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A Study on the Presence of Inter-Area Oscillation Mode in Bangladesh Power System Network

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***Abstract*—Inter-Area modes of oscillation are of significant concern in interconnected system operation, considering the fact that these oscillations involve units from different areas of a power system and hence may result in a higher oscillation in the tie-line by adding up effects from each of the units participating. Research has been going on in this area ever since the growth of interconnection among electric utilities, to fully understand, monitor and control this phenomenon. Bangladesh Power System Network (BPSN), being an interconnected system consisting of greater Eastern and Western Grid, might also be vulnerable to the effects of inter-area modes and if not identified and studied, might lead to unexpected contingencies. In this paper, a study on the presence of inter-area mode in BPSN has been performed. A detailed model of BPSN has been used, represented by a 166 Bus and 27 Generator system.**

***Index Terms*— Bangladesh Power System Network, interconnected system, grid, inter-area mode.**

I. INTRODUCTION

ELECTRIC power systems, being highly non-linear and dynamic in nature, give rise to numerous modes of oscillation “inherently” [1]. Among different types of these oscillations reported in the literature [2], the Inter-Area ones have attracted considerable attention of the research community, especially, since the “sudden” growth of interconnection requirement among utilities in the western world, in the 1960s [2].

As the term suggests, “inter-area” modes are related to the phenomenon where synchronous generators in one area oscillate with the ones in another area, interconnected by “weak” ties [2]. Poorly damped oscillations, whether local or inter-area, pose threats to secure system operation; inter-area ones deserve rather more attention, as they involve generating units in more than one area and contributions from individual units might produce larger oscillations in the tie-lines [2]. This fact might considerably affect inter-area bulk power transactions and is treated with high importance, especially in the deregulated environment, where system operators are quite often compelled to maximize utilization of transmission assets for commercial sustainability.

As per literature, nature of these modes of oscillations is yet to be fully understood [1]. Typically, these modes have frequencies in the range of 0.1 to 1 Hz, which is lower compared to the local modes with frequencies ranging from 1 to 2 Hz [2]. Minimum acceptable damping co-efficient associated with any mode of oscillation depends on several factors such as, the system under study, operating philosophy of the utility, previous experience and studies performed on the system; typical acceptable damping has been reported as 0.03 to 0.05 [2]. For an interconnected power system, study of inter-area oscillation modes is typically essential to take correct actions against contingencies in day-to-day operations, and in long-term planning as well, as natural growth in amount of power transfer with time may be hindered due to lower damping at higher line-loading.

Bangladesh Power System Network (BPSN) has been consisting of two major isolated areas, namely the Eastern Grid and the Western Grid, until the first interconnection was commissioned in the early 1980s. Strength of the transmission corridor between these two regions has been further enhanced by commissioning a second tie-line, approximately three decades later, in March 2009. This paper presents the findings of an investigative study on the presence of inter-area mode in BPSN, as an interconnected power system.

Section 2 of this paper provides a brief description on system model. Analytical techniques and the simulation tool used in this work have been described in Section 3. Results have been presented in Section 4.

II. SYSTEM DESCRIPTION AND MODELING

Study of inter-area mode requires detailed representation of the full interconnected system [3]. BPSN is divided into five operational regions, namely – Dhaka, Central, Southern, Northern and Western region. Dhaka, Central and Southern regions together form the greater Eastern Grid, whereas, the Northern (Rajshahi-Rangpur) and Western (Khulna-Barisal) region form the Western Grid. The network model used in this study is fully based on the detailed transmission system of BPSN, consisting of 132 kV and 230 kV grids, as available from Power Grid Company of Bangladesh (PGCB) website [4]. The Interconnections between Eastern and Western grid is at 230 kV level. The old tie-line is from Ghorashal to Ishurdi substation, whereas the new one is between Ashuganj and Sirajganj. Power transfer has been simulated from east to west direction only, as this is the usual transfer direction.

Base case of the system has been set up based on the load and generation pattern of a peak period data from 24th April, 2009, with a deviation that generating units in

Rangpur and Shikalbaha has been modeled as “in-service”, whereas, these units have been found in outage as per practical data. Voltage set points of the units have been adjusted to simulate the low voltage characteristic of BPSN.

A. Synchronous Generator and Controls

Synchronous generator model used in power system studies vary from the simple electromechanical model to more complex ones with various types of impedance parameters and time constants included to capture more accurate dynamics of the system. As the study involves inter-area modes, demanding detailed dynamic representation, sub-transient machine model has been used. Detailed description of sub-transient model of synchronous machines is available in several textbooks, including [5-6]. Preparation of model data for dynamic studies is a rather complex task and is further complicated by the unavailability of access to manufacturer’s design data. Additionally, data provided by manufacturers are often needs to be modified to fit experimental results [5]. Machine data used in this study are based on typical parameter used for stability studies, as available and described in [5]. Each of the generating units consists of an excitation control system, represented by IEEE Type-1 DC Exciter and a speed governing system, represented by a Simple Turbine-Governor model available with the simulation tool used.

B. Load Model and Shunt Capacitors

Static load model has been used. System load data has been obtained from operational records of PGCB. Load power factor has been assumed 0.9 lagging as per the discussions presented in Bangladesh Power System Master Plan Update 2005 [7]. BPSN contains capacitive shunt compensation at 33 kV sides of the grid substations. As loads are applied in aggregate manner at 132 kV buses, capacitive shunts are also modeled in the same way for the respective buses.

III. ANALYSIS TECHNIQUES AND TOOL

A. Analysis Techniques

Linear analysis is widely used to study oscillatory behavior of power systems. In this technique, the system is linearized about an operating point and typically involves computation of eigenvalues, eigenvectors and system modes from state-space representation of power system model. This is also termed as “Small Signal Stability Analysis”, “Modal Analysis” or “Eigenvalue Analysis”. Techniques used in this paper for studying oscillatory modes are also based on linear analysis techniques. Though there are numerous textbooks available in this subject, interested readers are referred to [6, 8], for particular application in power systems. For a readily available reference, a brief review has been presented here, based on these references. Linear approximation of power systems, which are essentially non-linear, can be represented by the following state-space equations:

$$\begin{aligned}\Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u\end{aligned} \tag{1}$$

Δx is the state vector of length equal to the number of states, n
Δy is the output vector of length m
Δu is the input vector or length r
A is the n x n state matrix
B is the input matrix of n x r
C is the output matrix of m x n
D is the feed forward matrix of m x r

Now eigenvalues of the system state matrix is available from the characteristic equation of the state matrix A, expressed as

$$\det(A - \lambda I) = 0 \tag{2}$$

For each of the eigenvalues, there are two sets of orthogonal eigenvectors, namely the left and right eigenvectors, satisfying the following equations:

$$\begin{aligned}A\Phi_i &= \lambda_i\Phi_i \\ \Psi_i A &= \lambda_i\Psi_i\end{aligned} \tag{3}$$

λ_i is the ith eigenvalue
Φ_i is the right eigenvector corresponding to λ_i
Ψ_i is the left eigenvector corresponding to λ_i

To be able to identify the states which most significantly influence the dynamics of the system under study, certain transformation is applied to original state vector Δx, which decouples the coupled system of equations in (1). This transformation gives rise to a new state vector z, related to the original one by

$$\Delta x = \Phi z \tag{4}$$

Each variable of z is associated with only one mode of the system. Eigenvalues corresponding to the system modes provide stability information of the system. Real eigenvalues are associated with non-oscillatory modes, whereas the complex ones, appearing in conjugate pairs, correspond to oscillatory modes – one mode for each pair. If the eigenvalue of an oscillatory mode is expressed as,

$$\lambda_i = \sigma \pm j\omega \tag{5}$$

the damping coefficient for that mode is given by,

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{6}$$

and the frequency of oscillation in Hertz is determined by,

$$f = \frac{\omega}{2\pi} \tag{7}$$

A negative real part of the eigenvalue represents positive damping coefficient that is, decaying oscillation, whereas the positive real part indicates negative damping, i.e., increasing oscillation.

The right eigenvector of a mode gives an idea how this mode is distributed among different states of the system and hence defined as **Mode Shape**. Based on this idea, if a mode is found to be distributed among any specific state variable of generating units in different areas, then that mode can be identified as an inter-area one. Typically, rotor speed is used as the test state variable for mode shape analysis in inter-area oscillation study [1, 6, 8].

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. For example, participation factor pki of any kth state variable in any ith mode can be measured as,

$$p_{ki} = \phi_{ki}\psi_{ik} \tag{8}$$

Φ_{ki} is the kth entry of the right eigenvetor of ith mode
ψ_{ik} is the kth entry of the left eigenvetor of ith mode

Participation factors are non-dimensional quantities and can be calculated without much computational effort. These are of particular interest in damping of system oscillation; the machine containing positive real part of the participation factor of its speed state may be a potential candidate for placement of a stabilizer. However, as this study mainly aims at identifying inter-area modes, discussions are limited to observation of participation factors only. Inter-area modes can be identified by observing rotor speed participation factor of the generating units in different areas. To have an idea on the actual oscillatory behavior of the system in the presence of a disturbance, time-domain simulations are performed. Usually a severe disturbance, such as a three phase fault is applied, or, outage of an important line or generating unit is performed and network variables of interest are observed.

B. *Simulation Tool*

Power System Toolbox (PST) has been used for all the linear and transient analysis required in this work. PST is a MATLAB based tool, initially designed and developed by Prof. Joe Chow of Rensselaer Polytechnic Institute, Troy, New York. Since 1993, it has been marketed and further developed by Graham Rogers from Cherry Tree Scientific Software, Ontario, Canada. This tool has been used in many of the publications of dynamic analysis of power systems. The version of PST which has been used for this work is based on the version that Graham Rogers has used for [6].

PST can be used for dynamic analysis of AC/DC/FACTS power systems. The most attractive feature of PST is that it can integrate user-defined models into simulation environment; and as the program codes are open, users can modify or extend the computational capabilities to cater for specific simulation requirements.

In this tool, basic topology of the network to be studied is described by a ‘bus’ and ‘line’ matrix, that are stored in a data file. Machine and associated controls, such as exciter, governor, PSS and FACTS devices are modeled according to pre-specified data format and are also stored in the data file. Linearization algorithm has been implemented in a built-in routine, named “svm_mgen”, of the simulation package. This routine performs linearization of the network at the operating point specified in the data file based on a load flow analysis. Eigenvalues, left and right eigenvectors, system modes specified by damping co-efficient and frequency, participation factors and other required information for linear analysis are readily available upon running this routine. Built-in plotting functions of MATLAB then can be easily used for graphical representation of mode shapes and participation factors. The program, manuals and associated information can be obtained on request from [9].

TABLE I
POWER TRANSFER THROUGH TIE-LINES IN BASE CASE

Voltage (kV)	Transfer through Tie-Lines (MW)
Ghorashal: 204.90 Ishurdi: 206.91	Into Ishurdi 230 kV Node: 143.24
Ashuganj: 206.77 Sirajganj: 209.04	Into Sirajganj 230 kV Node: 280.80

TABLE II
DAMPING CO-EFFICIENT AND FREQUENCY OF THE CRITICAL MODE

Mode No.	Damping Co-efficient	Frequency (Hz)
166	0.0310	0.9093

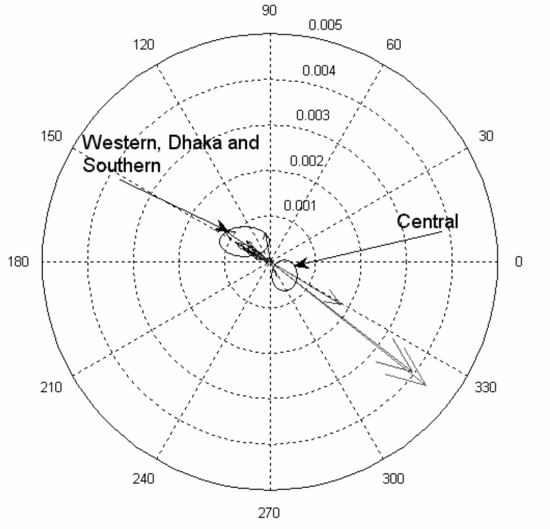

Fig. 1. Compass Plot of Generator Speed Mode Shape in Base Case Scenario.

IV. RESULTS OBTAINED FROM ANALYSIS

Analysis has been started from a healthy condition of the base case set-up, i.e., without any contingency. Both circuits of the tie-lines are in operation. Power transfer scenario from Eastern to Western Grid, as obtained from load-flow study, is summarized in Table I and resembles operational records. Modal analysis has been performed at this network condition and only one system mode has been identified for further study, with damping co-efficient less has 0.05, as in shown Table II.

Mode shape corresponding to this mode has been presented in the compass plot shown in Fig. 1 which shows that generators in the Central region oscillate with the ones in the Western grid almost in anti-phase and the ones in Dhaka and Southern region oscillate nearly in-phase.

TABLE III
GENERATOR NUMBERS OF DIFFERENT REGIONS OF BPSN

Generator Number	Region
1, 10-17, 27	Dhaka
20-23	Central
19, 24-26	Southern
2-9, 18	Western*

** Western grid encompasses all the units in Northern and Western region.*

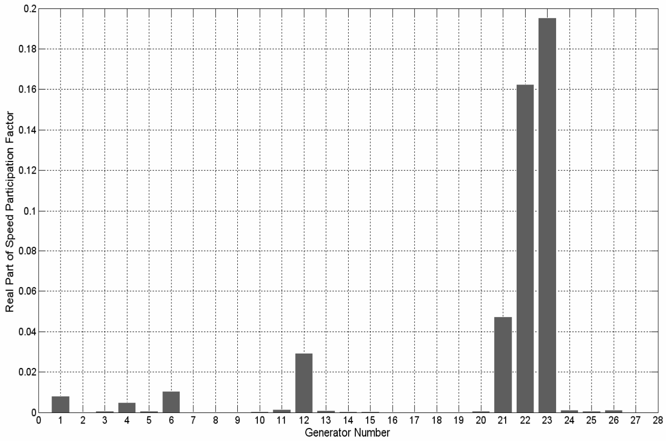

Fig. 2. Bar Chart of Generator Speed Participation Factor in Base Case Scenario.

TABLE VI
DAMPING RATIO AND FREQUENCY OF CRITICAL MODE

Mode No.	Damping Co-efficient	Frequency (Hz)
166	0.0291	0.9049

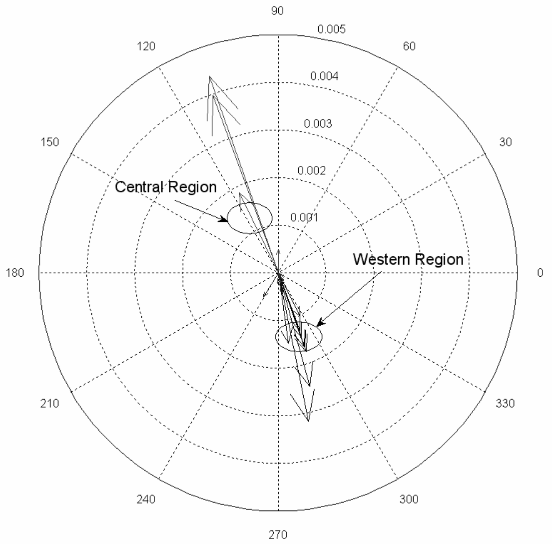

Fig. 3. Compass Plot of Generator Speed Mode Shape of Mode 166 with Single Circuit Operation of New Interconnection.

Real part of the participation factors of rotor speed has been plotted in Fig. 2 and compares the participation of generators in Eastern and Western grid in the critical mode of oscillation. Generator numbers of different regions of BPSN has been listed in Table III, which would help the reader to understand how intensely the generators of different areas participate in oscillation. It is to be noted that these are not actual number of the units in BPSN; rather these are identification of the units, as used in this study. The participation bar chart in Fig. 2 shows that generators both in Eastern and Western grid participate in the oscillation, though the ones in the Central region have very high participation compared to the units in the other regions.

Considering the fact that presence of an inter-area mode is influenced by the "weakness" of a tie-line [1-2], studies have been performed with increasing degree of "stress" on the system to investigate the appearance of inter-area mode with different stress level. At first, one of the circuits in the new inter-tie has been tripped off and modal analysis has been performed. Reason for choosing the new interconnection at first is, the transfer capacity of this line is nearly double of the older one due to twin conductor configuration [10] and tripping off one circuit may not pose severe threat to the system at the base case transfer scenario presented in this study, yet stresses the system more than base case.

Observation of system modes confirms that the critical one exceeds typical minimum satisfactory damping level of 0.03, as shown in Table IV. Compass plot of the mode shape of generator rotor speed has been shown in Fig. 3, which depicts the similar condition as before, i.e., machines in Central region oscillate with the ones in the Western grid nearly in anti-phase and the ones in Dhaka and Southern region oscillate about in-phase; but in this case participation of the Western grid units is much higher than before.

Bar chart of real part of speed participation factor shown in Fig. 4 confirms this. A time-domain simulation profile of the generator speeds, upon occurrence of a severe disturbance near Ishurdi 132 kV bus, has been presented in Fig. 5 and is observed that oscillation of rotor speeds of Western grid units are almost in anti-phase with the ones in Central region – which correspond findings of linear analyses.

Now the system is turned into a more stressed one by tripping off one circuit in the older inter-connection, i.e., both the tie-lines are operating with single circuit. Eigenvalue analysis has been performed and the critical mode has been found with the damping coefficient and frequency shown in Table V. Mode shape and participation factor in this condition has been shown in Figs. 6 and 7, respectively. In this case all of the generating units in Western grid oscillate with the units in greater Eastern grid with a phase difference of about 150°.

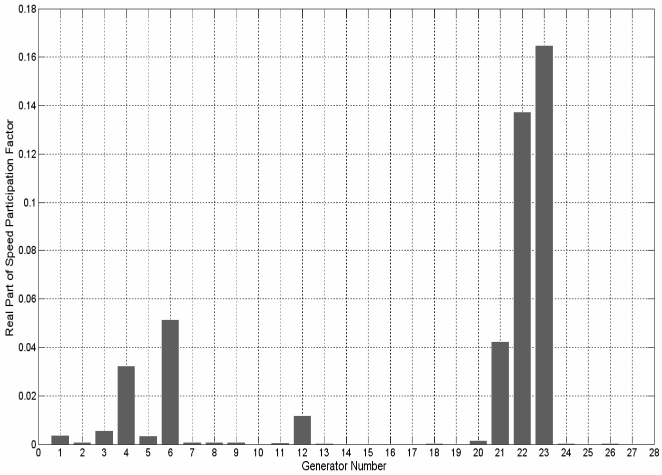

Fig. 4. Bar Chart of Generator Speed Participation Factor of Mode 166 with Single Circuit Operation of New Interconnection.

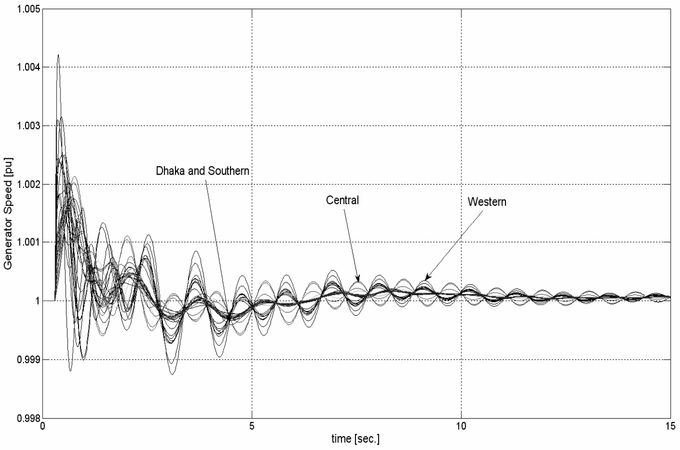

Fig. 5. Generator Speed Transient Profile of Different Regions with Single Circuit Operation of New Interconnection.

TABLE V

DAMPING RATIO AND FREQUENCY OF CRITICAL MODE

Mode No.	**Damping Co-efficient**	**Frequency (Hz)**
166	0.0247	0.8869

Similar to the previous case, time domain simulation has been performed and generator speeds are plotted in Fig. 8; oscillations in rotor speed show similar characteristic as found with linear analysis. Though the amplitude of oscillations in the individual machines does not seem to be significant, the resulting oscillations in the tie line power flow has been appeared as considerable, as shown in Fig. 9.

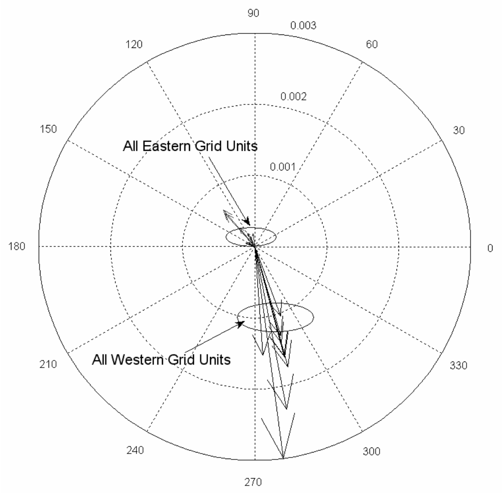

Fig. 6. Compass Plot of Generator Speed Mode Shape of Mode 166 with Single Circuit Operation of Both Tie-Lines.

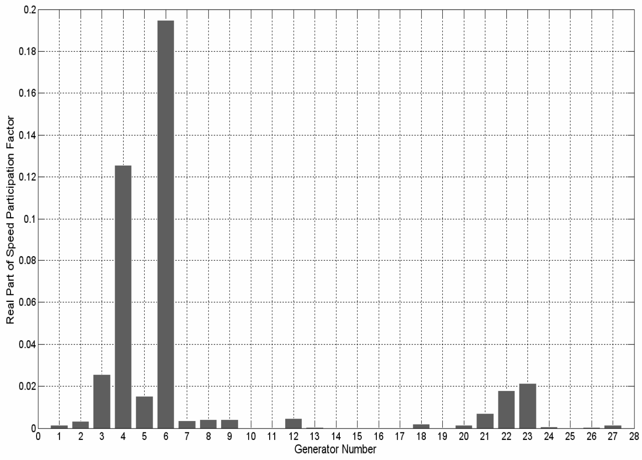

Fig. 7. Speed Participation Factor of Mode 166 with Single Circuit Operation of Both Tie-Lines.

V. DISCUSSION AND CONCLUSION

An exploratory study on probable existence of inter-area mode in BPSN has been performed. Mode Shape and Participation Factor analyses have been carried out with varying degree of "stress" on the system implemented by outage of one circuit in each of the double circuit tie-lines. Results suggest presence of inter-area mode in the system and reduction in damping has also been observed with higher level of stress, as expected. Typical dynamic data has been used, as BPSN does not have any reported complete set of dynamic database. At healthy network condition, i.e., without any contingency, the inter-area mode has a damping coefficient of 0.031, which is at the lower range of satisfactory level.

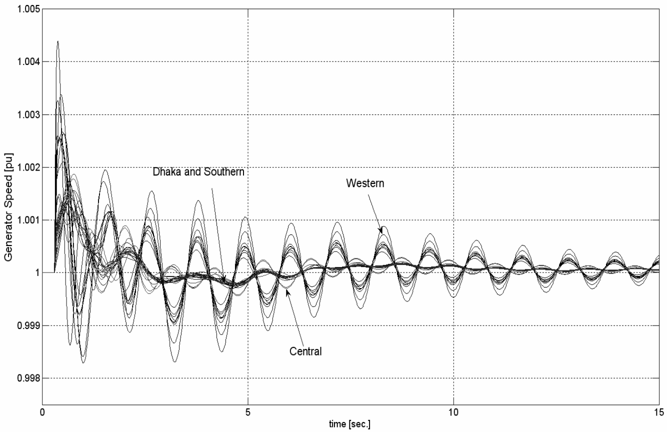

Fig. 8. Generator Speed Transient Profile of Different Regions with Single Circuit Operation of Both Tie-Lines.

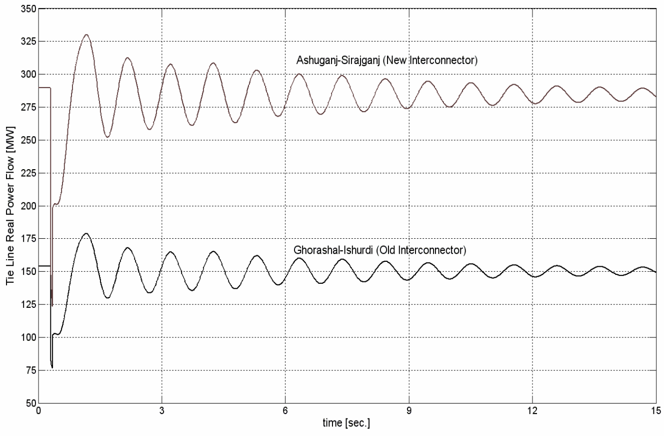

Fig. 9. Tie-Line Active Power Flow Oscillations.

As the transmission gateway between Eastern and Western grids is weakened by tripping off circuits, damping falls below the satisfactory level of 0.03; with outage of one circuit in the new interconnection, damping has been found as 0.0291, whereas with single circuit operation of both inter-ties, the inter-area mode damping has been found 0.0247. In healthy condition, units in central region have very high participation factor compared to other units. In single circuit operation of new tie-line, participation of Western grid units is higher than before, and with single circuit operation of both interconnections, Western grid units oscillate with highest level of participation among all the units in BPSN. As the level of tie "weakness" is increased, more of the units participate in the inter-area mode. Contributions from the units participating results in a considerable oscillation in the tie-line power flow in post contingency scenario.

This study does not intend to provide any certain conclusive remark on the presence and behavior of inter-area mode in BPSN, rather proposes a scope for further research in this area, to be able to identify and characterize inter-area oscillation modes more confidently. Especially, variation of dynamic model types and parameters, that corresponds actual equipment data more accurately, may discover practically useful findings on the presence of inter-area mode in BPSN. Further studies are also required to design appropriate damping controller to stabilize this kind of low-frequency oscillations, considered harmful for secured operation of interconnected power systems. PSS and FACTS devices could be potential technology-candidates in implementing these damping controllers.

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