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Stability Analysis of Multi-Machine Power System for Inter-Area Oscillations under Different Time-Delay in Control Signal for PSS

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Abstract – **This paper presents a novel approach in order to improve power system stability by designing phasor measurement technology (PMU) based wide area damping controller (WADC). Wide area power system stabilizer (WPSS) is one of the most potentially effective approaches to damp inter-area oscillations in power system in WADC. Data measured by PMUs transmitted to controller through the communication channels, in this transmission network time delay is unavoidable, and to deal with this kind of time delay problem we used Padé approximation approach. The work is related to designing a wide area damping controller for inter-area oscillations damping for two-area four-machine power system model which identify the inter-area oscillations through modal analysis and selected most affective wide area signal for power system stabilizer by using geometric approach. Proposed methodology is used to damp out inter-area oscillations under different signal delay. Simulation results concluded that for multi machine power system, the inter-area oscillation with signal delay which is very dangerous and can be easily damped out with the proposed approach.**

Keywords – **DAE, GA, Padé Approximation, PMU, PSS, WADC, WPSS.**

I. INTRODUCTION

The capability of the system to sustain steadiness in normal circumstances and to recover its equilibrium state after enduring disturbing situations is known as the stability of power system.

Categories for the stability of power system: electromagnetic, thermodynamic, wave and electromechanical. The electromechanical process occurs at the synchronous machine windings. Here the electromechanical process is only considered. Fluctuations may occur in the electrical network and generating units due to some disturbance in the network. Even the rotatory components of the power system also get affected because of the disturbance occurring due to electromechanical process [1]. The power system's security totally depends upon the competence of the system to tackle the disturbance and survive throughout without any interruption of service.

Power-system depends on the capability to its security to endure any instabilities that may arise in service. Figure 1 shows a generalized block diagram for synchronous generator.

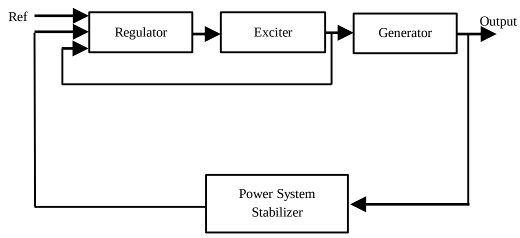

Figure 1: Standard excitation control system [2]

The reliability of a power system has been an important topic of study in recent decades. Stability in power system is a major factor required for a system to operate securely. A secure system provides a constant frequency and constant voltage within limits to customers. To achieve this aim a highly reliable and cost effective long term investment technology is required. Stability limits can define transfer capability. Also in a complex interconnected system, stability has a great impact to increase the reliability and the profits. Although this interconnection gives the system a complicated dynamic. It has advantages such as reduced spinning reserves and a lower electricity price. To achieve these benefits, appropriate control is required to synchronize the machines after a disturbance occurs.

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With the growing electricity demand and the aging utility infrastructure, the present-day power systems are operating close to their maximum transmission capacity and stability limit. Power system stability is the ability of an electric power system to regain operating equilibrium after being subjected to a physical disturbance. Power system stability is the most important issue in achieving secure and reliable operation [3-4].

In the past few decades, the angular instability, caused by small signal oscillations, has been observed in the power systems under certain system conditions, such as during the transmission of a large amount of power over long distance through relatively weak tie lines and under use of high gain exciters. Oscillations in the power system may affect the stability of entire power systems. If the oscillations are not damped successfully, then power outages may occur and millions of people can be affected. The Western US/Canada power outage that occurred on 10 August 1996 is an example [5].

The outages were due to the excessive power flow through the US/Canada interconnection and the sequence of small disturbances. Oscillations in synchronous generators are the core phenomena behind the collapse of power systems [6-8].

Local area modes of oscillation oscillate the nearby generators or the generators in the same region. Thus, the local area modes of oscillation affect the generators in the same region or nearby regions. By contrast, the inter-area modes of oscillation are the oscillations in the coherent generators of different regions connected through long tie lines.

The inter-area oscillations produce serious damages on the stable and efficient operation of power system especially in large interconnected grids. If inter-area oscillations have weak or negative damping ratio then it easily leads to interconnected grids and as a result cascading failures and finally black out could be happen. Thus, to ensure the stable and efficient operation of interconnected grids system the damping strategies should be performed to prevent or eliminate such inter-area oscillations.

For this, the traditional approach to damp out the inter-area oscillations by using Conventional Power System Stabilizer (CPSS). The basic function of PSS is to add damping to the generator rotor oscillation by controlling its excitation using auxiliary stabilizing signal. These controllers use local signals as an input signal and it may not always be able to damp out inter-area oscillations, because, the design of CPSS used local signals as input and local signal based controller do not have global observation and may does not be effectively damps out the inter-area oscillations [9].

The effective damping mechanism is that the damping torque of synchronous generator is enhanced through proper field excitation. The application of remote signal for damping controller has become successful due to the recent development of Phasor Measurement Units (PMUs). PMUs have very useful contribution in newly developed Wide Area Measurement System (WAMS) technology. The initial development of PMU based WAMS was introduced by Electric Power Research of Institute (EPRI) in 1990. It is found that if remote signals comes from one or more distant location of power system are used as a controller input then, the system dynamics performance can be improved in terms of better damping of inter-area oscillations [10]. The signals obtained from PMUs or remote signals contain information about overall network dynamics whereas local control signals lack adequate observability with regard to some of the significant inter-area mode. The real time information of synchronous phasor and sending the control signal to major control device (e.g. PSSs, HVDC controllers, and FACTS based controllers) at high speed has now become easier due to the use of PMU [11].

The PMU can provide wide area measurement signals. The signals can be used to enhance the wide area damping characteristics of a power system. The global signals or wide area measurement signal are then sent to the controllers through communication channel. Thus, network time delay is unavoidable. Such kind of delay varies from tens to several hundred milliseconds. Several experiments, reported in [12-14], have been carried out to measure the time delay.

As even a very small delay can result in loss of power system stability [15], input delay cannot be neglected in controller design. For wide-area damping control, once the control location and feedback signal are selected, the path and mode of signal transmission are also fixed. Usually, this transmission path will not change in the short-term, so that Wide-area Power System Stabilizer (WPSS) input delay becomes stable. Thus, the delay can be modeled as a constant delay in controller design.

Although, WPSS provides a great potential to improve the damping inter-area oscillation, the delay caused by the transmission of remote signals will degrade the damping performance or may even cause instability of the closed loop system [14] [16]. Therefore, the influence of time delay must be fully taken into consideration in the controller design. Padé approximation [17]-[20] is the effective

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International Journal of Digital Application & Contemporary Research
Website: www.ijdacr.com (Volume 8, Issue 11, June 2020)

approach to deal with this kind of constant time delay problem.

The wide area signals or the global signals are nothing but the remote stabilizing signals or the global signals. For the local mode of oscillations the most controllable and observable signals are the local signals such as generator speed deviation. But for inter-area modes the local signals may not have maximum observability to damp these modes. Rather this can be effectively damped by the use of remote signals from a distant location or combination of several locations. Another important advantage of use of wide area signals is that it needs very small gain for the controller compared to the local controllers in order to achieve the same amount of damping.

The major contribution of this research work is to design a wide area damping controller for inter-area oscillations damping and different (fixed value) latency compensation. At first, modal analysis of the linear model of power system excluding Wide-area is applied to find out the low-frequency oscillation modes and then identify the critical inter-area modes. Secondly, geometric approach has been used to select the most efficient wide-area signal. Then the controller gain is determined based on the Integral of Time Error (ITE) criterion and optimized by Genetic Algorithm.

II. Proposed Methodology

A. Small Signal Stability Analysis of Power System by Modal Analysis

Small perturbation continuously occurs in any power system due to small changes in load and generation. A set of non-linear differential and algebraic (DAE) equations are used for the study of multi-machine power system dynamic behaviour as follows [21]:

$$\dot{x} = f(x, z, u) \tag{1}$$

$$0 = g(x, z, u) \tag{2}$$

$$y = h(x, z, u) \tag{3}$$

Where, ‘f’ and ‘g’ are vectors of differential and algebraic equations and ‘h’ is a vector of output equations. The notation $x \in R^n, z \in R^m$, $u \in R^p$ and $y \in R^q$ are the state, algebraic, input, output vectors respectively. ‘n’ is the dimension of system, ‘p’ is the no. of inputs, ‘q’ is the no. of outputs. The inputs are normally reference values such as speed and voltage at individual units and can be voltage, reactance and power flow as set in FACTS devices. The output can be unit power output, bus frequency, bus voltage, line power or current etc. After linearizing, around the equilibrium point $\{x_o, z_o, u_o\}$, the above mentioned non-linear equations can be linearized in terms of the following equations

$$\Delta\dot{x} = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial z}\Delta z + \frac{\partial f}{\partial u}\Delta u \tag{4}$$

$$0 = \frac{\partial g}{\partial x}\Delta x + \frac{\partial g}{\partial z}\Delta z + \frac{\partial g}{\partial u}\Delta u \tag{5}$$

$$\Delta y = \frac{\partial h}{\partial x}\Delta x + \frac{\partial h}{\partial z}\Delta z + \frac{\partial h}{\partial u}\Delta u \tag{6}$$

Elimination of the vector algebraic variable Δz from (3) and (5), provides

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{7}$$

$$\Delta y = C\Delta x + D\Delta u \tag{8}$$

where A, B, C, D are the matrices of partial derivatives in (3) to (5) evaluated at equilibrium (x_o, z_o, u_o) as follows:

$$A = \left[\frac{\partial f}{\partial x} - \frac{\partial f}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial x}\right],$$

$$B = \left[\frac{\partial f}{\partial u} - \frac{\partial f}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial u}\right] \tag{9}$$

$$C = \left[\frac{\partial h}{\partial x} - \frac{\partial h}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial x}\right],$$

$$D = \left[\frac{\partial h}{\partial u} - \frac{\partial h}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial u}\right] \tag{10}$$

Power system state space representation is normally linearized around an operating point (hence the term small signal). The symbol Δ of (7) and (8) can be omitted so as to follow the standard state space representation by referring ‘x’ and ‘u’ (instead of ΔxandΔu) as the incremental values. Hence (7) and (8) can be written as per the following equations:

$$\dot{x} = Ax + Bu \tag{11}$$

$$y = Cx \tag{12}$$

In equation (8) the term ‘Du’ is omitted because ‘D’ is a null matrix. Now this becomes the representation of a linearized DAE model of a power system on which standard linear analysis tools can be applied.

B. Eigen Value Analysis

Once the state space model of a power system is obtained the small signal stability of the system can be calculated and analysed and the eigenvalues ‘λ_i’ are calculated for the A matrix. They are the non-trivial solutions of the equation:

$$A\phi = \lambda\phi \tag{13}$$

Where,

‘A’ is an ‘$n \times n$’ matrix and ‘ϕ’ is a ‘$n \times 1$’ vector, rearranging (13) to solve for ‘λ’ yields

$$\det(A - \lambda I) = 0 \tag{14}$$

The solutions of (14) are the eigenvalues of the ‘$n \times n$’ matrix ‘A’. These eigenvalues are of the form ‘$\sigma \pm j\omega$’ .

The damped frequency of the oscillation in Hertz and damping ratio are given by:

IJDACR
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Website: www.ijdacr.com (Volume 8, Issue 11, June 2020)

$$f = \frac{\omega}{2\pi} \tag{15}$$

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{16}$$

Provided that 'ψ' and 'ϕ' are available, the ODE of a system can be transformed into modal Coordinates 'z' through a transformation:

Substituting the value of, $x = \phi z$, in $\dot{x} = Ax + Bu$ and $y = Cx + Du$, the equations can be obtained as follows:

$$\dot{z} = \Lambda z + \psi Bu \tag{17}$$

$$y = C\phi z + Du \tag{18}$$

C. Participation Factors

Due to large size of power system, it is often necessary to construct reduced order models for dynamic stability studies by retaining only a few modes. This appropriate definition and determination as to which state variables significantly participate in the selected modes become very important. This requires a tool for identifying the state variables that have significant participation in a selected mode. It is natural to suggest that the significant state variables for an eigenvalue 'λ_i' are those that correspond to large entries in the corresponding eigenvector 'Φ_i'.But the entries in the eigenvector are dependent on the dimensions of the state variables which are, in general, incommensurable (for example angle, velocities and flux). Which is suggested as related but dimensionless measure of state variable participation called participation factors.

Participation factor analysis aids in the identification of how each dynamic variable affects a given mode or eigenvalue. Specifically, given a linear system

$$\dot{x} = Ax \tag{19}$$

A participation factor is a sensitivity measure of an eigenvalue to a diagonal entry of the system 'A' matrix. This is defined as :

$$P_{ki} = \frac{\partial \lambda_i}{\partial a_{kk}} \tag{20}$$

Where 'λ_i' is the 'i^{th}' eigenvalue of the system, 'a_{kk}' is a diagonal entry in the system A matrix, and 'P_{ki}' is the participation factor relating the 'k^{th}'state variable to the 'i^{th}' eigenvalue. The participation factor may also be defined by

$$P_{ki} = \frac{\psi_{ik}\phi_{ki}}{\psi_i^t \phi_i} \tag{21}$$

Where 'ψ_{ik}' and 'Φ_{ki}'are the 'k^{th}' entries in the left and right eigenvector associated with the 'i^{th}'eigenvalue. The right eigenvector 'ϕ_i' and the left eigenvector 'ψ_i' associated with the 'i^{th}' Eigenvalue 'λ_i' satisfy

$$A\phi_i = \lambda_i \phi_i \tag{22}$$

$$\psi_i^t A = \psi_i^t \lambda_i \tag{23}$$

Consider the system

$$[A - \lambda_i I]v_i = 0 \tag{24}$$

$$\psi_i^t [A - \lambda_i I] = 0 \tag{25}$$

Where 'ϕ_i' and 'ψ_i' need not be normalized eigenvectors.

An eigenvector may be scaled by any value resulting in a new vector, which is also an eigenvector. We can use this property to choose a scaling that simplifies the use of participation factors, for instance, choosing the eigenvectors such that $\psi_i^t \phi_i = 1$ simplifies the definition of the participation factor. In any case, since$\sum_{k=1}^{n} \psi_{ik}\phi_{ki} = \psi_i^t \phi_i$, it follows from, $\frac{\Delta\lambda_i}{\Delta a_{kk}} = \frac{\psi_{ik}\phi_{ki}}{\psi_i^t \phi_i} = p_{ki}$, that the sum of all the participation factors associated with a given eigenvalue is equal to 1, i.e.,

$$\sum_{k=1}^{n} p_{ki} = 1 \tag{26}$$

This property is useful, since all participation factors lie on scale from zero to one. To handle participation factors corresponding to complex eigenvalues, we introduce some modification as follows. The eigenvectors corresponding to a complex eigenvalues will have complex element. Hence, 'p_{ki}' is defined as

$$p_{ki} = \frac{|\phi_{ki}||\psi_{ik}|}{\sum_{k=1}^{n} |\phi_{ki}||\psi_{ik}|} \tag{27}$$

A further normalization can be done by making the largest of the participation factors in order to make it unity.

D. Selection of Remote Signal and Control Location

To obtain the efficiency and effectiveness of the damping controller of a power system to damp a given critical inter area mode signal selection is an important factor. In order to damp the inter area oscillations; wide area controller employing signals from remote locations are very much necessary because they are more controllable and observable compared to local signals. The remote stabilizing signals are often considered to as "global signals". In the selection of stabilizing signals and control location the effort should be to use as few measurement and control device as possible to achieve acceptable damping effect. This is more important from the economic point of view because the less measurement and control location the less cost for communication link and/or controllers.

IJDACR
International Journal Of Digital Application & Contemporary Research

International Journal of Digital Application & Contemporary Research
Website: www.ijdacr.com (Volume 8, Issue 11, June 2020)

The controllability and observability methods are often used to select controller location and stabilizing signals. There are two different approaches are used for measurement and control signal selection such as

Residue approaches

Geometric approach

But in this research geometric approach is used for signal selection and controller location site.

Let us consider the identified linear model of network given by equation (28)

$$x = Ax + Bu$$
$$y = Cx \tag{28}$$

Where $x \in R^{n\times n}$, $u \in R^{n\times m}$ and $y \in R^{p\times n}$ are the state, inputs and output vectors respectively. $A \in R^{n\times n}$, $B \in R^{n\times m}$ and $C \in R^{p\times n}$ are state, input and output matrices, respectively.

An eigenanalysis of matrix 'A' produces the distinct eigenvalues $\lambda_i (i = 1,2,3, \dots \dots n)$and corresponding matrices of right and left eigenvectors 'ϕ' and 'ψ', respectively. Modal analysis of linear model is applied to find out the low-frequency oscillation modes and then identify the critical inter-area mode. Modal observability have been used to select a suitable feedback signal for WADC, such as geometric measures [12].

Geometric Approach: The geometric measure of controllability $gm_{ci}(k)$ and observability $gm_{oj}(k)$ associated with the mode 'kth'are given by [22]:

$$gm_{ci}(k) = \cos\big(\alpha(\psi_k, b_i)\big) = \frac{|\psi_i b_i|}{\|\psi_k\|\|b_i\|} \tag{29}$$

$$gm_{oj}(k) = \cos\left(\theta\left(\phi_k, c_j^T\right)\right) = \frac{|c_j \phi_k|}{\|\phi_k\|\|c_j\|} \tag{30}$$

In (29) and (30), 'b_i' is the 'i^{th}' column of matrix 'B' corresponding to 'i^{th}' input, 'c_j' is the 'j^{th}' row of output matrix 'C' corresponding to 'j^{th}' output. $|z|$ *and* $\|z\|$ is the modulus and Euclidean norm of 'z' respectively. $\alpha(\psi_k, b_i)$ is geometrical angle between input vector 'i' and'k^{th}' left eigenvector and $\theta\left(\phi_k, c_j^T\right)$ geometric angle between the output vector 'j' and 'k^{th}' right eigenvector. The joint controllability and observability index of geometric approach is defined by:

$$C = gm_{ci}(k) * gm_{oj}(k) \tag{31}$$

In the geometric approach it can prove that the higher the value of joint controllability and observability index more the stability of signal selected.

E. Controller Design Considering Time-delay

The wide-area PSS is designed to damp a critical inter-area oscillation mode-k by providing supplement damping control signal for excitation system of the i^{th} generator, and the overall structure of closed-loop feedback control system with time-delays for multi-area interconnected power system is illustrated in Figure 2.

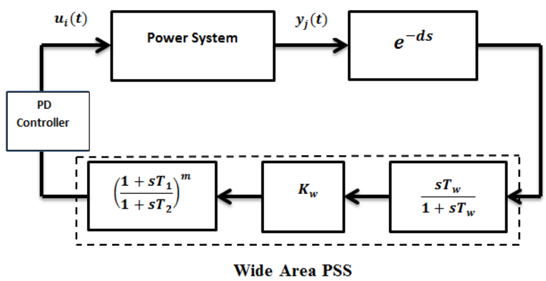

Figure 2: The proposed structure of wide-area PSS

As shown in Figure 2,'d' is the signal transmission delays between measurement location and wide-area PSS. The transfer function of wide-area PSS is:

$$H_{WADC}(s) = K_W \frac{sT_W}{1 + sT_W} \left(\frac{1 + sT_1}{1 + sT_2}\right)^m \tag{32}$$

The value of T_1 and T_2, are calculated as follows

$$\phi = 180^0 - arg(R_i) \tag{33}$$

$$\alpha = \frac{T_1}{T_2} = \frac{1 - sin(^{\Phi}/_m)}{1 + sin(^{\Phi}/_m)} \tag{34}$$

$$T_2 = \frac{1}{\omega_i \sqrt{\alpha}}; \; T_1 = \alpha T_2 \tag{35}$$

Where TW is the washout constant and usually chosen as 5- 10s, T_1 and T_2 are phase-compensation parameters, KW is the positive constant gain, m is the number of lead-lag compensation stages (usually equal to 2).The stabilizer gain KW determines the amount of damping introduced by the PSS. The signal washout block is a high pass filter, with time constant TW, which eliminates the low frequencies that are present in the speed signal and allows the PSS to respond only to speed changes. The phase compensation block is usually a single first order lead-lag transfer function or cascade of two first order transfer function used to compensate the phase lag between the excitation voltage and the electrical torque of the synchronous machine. The output is the stabilization voltage to connect to the input of the excitation system block used to control the terminal voltage of the synchronous machine.

In MATLAB, time-delays are expressed in the exponential form (e^{-ds}) in the Laplace domain. It can be replaced by a first-order Padé approximation:

IJDACR
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IJDACR
International Journal Of Digital Application & Contemporary Research

International Journal of Digital Application & Contemporary Research
Website: www.ijdacr.com (Volume 8, Issue 11, June 2020)

$$e^{-ds} \approx \frac{-\frac{1}{2}sd + 1}{\frac{1}{2}sd + 1} \qquad (36)$$

F. *Genetic Optimization of Controller Gain*

Genetic Algorithms (GAs) are adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and genetic process. The basic principles of GAs were first proposed by John Holland in 1975, inspired by the mechanism of natural selection, where stronger individuals are likely the winners in a competing environment. GAs assumes that the potential solution of any problems an individual and can represented by a set of parameters. These parameters are recharged as the genes of a chromosome and can be structured by string of values in binary form. A positive value, generally known as a fitness value, is used to reflect the degree of "goodness" of the chromosome for the problem which would be highly related with its objective value. The pseudo code of a GAs is as follows:

1. Start with a randomly generated population of n chromosome (Candidate a solutions to problem).
2. Calculate the fitness of each chromosome in the problem.
3. Repeat the following steps until n off spring have been created:
   a. Select a pair of parent chromosome from the concurrent population, the probability of selection being an increasing function of fitness. Selection is done with replacement, meaning that the same chromosome can be selected more than once to that the same chromosome can be selected more than once to become a parent.
   b. With the probability (crossover rate), perform crossover to the pair at a randomly chosen point to form two offspring.
   c. Mutate the two offspring at each locus with probability (mutate rate), and place the resulting chromosome in the new population.
   d. Replace the current population with the new population.
4. Go to step 2.

G. *Experiment Methodology*

To perform this experiment the simulation work was undertaken on MATLAB Sim Power System [2010a]. For this, first load flow analysis of the non-linear system was performed. Then this non-linear system was linearized about a stable operating point without using power system stabilizer. After this, the linearized differential algebraic equation (DAE) model of the power system was developed. Using the PST software on MATLAB platform, Eigen value analysis of the DAE was done to find out the poorly damped inter-area oscillations by observing the value of frequency and damping ratio, by which the critical mode of oscillation was obtained. For this identified mode, most stabilizing control signal and control location sites were obtained using the geometric approach of joint controllability/ observability with the PST. By using selected signals and control location site, a 'wide area damping controller (WADC) was developed by considering the signal delay based on the Integral of Time Error (ITE) criterion and optimized by Genetic Algorithm for the gain of LPSS and WPSS. By this inter-area oscillations was damped out more effectively. The Figure 3 shows the flow diagram of doing this experiments.

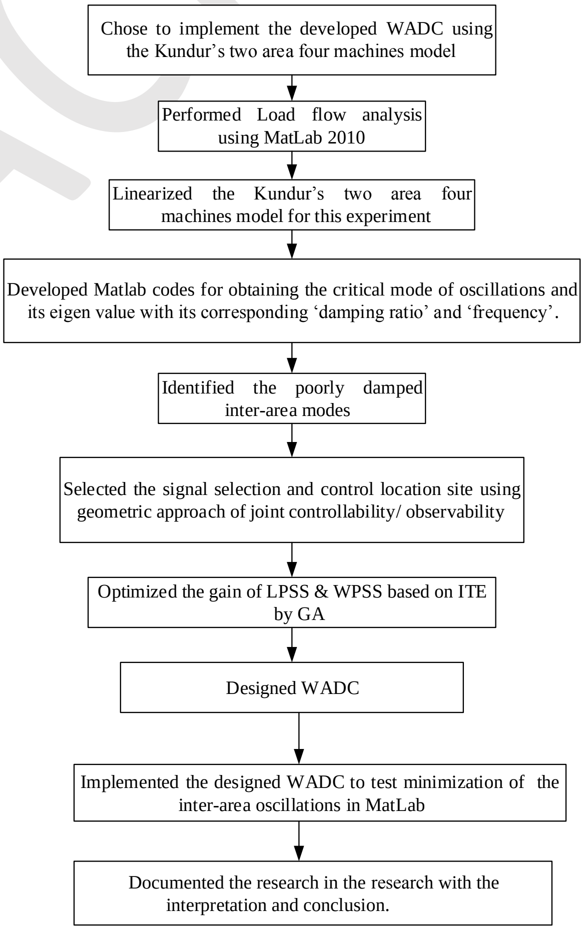

Figure 3: Flow chart of signal selection for lead lag based damping controller

IJDACR
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International Journal Of Digital Application & Contemporary Research
International Journal of Digital Application & Contemporary Research
Website: www.ijdacr.com (Volume 8, Issue 11, June 2020)

III. SIMULATION RESULTS

For the modelling of power system; MATLAB 2010 Sim Power System environment is chosen. Linearization of power system model have been done by Power System Toolbox (PST), data sheet which is used in PST is prepared in MATLAB. To perform the non-linear time domain simulation MATLAB Control System Toolbox has been used. The Simulink library has been used to develop the complete model of Kundur's proposed test system. In the test system all the generators are equipped with governor, AVR, and IEEE ST1A type static exciter. The loads taken here are constant impendence type and connected to bus no. 4 and 14. The structure of the case study power system is given in Figure 4.

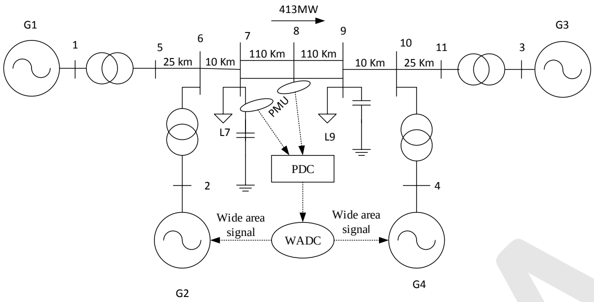
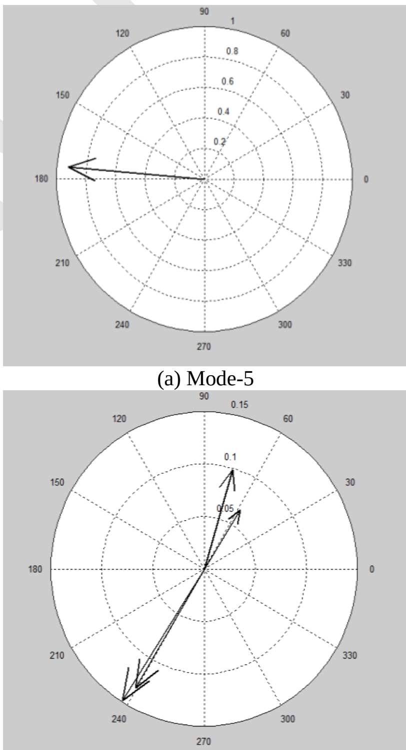


Figure 4: Kundur's two-area four-machine system

Table 1: Inter area mode of oscillation of two-area four-machine system

Mode No.	Eigen Value	Damping Ratio	Frequency (Hz)
1.	0	1	0
2.	-0.2	1	0
3.	-0.2	1	0
4.	-0.2	1	0
5.	-0.25-0.65i	0.36	0.1
6.	-0.25+0.65i	0.36	0.1
7.	-1.58	1	0
8.	-1.91	1	0
9.	-1.93	1	0
10.	-1.94	1	0
11.	-3.45	1	0
12.	-3.51	1	0
13.	-3.59 - 0.04i	1	0.01
14.	-3.59 + 0.04i	1	0.01
15.	0.05 - 4.1i	-0.01	0.65
16.	0.05+ 4.1 i	-0.01	0.65
17.	-0.54 - 7.38i	0.072	1.17
18.	-0.54 + 7.38i	0.072	1.17
19.	-0.53 - 7.58i	0.07	1.21
20.	-0.53 + 7.58i	0.07	1.21
21.	-10.06	1	0
22.	-10.06	1	0
23.	-10.10	1	0
24.	-10.11	1	1
25.	-8.2 - 9.49i	0.65	1.51
26.	-8.2 + 9.49i	0.65	1.51
27.	-8.12 - 9.68i	0.64	1.54
28.	-8.12 + 9.68i	0.64	1.54
29.	-5.66 - 14.81i	0.36	2.36
30.	-5.66 + 14.81i	0.36	2.36
31.	-4.45 - 16.63i	0.26	2.65
32.	-4.45 +16.63i	0.26	2.65
33.	-30.46	1	0
34.	-31.22	1	0
35.	-36.2 - 0.02i	1	0
36.	-36.2 + 0.02i	1	0
37.	-41.54 - 0.02i	1	0
38.	-41.54 + 0.02i	1	1
39.	-41.91	1	0
40.	-42.01	1	0
41.	-100.60	1	0
42.	-100.62	1	0
43.	-101.01	1	0
44.	-101.18	1	0



(a) Mode-5

(b) Mode-15

Figure 5: Compass plots for Coherent Group Identification for Mode-5 and Mode-15

The compass plot of rotor angle state of mode-5 and mode-15 is obtained from participation factor analysis and shown in Figure 5. For mode-5, figure 5 (a) shows a single arrow, but actually there are four arrows of representing four generators with the same magnitude and direction superimposed one over the other, so they form only one area. For mode -15,

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International Journal Of Digital Application & Contemporary Research

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Figure 5 (b) Gen-1 and Gen-2 form area-1 and Gen-3 and Gen-4 form area-2 and they are oscillating with respect to each other. So, mode -15 is considered for further analysis of feedback signal selection and control device location.

Table 2: Geometric Measure of Controllability/ Observability Approach for Signal Selection for Mode-15 (0.05±4.1i)

Signals	Generators			
	G-1	G-2	G-3	G-4
P_{7-6}	0.2726	0.3588	0.2890	0.3871
P_{7-8}	0.7042	0.9269	0.7466	1
P_{5-6}	0.1314	0.1730	0.1394	0.1867
P_{3-11}	0.1878	0.2473	0.1991	0.2667
P_{4-10}	0.1397	0.1839	0.1481	0.1984
P_{9-8}	0.6988	0.9198	0.7409	0.9923
P_{9-10}	0.3629	0.4777	0.3847	0.5153
P_{11-10}	0.1878	0.2473	0.1991	0.2667
$\boldsymbol{\omega_1}$	0.0046	0.0060	0.0049	0.0065
$\boldsymbol{\omega_2}$	0.0031	0.0040	0.0033	0.0044
$\boldsymbol{\omega_3}$	0.0069	0.0091	0.0073	0.0098
$\boldsymbol{\omega_4}$	0.0061	0.0081	0.0065	0.0087
$\boldsymbol{\theta_7}$	0.3454	0.4565	0.3677	0.4925
$\boldsymbol{\theta_9}$	0.4684	0.6166	0.4966	0.6652
$\boldsymbol{\theta_8}$	0.1255	0.1653	0.1331	0.1783

The results obtained in Table 2 is summarized in Table 4

Table 3: Summary of Signal Selection

Method	Selected Signal	Control Location
Geometric controllability/Observability	Real power of line connecting bus 7 to 8	Generator 2 & 4

Table 4: Different parameters for PSS without any delay

Parameters	K_{WADC}	T_W (s)	T_1(s)	T_2(s)	T_3(s)	T_4(s)	Limits
LPSS (G-2, G-4)	11	10	50 e-3	20 e-3	3	5.4	-0.15(Lower), 0.15(Upper)
GPSS (G-2, G-4)	0.1	10	0.1	0.02	0.05	0.01	-0.15(Lower) , 0.15(Upper)

Now, considering different condition for signal delay and optimized value of gain tabulated in Table 5. Rest of the parameter of LPSS and WPSS as follows at different condition of signal delay tabulated in Table 6.

Table 5: Gain of PSS at different conditions of signal delay

Disturbance	PSS / Delay	LPSS		GPSS (gain*e-04)	
		G-2	G-4	G-2	G-4
Small	50ms	62.6976	69.1248	4.0748	3.0835
	100ms	61.3458	48.7599	3.3398	7.8815
	150ms	50.4641	58.7675	9.1003	4.8302
Large (3-phase fault)	150ms	42.9863	65.2970	4.1649	2.4596

Table 6: Different Parameters of LPSS & WPSS

Gen / PSS	G-2,G-4		
	TW(s)	T1 (s), T2 (s)	T3 (s), T4 (s)
LPSS	10	50e-03,20e-03	3,5.4
GPSS	10	0.1, 0.02	0.05,0.01

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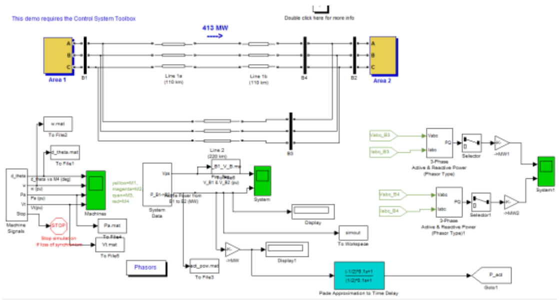

Figure 6: Simulation model for Kundur Two-Area Four-Machines System

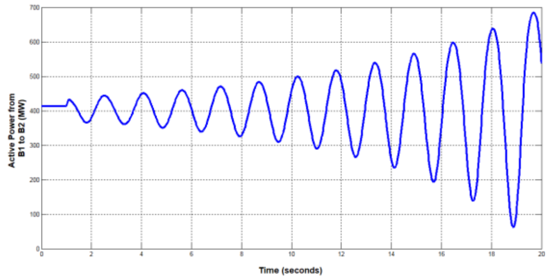

Figure 7: Tie-Line Active Power Flow without any controller

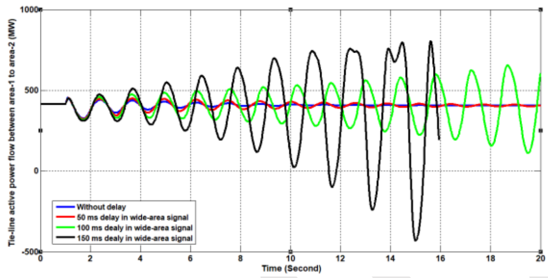

Figure 8: Tie-line active power flow for different delay

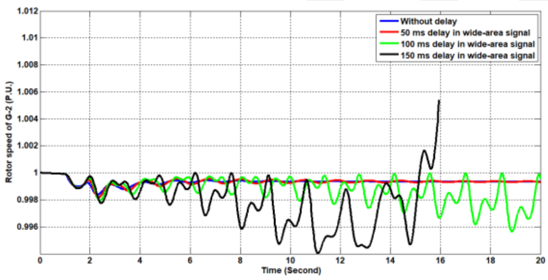

Figure 9: Rotor speed of G-2 for different delay

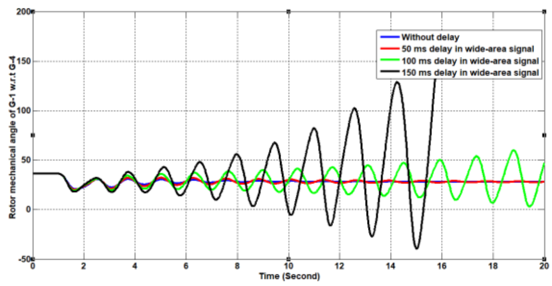

Figure 10: Rotor mechanical angle of G-1 w.r.t. G-4 (degree)

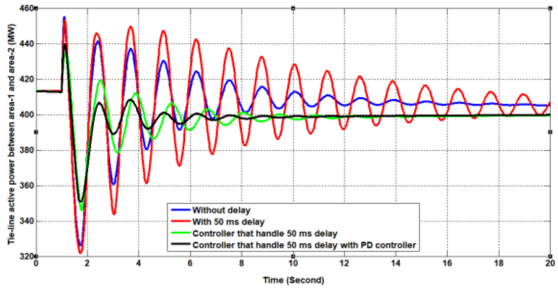

Figure 11: Tie-line active power flow

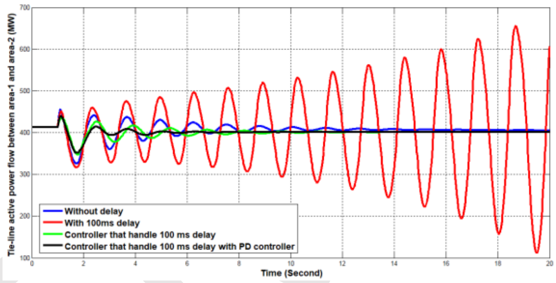

Figure 12: Tie-line active power flow

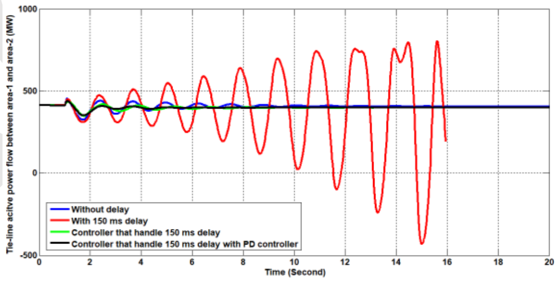

Figure 13: Tie-line power flow

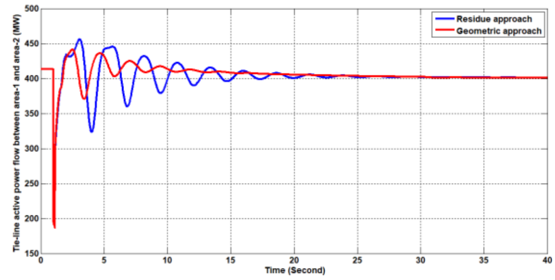

Figure 14: Tie line active power flow after 3-phase fault

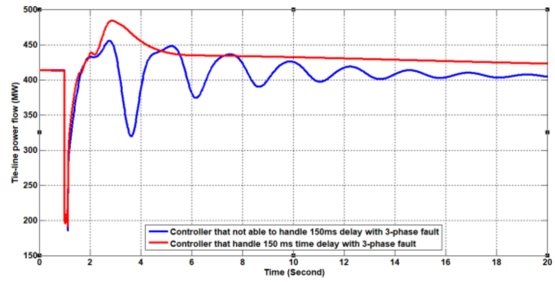

Figure 15: Tie-line active power flow under 3-phase fault

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IV. CONCLUSION

Based on the experimental simulation of the designed WADC which handle the signal delay, the results the conclusion that can be drawn based on the interpretation of the results, the following conclusion are arrived for Kundur two-area four-machines system.

Based on the objective and its implementation discussed in proposed methodology and its interpretation discussed in paragraphs of same section, it can be concluded that the proposed WADC with signal delay is effective in damping out the inter-area oscillation effectively compare to CPSS. It can be concluded that the signal selection method used for the WADC, is more effective and economical than the conventional methods; selected by geometric measure of joint controllability / observability selected as global signal and speed deviation as local signal. It was realized that mode-15 initiated the inter-area oscillations in power system after small disturbance. The comparison of the proposed design not only with CPSS, but also with a variation such as 'WADC with PD' would help to further confirm the damping out the solution as conceived by the researcher.

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