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# A New Methodology for Allocation of Stabilizers in Uncontrollable poles of Multi-Machine Power Systems

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**ABSTRACT**

One of the main problems in power systems is dynamic stability and damping of Electromechanical oscillations which for this reason power system stabilizers are being used and the method for determining the location of stabilizer for the purpose of damping critical modes, is using participation factors, in which controllability and observability of modes have influence. The real value or the amplitude of participation factor is usually used as evaluation criterion, while in case that the real values of participation factors are close, the imaginary part of these coefficients are also influential, and if the imaginary part of coefficients are either negative or positive, different results will be obtained. The method introduced in this paper, in modes that the value of participation factors are close to each other, priority for the placement of generator, installation of stabilizer and the optimum value for the stabilizer's gain, is very accurate and appropriate.



## 1. INTRODUCTION

These days by increasing growth of industries, need to electric energy has became a necessary issue in developed countries and for this reason optimum use of generators and transmission lines is an important issue and the importance of dynamic stability of power systems might be seen from the number of publications in this area. The results presented in this study indicate that nearly50 percent of papers concerning to power systems, is about dynamic stability [1].The Komsan Used the stabilizers, and displaced a poles according to a genetic algorithm method in a 16 machines power system and examined the degree of improvement in the stability of the above mentioned system and compared these two cases [2].

Using participation factor, E. L, Mitto, determined the place of stabilizers in a 4 machines power system and studied the behavior of this system by installing and running them in the aforementioned generators [3]. Angelo has considered a new cost function for adjustment of stabilizers, wherein stabilizer's Gain were also applied, and studied the behavior of the system [4]. By adjustment of stabilizers along with FACTS Device L. J. Cai, showed graphically in an article the path of displacement of poles and increased damping coefficients from the basic cost function. In a majority of articles that are presented for Identification of optimum site for stabilizers, real values of participation factors are used as selecting criterion. [5-9].

Method" to describe the step of research and used in the chapter "Results and Discussion" to support the analysis of the results [2]. If the manuscript was written really have high originality, which proposed a new method or algorithm, the additional chapter after the "Introduction" chapter and before the "Research Method" chapter can be added to explain briefly the theory and/or the proposed method/algorithm [4].

## 2. GENERALDESCRIPTION

### 2.1The understudied power system

The power system that is studied in this paper as a sample is 10-machines New England power system with39 bus, which its system information is available in table 2. Of course No. 1 machine is itself comprised of several machines, which constitute in area. The reason for choosing this power system is it's especially conditions about having poles with less controllability. The main problem is that uncontrollable poles in multivariable systems.

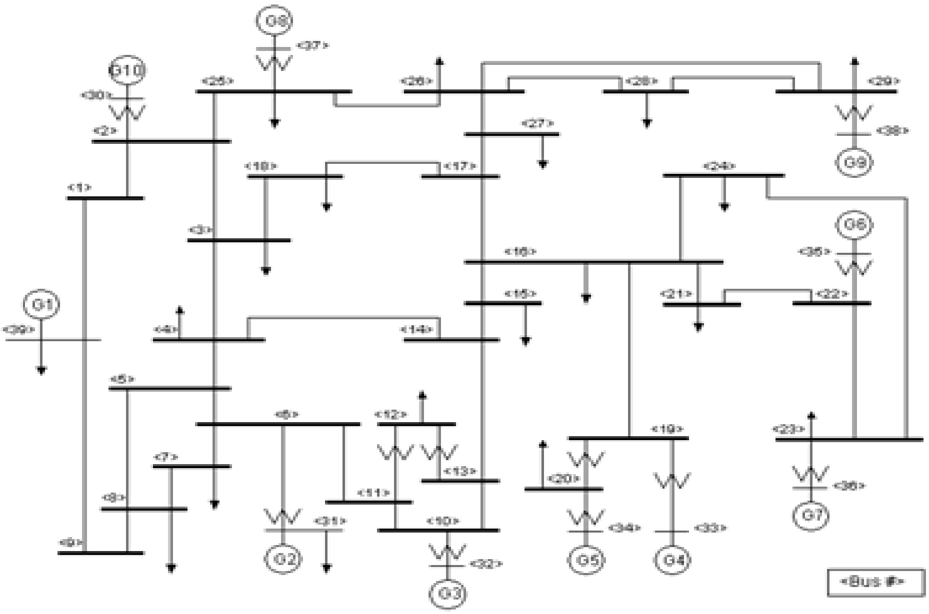



Fig. 1.single line diagram of New England network

### 2.2 Dynamic model of AVR

Generators in multi-machine power systems is considered in Fig2 and state equations governing on it are presented in below relations ( 1).

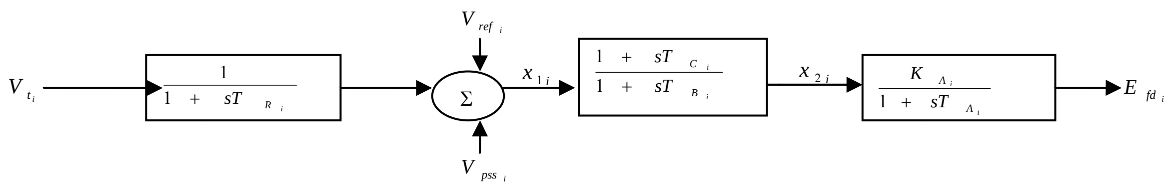



Fig. 2.simple block diagram of AVR

X represents the vector composed of variables of state equation, and i is the number of machines in the understudied power system (i=10). Assuming that the variation of variables around the operation point is small, linearized state equation might be obtained by linearization of, $f(X,U)$ equation around theoperation point. Operation point of the system $(V_i, \delta_i)$ is calculated by load flow according to Newton - Raffsoon method that used a MATLAB software. Of course voltage angle of one of the generators was taken as basis and other angles are measured with respect to it [21].

$$\frac{d\delta_i}{dt} = \omega_b(\omega_i - 1)$$
$$\frac{d\omega_i}{dt} = \frac{1}{M_i}[T_{m_i} - T_{e_i} - D_i(\omega_i - 1)]$$
$$\frac{dE'_{q_i}}{dt} = \frac{1}{T'_{d0_i}}[E_{fd_i} - (x_{d_i} - x'_{d_i})i_{d_i} - E'_{q_i}]$$
$$\frac{dE'_{d_i}}{dt} = \frac{1}{T'_{q0_i}}[-E'_{d_i} + (x_{q_i} - x'_{q_i})i_{q_i}]$$
$$\frac{dx_{1i}}{dt} = \frac{-x_{1i}}{T_{R_i}} + \frac{V_{t_i}}{T_{R_i}}$$
$$\frac{dx_{2i}}{dt} = \frac{-x_{2i}}{T_{C_i}} + (\frac{T_{B_i}}{T_{C_i} \times T_{R_i}} - \frac{1}{T_{C_i}})x_{1i} + \frac{T_{B_i}}{T_{C_i}} \times \frac{dV_{PSS_i}}{dt} + \frac{1}{T_{C_i}}(V_{ref_i} + V_{PSS_i} - \frac{T_{B_i}}{T_{C_i}}V_{t_i})$$
$$\frac{dE_{fid_i}}{dt} = \frac{-1}{T_{A_i}}E_{fid_i} + \frac{K_{A_i}}{T_{A_i}}x_{2i}$$
$$V_{t_i} = (V_{d_i}^{\ 2} + V_{q_i}^{\ 2})^{\frac{1}{2}}$$
$$V_{d_i} = x_{q_i}i_{q_i}$$
$$V_{q_i} = E'_{q_i} - x'_{d_i}i_{d_i}$$
$$i_{d_i} = \sum_{j=1}^{n} Y_{ij}(E'_{d_j}\cos\delta_{ji} - E'_{q_j}\sin\delta_{ji})$$
$$i_{q_i} = \sum_{j=1}^{n} Y_{ij}(E'_{q_j}\cos\delta_{ji} - E'_{d_j}\sin\delta_{ji})$$
$$T_{e_i} = i_{q_i}E'_{q_i} + i_{q_i}(x_{q_i} - x'_{d_i})i_{d_i}$$
$$X = [\delta_i \quad \omega_i \quad E'_{q_i} \quad E'_{d_i} \quad x_{1i} \quad x_{2i} \quad E_{fd_i}]^T$$
$$U = [V_{PSS_i} \quad V_{ref_i}]$$
$$\frac{dX}{dt} = f(X, U) \tag{1}$$

$$\frac{d\Delta X}{dt} = A\Delta X - B\Delta u$$
$$\Delta X = \left[\Delta\delta_i \quad \Delta\omega_i \quad \Delta E'_{q_i} \quad \Delta E'_{d_i} \quad \Delta x_{1i} \quad \Delta x_{2_i} \quad \Delta E_{fid_i}\right]^T$$
$$\Delta u = \left[\Delta V_{PSS_i} \quad \Delta V_{t_i}\right]^T$$
$$\Delta V_{t_i} = f\left(\Delta\delta_i \quad \Delta E'_{q_i}\right)$$
$$\frac{d\Delta X}{dt}_{(7i\times1)} = [A_C]_{(7i\times7i)}\Delta X_{(7i\times1)}$$
$$\Delta V_{PSS_i} = 0 \tag{2}$$

The value of participation factors are obtained from left and right eigenvectors of [ $A_c$ ] matrix, which are given by relation (3) and are shown as a curve in Fig 3.

$$\Phi = [\phi_1 \quad \phi_2 \quad \dots \quad \phi_n \ ]$$
$$\Psi = [\psi_1 \quad \psi_2 \quad \dots \quad \psi_n]^T \tag{3}$$
$$P_{ij} = \phi_{ij} \times \psi_{ij}$$

The degree of interaction between stabilizers in a multi-machine power system was always placed in the focus of attention of researchers, who most of them consider participation factor as an appropriate criterion in determining this interference, which is used for determining the location ofinstallation of stabilizer. Participation coefficients are complex numbers and in most of the papers their real parts are taken into computation, because variation in imaginary part of the poles is not significant after installing stabilizer, though in some papers amplitude of participation factor were also considered as a criterion [7]. But the reality is that none of these criteria are exact in case of uncontrollable pole, because in uncontrollable poles the values for participation coefficients of rotor speed and/or rotor angle in generators are very close to each other and the extent of influence that stabilizers have on damping of uncontrollable poles is very small, so that it is impossible to damp controllable pole to a standard level by using a stabilizer, but by simultaneous adjustment of stabilizers, the amount of damping will be slightly increased, while in uncontrollable poles, damping of pole might be varied in a wide range by using a stabilizer[18].

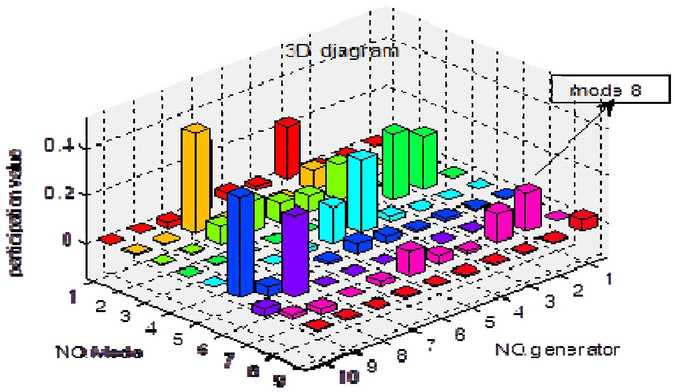


Fig. 3. Curve of participation factor for the speed of generator.

The curve of participation coefficients of rotor speed in generators of the understudied system is shown in Fig. 3. This graph shows the extent to which each generator participates in the stability of electromechanical oscillations of other generators. Uncontrollable modes might be determined as well by using this curve. In facts, having modes that the value of participation factor of one mode in several generators are small and close to each other, indicate that this mode has low controllability. As we can see in Fig. 3, No. 3 and 8 local modes are modes with low controllability and according to the method presented in this paper which is a very accurate method, the appropriate location of stabilizing which has the greatest influence on uncontrollable poles, might be determined. Choosing the appropriate place for installing PSS's and simultaneously their optimum adjustment will be possible using this method.[10],[11],[12],[13],[14].

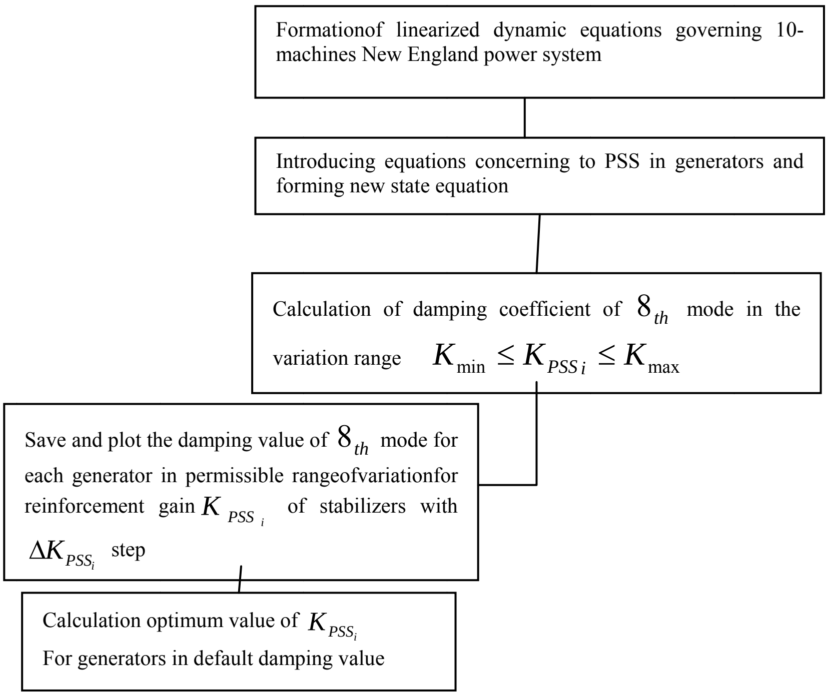


Fig 4. Flowchart of Algorithm for allocation of stabilizers

According to the algorithm presented in Fig. 4, general state equation of relations (5) will be obtained using stabilizer equations which are presented in relations( 4) and dynamic equations became linearized around the operation point by MATLAB software.

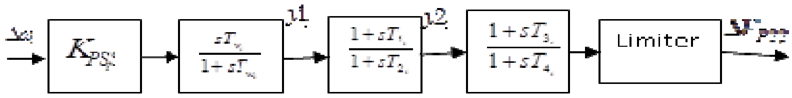



Fig. 5. block diagram of power system stabilizer.

$$\frac{dy_{1i}}{dt} = \frac{-1}{T_{W_i}} y_{1i} + K_{PSS_i} \frac{d\Delta_{\omega_i}}{dt}$$
$$\frac{dy_{2i}}{dt} = (\frac{1}{T_{2_i}} - \frac{T_{1_i}}{T_{2_i} T_{W_i}}) y_{1i} - \frac{1}{T_{2_i}} y_{2i} + \frac{T_{1_i}}{T_{2_i}} K_{PSS_i} \frac{d\Delta_{\omega_i}}{dt}$$
$$\frac{dV_{PSS_i}}{dt} = (\frac{T_{3_i}}{T_{2_i} T_{4_i}} - \frac{T_{1_i} T_{3_i}}{T_{2_i} T_{4_i} T_{W_i}}) y_{1i} + (\frac{1}{T_{4_i}} - \frac{T_{3_i}}{T_{2_i} T_{4_i}}) y_{2i} - \frac{1}{T_{4_i}} V_{PSS_i} + \frac{T_{1_i} T_{3_i}}{T_{2_i} T_{4_i}} K_{PSS_i} \frac{d\Delta_{\omega_i}}{dt}$$
$$i = 1,\ldots,m_p \qquad (4)$$
$$\Delta\widetilde{X}_{(7i+3j)\times 1} = \left[\Delta\delta_i \quad \Delta\omega_i \quad \Delta E'_{q_i} \quad \Delta E'_{d_i} \quad \Delta x_{1i} \quad \Delta x_{2_i} \quad \Delta E_{fid_i} \; y_{1j} \quad y_{2_j} \quad \Delta V_{PSS_j}\right]^T$$

$$\left[\widetilde{A}_C\right]_{(7i+3j)\times(7i+3j)} = \begin{bmatrix} [A_C]_{(7i\times 7i)} & [P_1]_{(7i\times 3j)} \\ [A_p]_{(3j\times 7i)} & [P_2]_{(3j\times 3j)} \end{bmatrix}$$
$$i = 1,\ldots, n$$
$$j = 1,\ldots, m_p$$
$$\alpha_i = \frac{1+\sin\theta_i}{1-\sin\theta_i} \qquad (5)$$
$$T_{1_i} = T_{3_i} = T_{2_i}\alpha_i = T_{4_i}\alpha_i$$
$$T_{2_i} = T_{4_i} = \frac{1}{\omega_{n_i}\sqrt{\alpha_i}}$$
$$K_{pss_i} = \frac{2\zeta_{ci}\omega_{n_i} M_i}{K_{2_{ii}} |G_{c_i}||G_{e_i}|}$$

Matrices [$A_C$] and [$P_1$] and [$A_P$ ] and [$P_2$] are obtained by substituting relations 4 in relations 2. Modified state equation of $\left[\widetilde{A}_C\right]$ are also presented in relations 5, in which ΔX stands for the vector of state variable, $\omega_{n_i}$ angular velocity of electromechanical mode, $K_{PSS_i}$ the gain of stabilizer, $M_i$ inertia of generator, $G_{c_i}$ transfer function of stabilizer, $G_{e_i}$ transfer function of torque toreference voltage input of generator and the stabilizer parameters are obtained by calculating $\theta_i$, phase difference between electric torque and reference voltage, which damping coefficients of poles might be obtained by adjusting default damping coefficient. Table (2) shows the values of stabilizer's parameters which is calculated according to the default damping coefficient $\xi_{c_i} = 0.15$ ,of course reciprocal influence of stabilizers and limitation in controllability of poles cause that the value of damping for poles will not be equal to the default value, so identification of uncontrollable poles and coordinated adjustment of stabilizers in these poles has considerable importance. Using the method presented in this paper, the first step is to identify uncontrollable poles and the next step is to adjust coordinately those stabilizers that have influence in that pole. The value of damping in $m_{th}$ pole might be obtained by changing the gain of $j_{th}$ stabilizer $K_{PSS_i}$ the $\xi_{m_j}$ is the damping of $m_{th}$ pole as a result of $j_{th}$ stabilizer [15],[16],[17].

$$\zeta_{m_j} = \frac{-\sigma_{m_j}}{\sqrt{\sigma_{m_j}^{\ 2} + \omega_{m_j}^{\ 2}}} \qquad (6)$$

In the above relations $m_p$,is the number of stabilizer existing in the power system and j is the generator in which the stabilizer is installed, so it is possible to obtain damping of a given electromechanical mode in every given generator, by installing stabilizer and changing the coefficient of the stabilizer's gain, and illustrate it as a curve of damping versus gain of stabilizer.

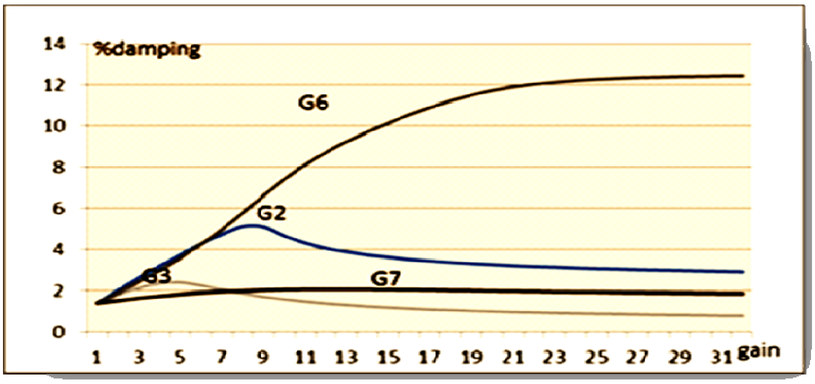



Fig. 5. The Damping curve of stabilizer's on electromechanical mode.

Using computer simulation of flowchart given in Fig. 4 and employing MATLAB programing software, damping curve of poles versus gain of stabilizers having influence on that mode will be obtained. For instance, damping of $8_{th}$ mode of electromechanical modes will be studied, which is a pole with low controllability. Fig 5 shows the curve of damping of $8_{th}$ mode versus gain of stabilizer for$G_7$,$G_6$,$G_2$ and $G_3$ generators. According to Our criterion, we can see $6_{th}$generator, creates the greatest damping in $8_{th}$ mode( $\xi_{\max} = .122$ ), while according to criterion the real values of participation factor, appropriate generator, for installing is for $8_{th}$ mode of generator $G_2$. As the results of simulation indicate, participation factor method is erroneous in such cases. The importance of the method employed in this paper is compensation of the weak points of participation factor method in determining the location forinstalling stabilizer for uncontrollable poles, which in case of the understudied New England power system, mode $8_{th}$ is a pole with low controllability, but in case of poles that are absolutely controllable, the criterion of participation factor with the method presented in this paper is the same for allocation of stabilizers [19],[20].

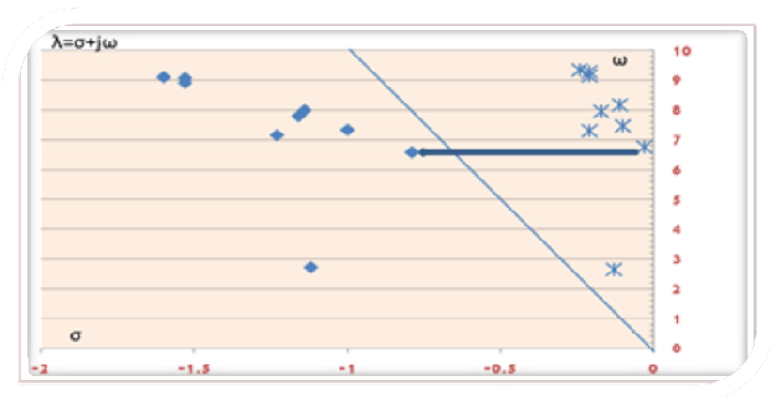



Fig 6. Graph showing the displacement of local modes ( location of local modes before install of stabilizers* after install).

Time response of variation in generators velocity as a result of small variation in electric torque is presented in appendix 2. Electromechanical oscillations of all generators are calculated with respect to generator 2($G_2$) as we can see, in the most of the generators, oscillations of speed have been damped in less than 7 seconds using coordination of stabilizers. Electromechanical oscillations are inter-area oscillations that are between the region of equivalent generator and other generators.

## 3. CONCLUSIONS

One of the very important results that obtained from analyzing damping curve of uncontrollable poles in this paper is that it is possible to define a new cost function for adjustment of stabilizers in multi-machine power systems, which is proportional to the square of stabilizer's gain [4]. Upon taking a look to the curve obtained from computer simulation (MATLAB programming), damping function of poles versus the gain of stabilizers, indicates that this relation is inherently non-linear. If the operation point of stabilizer is located in a roughly linear part of damping curve of the stabilizer, it can be approximated with a linear function, and local modes damping proportional with PSS's gain but in uncontrollable poles, operation point of the stabilizer is the peak of the above curve and damping curve of the stabilizer might not assumed to be linear. Hence we need a target function that could indicate the non-linear relation between damping coefficient of modes and gain of the system stabilizers, which might be considered as a subject for new researches, and identifying the uncontrollable poles and the manner of controlling them in multi-machine power systems is of fundamental importance and coordinated adjustment of stabilizers is also difficult in such poles. Studying damping curves shows that in case of uncontrollable poles participation factor method is not accurate in selecting the appropriate location for installing stabilizers, and other criteria have to be introduced by researchers.

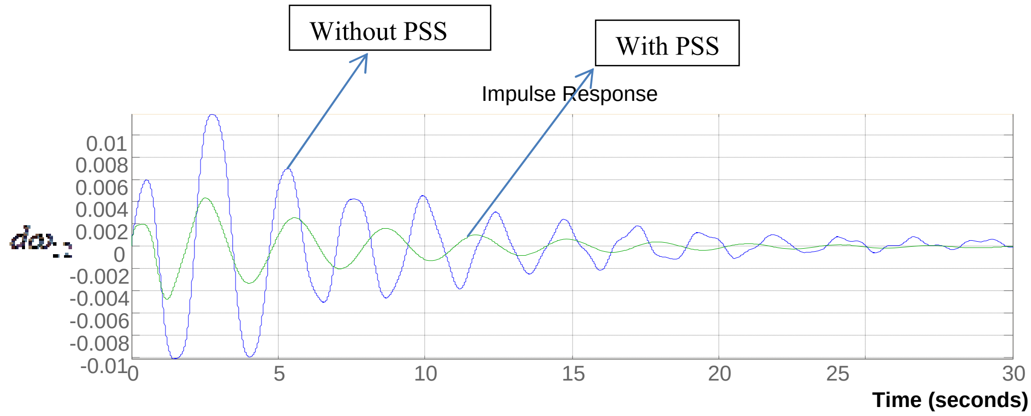
Table 1. Generator specifications and system stimulation

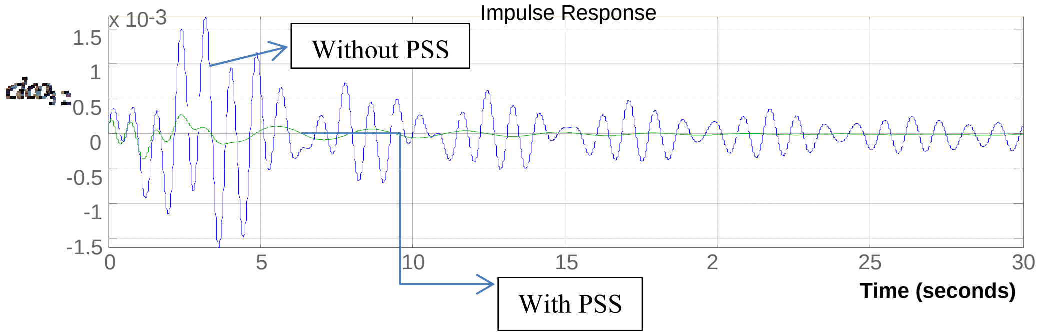
| $G_i$ | $T'_{d0}$ | $T'_{q0}$ | $T_A$ | $K_A$ | $T_b$ | $T_C$ | $T_r$ | $T_W$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 7 | 0.70 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 2 | 6.56 | 1.50 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 3 | 5.70 | 1.50 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 4 | 5.69 | 1.50 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 5 | 5.40 | 0.44 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 6 | 7.30 | 0.40 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 7 | 5.66 | 1.50 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 8 | 6.70 | 0.41 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 9 | 4.79 | 1.96 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |
| 10 | 10.2 | 0.10 | 0.015 | 100 | 10 | 1 | 0.01 | 10 |

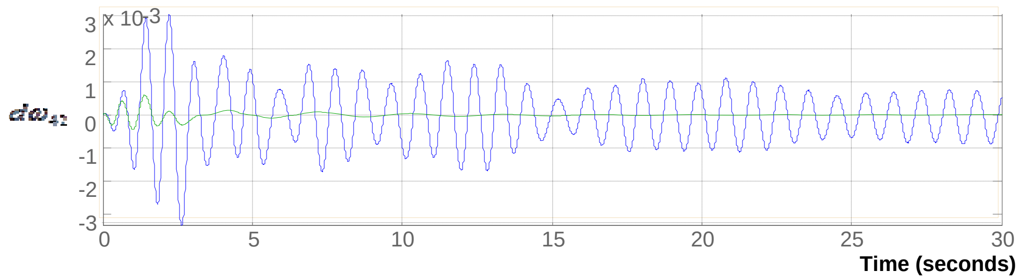
Table 2. Parameters of power system stabilizers

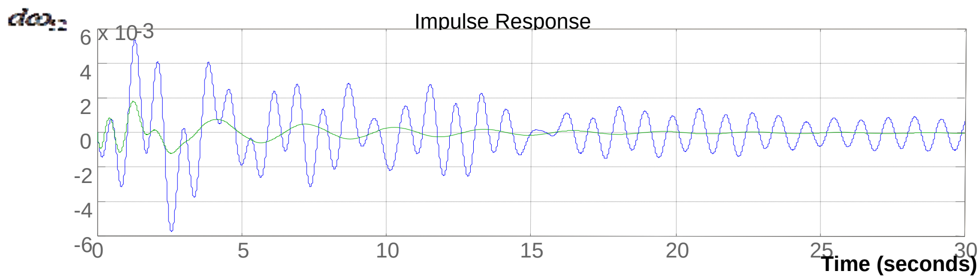
| Generator NO. | $K_{PSS_i}$ | $T_{1_i} = T_{3_i}$ | $T_{2_i} = T_{4_i}$ | $\alpha_i$ |
|---|---|---|---|---|
| $G_1$ | - | - | - | - |
| $G_2$ | 11.55 | 0.370 | 0.0517 | 7.17 |
| $G_3$ | 10.09 | 0.356 | 0.0521 | 6.83 |
| $G_4$ | 8.47 | 0.302 | 0.0428 | 7.07 |
| $G_5$ | 12.41 | 0.341 | 0.0493 | 6.92 |
| $G_6$ | 12.04 | 0.362 | 0.0500 | 7.24 |
| $G_7$ | 9.27 | 0.303 | 0.0430 | 7.04 |
| $G_8$ | 9.39 | 0.306 | 0.0411 | 7.44 |
| $G_9$ | 6.80 | 0.357 | 0.0539 | 6.62 |
| $G_{10}$ | 27.63 | 0.442 | 0.0586 | 7.55 |

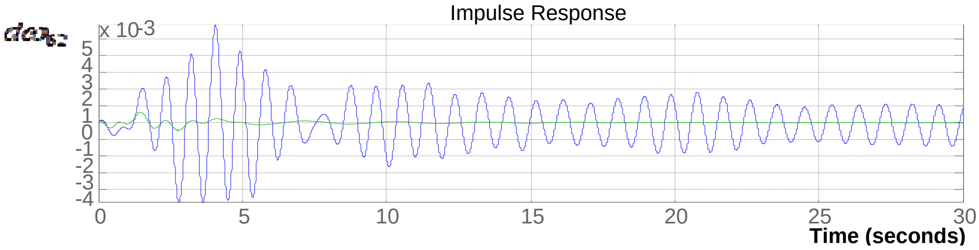
**Appendix.1**

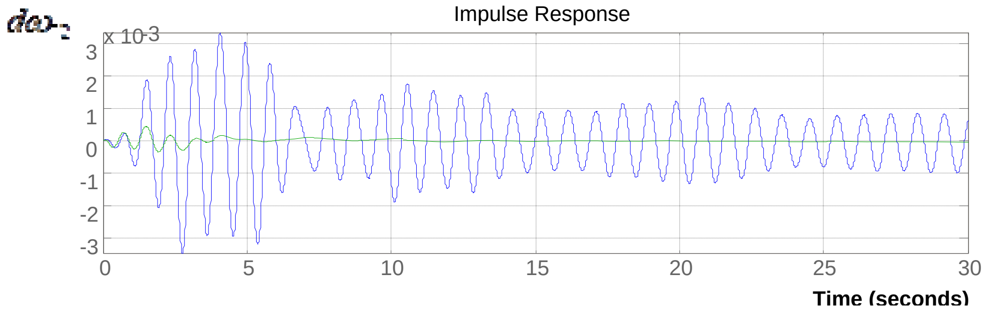

Without PSS
With PSS
Impulse Response
Time (seconds)

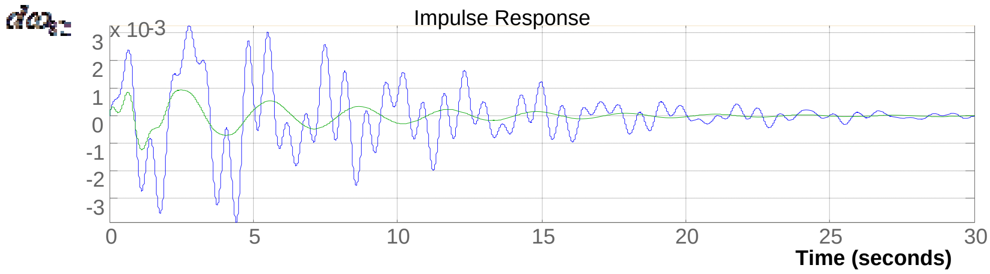

Impulse Response
x 10-3
Without PSS
With PSS
Time (seconds)

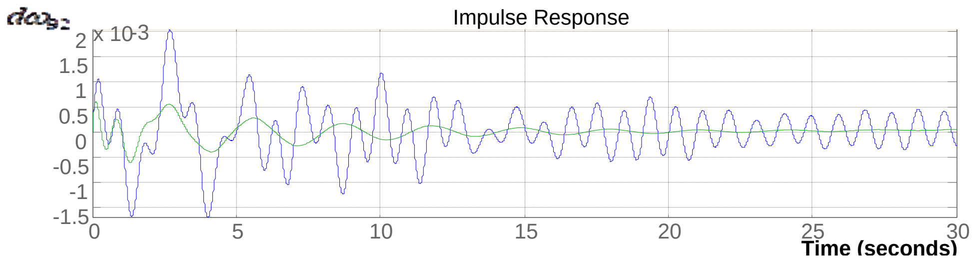

x 10-3
Time (seconds)

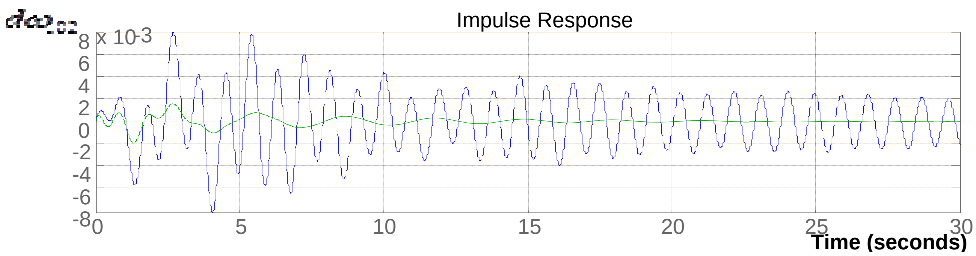

Impulse Response
x 10-3
Time (seconds)


Impulse Response
x 10-3
Time (seconds)

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