0.56 Hz Mode shape of rotor angles of generators in WR Grid and coherent group

The mode shape geographical plot based on the Eigenvalues obtained is shown in figure 4 from where it is observed that the Western Region grid is having four coherent groups, which are as follows:

1. The large power plants concentrated in the Western part of the WR Grid (G1)
2. The large power plants concentrated in Eastern Part of the WR Grid (G2)
3. The loads concentrated in Southern Part of the WR Grid (G3)
4. The loads concentrated in South-Western Part of the WR Grid (G4)

Dynamic Study: To further ascertain the 0.56 Hz mode and its characteristic, the dynamic simulation was performed wherein a three-phase fault was simulated on a 400 kV circuit (for 100 ms) connecting these major coherent groups of generators. The frequency data from the dynamic simulation for the same nodes as in figure 3 and 4 were analyzed with multi-matrix pencil analysis to find the dominant mode frequency, mode shape and coherent group.

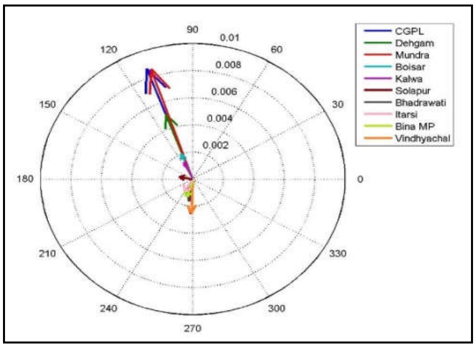

Figure 5. 0.55 Hz mode shape using multi-matrix pencil method on the frequency observed from the dynamic simulation.

The output of the analysis of the dynamic simulation confirms the presence of 0.56 Hz which was observed in the small signal analysis. The frequency of LFO observed from dynamic simulation was 0.55 and the mode shape for the 0.55 Hz mode as shwon in figure 5 is identical to the mode shape of 0.56 Hz seen from figure 3. Its damping was around 4 %

Thus, the model-based small signal stability and dynamic stability studies have confirmed the presence of 0.56 Hz intra-area mode and the coherent group of generators. To further ascertain the mode, the measurement-based analysis was also carried out as described in the next section.

B. Measurement-Based Analysis

To verify the presence of 0.56 Hz intra-area mode, Oscillation monitoring system (OMS) system based on Synchrophasor data was utilized in the Western Regional grid control centre. The observability of this mode was confirmed on several instances from the OMS. On one of the occasions, its damping was low resulting in its observability in the frequency parameters, which is shown in figure 6. The frequency observed at that time for the 0.56 Hz mode was 0.57 Hz with damping of around 3%.

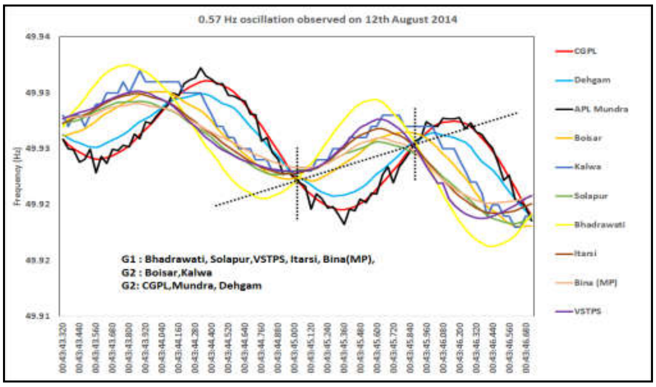

Figure 6. 0.57 Hz Mode observed in the frequency of various nodes in the Western regional grid using synchrophasor data.

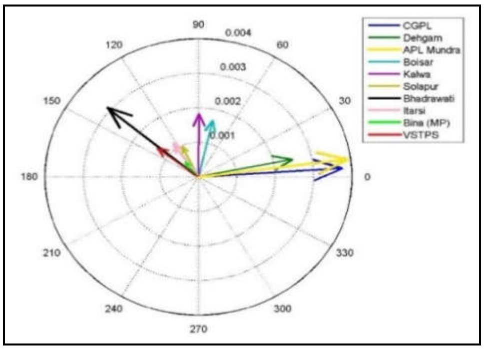

Figure 7. 0.57 Hz Mode shape based on measurement analysis using multi-matrix pencil method

Based on the analysis of the frequency data as shown in figure 6, it can be observed that there are three coherent groups of generators present in the system comprising of G1, G2 and G3 which are same as the coherent group G1, G2 and G3 as discussed in the model-based analysis. The coherent group 4 could not be observed due to the absence of Synchrophasor device at any of the nodes in that area. The mode shape of 0.56 Hz mode based on the multi-Matrix

Pencil is plotted in figure 7, which also confirms the presence of these coherent groups of generators.

Therefore, the model-based, as well as measurement-based analysis, has confirmed the presence of 0.56 Hz (0.55 Hz- 0.6 Hz) intra-area mode, its observability and associated coherent group of generators in the Western Region Grid. In order to examine the observability, controllability and characteristic of this intra-area mode, a detailed analysis was done on the various outputs from the Small signal stability studies (Eigenvalue analysis).

VI. INFERENCES FROM EIGENVALUE ANALYSIS

After validation and verification of the 0.56 Hz mode, the outputs from small signal stability study for this mode was further explored to find its observability and controllability aspects.

A. Observability based on Right Eigenvector

The magnitude of oscillation in the rotor angle of generators based on the Right Eigenvector obtained from the small signal stability analysis in PSS/E NEVA is shown in Figure 8. Maximum oscillation was observed in the CGPL, Vadinar and APL Mundra substation, which are major generating stations in the Western Part of the Western regional grid. Their high magnitude can also be confirmed in the mode shape based on measurement-based analysis shown in figure 7.

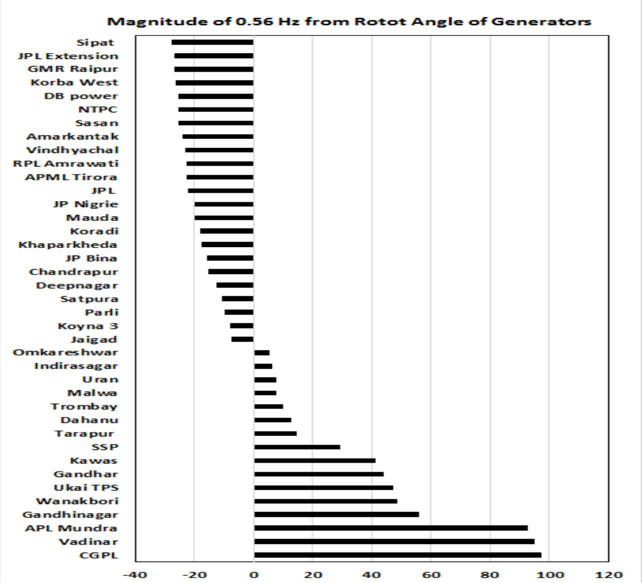

Figure 8. Mode Shape Magnitude for 0.56 Hz from rotor angles of WR generators indicating observability of the mode. Positive and negative magnitude indicate whether the generator is in the left and right half of the plane when mode shape of all generator rotor angle is shown in the polar plot as shown in figure 3.

In addition, generators of the Eastern part of the WR grid, which are phase opposition to these generators, are equally participating but their magnitude is around one-fourth of oscillation observed in the Western part. The reason behind is installed generation capacity in eastern part has 3 times more compared to Western part and during LFOs the energy is only exchanged between coherent group of generators. It can further be observed that the generators where the oscillation is minimum on either side corresponds to the generator in G3 and G4 group and can be treated as boundary generators showing the axis of separation in case this mode becomes unstable with negative damping.

Similar mode shapes and the coherent groups were also observed when mode shape of the frequency and active power of the generators were analysed.

B. Controllability based on Left Eigenvector

The eigenvalue analysis describes that the right Eigenvector provides the observability and mode shape of the LFO and the left Eigenvector provide the details about the controllability aspect of the LFO [2,3,6,7]. It weighs the contribution of the activity of the state variables for any LFO mode and how it influences any Eigenvalue. For example, if a generator rotor angle has a high influence on the oscillation mode compared to other generators then controlling this generator can result in either increase or decrease in the amplitude/damping of this LFO mode.

To find out the controllability of intra-area mode of 0.56 Hz in the Western Region of Indian Grid, the left Eigenvectors were analyzed for rotor angle and voltage magnitude. It was observed that voltage magnitude has a low contribution towards controllability when compared to the rotor angle. The high contribution of rotor angle to controllability reflects the need of Power system stabilizer (PSS) tuning of the generators [5-8]. The rotor angle participation from the left Eigenvalue is plotted in figure 9 where it can be observed that CGPL, APL and Vadinar in the Western Part and Several generators in Eastern part requires PSS tuning to improve the damping of this intra-area mode.

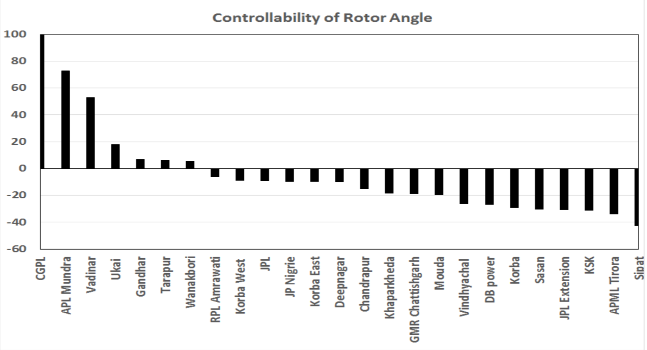

Figure 9. Magnitude (%) of Left Eigenvector from rotor angles of WR generators for Intra-Area mode.

Similar controllability aspect for voltage was also observed during the analysis which indicate measures like SVC/STATCOM. As the controllability is dependent on the unit of the Controllable quantity so a unitless quantity is required which can provide which controllability factor is more prominent. Such unitless quantity in Eigenvalue analysis is called participation factor which is explained in the next section.

C. Participation Factor

Participation Factor is a measurement of relative participation of any state variable in any specific mode and is mathematically expressed as the multiplication of left and right Eigenvectors. It does not have any unit and thus represents the controllability as well as observability of the power system state for a given mode shape [2,3,8].

When participation factors were calculated for rotor angle and voltage for 0.56 Hz mode, the magnitudes of rotor angle were found to be high (0.5-7) when compared to voltage magnitude (0.1-2) as given in table 1. It can be observed that the participation factor for rotor angle was around 3 to 40 times higher than the voltage magnitude at nodes which indicate that rotor angle control, which is PSS tuning, is more effective to damp this intra-area oscillation mode compared to voltage control devices. The higher magnitude of participation factors also provide the priority list of generators for PSS tuning [6,7].

TABLE I. COMPARISON OF PARTICIPATION FACTOR FOR ROTOR ANGLE MAGNITUDE AND VOLTAGE MAGNITUDE FOR NODES HAVING HIGH CONTROLLABILITY.

Nodes	Rotor Angle Magnitude	Voltage Magnitude	M=Rotor Angle/ Voltage
CGPL	6.60	1.77	3.7
APL Mundra	4.92	1.09	4.5
Vadinar	3.42	1.02	3.4
Sipat	0.80	0.02	40.0
Ukai	0.58	0.02	29.0
JPL Extension	0.56	0.05	11.2
Sugen	0.54	0.05	10.8
Tirora	0.53	0.05	10.6
KSK	0.53	0.99	0.5
Sasan	0.51	0.99	0.5
Korba	0.50	0.98	0.5
Korba West	0.47	0.95	0.5
Lanco	0.46	0.99	0.5

D. Residue for PSS Tuning

The participation factor helps in finding the suitable controller however, the input and output characteristic of the controller also needs to be checked which is done by calculating the residue factor [1-3,6,7]. The residue factor for PSS tuning is an open loop transfer function without PSS ($_{\Delta}\omega/ _{\Delta}V_{ref}$) and the PSS phase compensation (the partial derivative) at the Eigenvalue frequency. The residue factor for PSS tuning control for 0.56 Hz is given in figure 10.

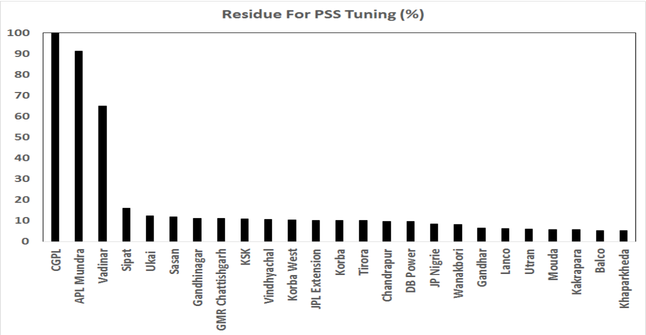

Figure 10. The Reside for PSS tuning for WR generators indicating best candidate for PSS tuning to damp 0.56 Hz.

It can be observed that the best places to damp oscillation are matching with table 1. These generating stations are mostly large generating complex ranging from 1200-4300 MW.

E. Impact of PSS Tuning Based on the study

Based on the study and assesment of PSS tuning, the tuning exercise has been completed at most of these generating stations in a phased manner and the damping of this intra area mode has improved. After this, the above oscillation mode is generally not observable in the Western region grid in Indian Power System. The details of the PSS tuning of few of these generating stations can be found in another paper by the author [11].

VII. CONCLUSION

The paper discusses the intra-area Mode assessment method using a hybrid approach of Model as well as Measurement based approach. It also shows how the intra-area mode in Indian power system needs a different damping control (PSS tuning) compared to inter-area mode (HVDC or FACTS Controller). The use case demonstrated effectively how the analytics and real-time measurement can be validated and an effective solution for damping of intra-area mode can be found. This study has provided the input on generating plants where PSS tuning exercise has to be carried out to damp this mode. Further, this paper highlights how such analysis helps in finding out the coherency of generators and their axis of separation that helps in defining the dynamic nature of the grid.

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