Design of UPFC-PSS using Firefly Algorithm for Stability Improvement of Multi Machine System under Contingency

M. Ravindrababu[1*], G. Saraswathi[2], K.R. Sudha[3]
1- Department of EEE, UCEK, JNTUK, Kakinada, Andhra Pradesh, India.
Email: raviravi1983@gmail.com (Corresponding author)
2- Department of EEE, UCEV, JNTUK,Vizianagaram, Andhra Pradesh, India.
Email: bksaraswathi@gmail.com
3- Department of EE, AUCE, Andhra Uniersity, Andhra Pradesh, India.
Email: arsudhaa@gmail.com

Received: September 2018 Revised: November 2018 Accepted: January 2019

ABSTRACT:
The multi machine power system, with the interconnection of number of generators and loads, has the dynamic stability as the important factor for maintaining the step with respect to the generators connected to it. The stability of individual machine, as well as, the stability of a generator with the other generators are more important terms. The supply of the damping torque required for getting the desired condition of stability enhancement is done by the power system stabilizer. In this paper a new method is proposed for stability enhancement of a three machine nine bus system by using the coordinated application of the unified power flow controller and the power system stabilizer designed by using the Firefly algorithm. The improved stability performance of the tested multi machine system was compared with Genetic search algorithm approach without and with the application of the unified power flow controller. From the pseudo spectrum analysis, it is observed that the better improvement of the stability of the multi machine system is achieved by using the proposed method. From the step responses it can be deduced that the relative variations of inter machine states with unified power flow controller and firefly-based power system stabilizer are settled at a faster rate. The contingency analysis is performed to consider the non-linearity problem. The responses of the system with unified power flow controller and firefly based power system stabilizer are settled at a faster rate in the normal case, as well as, in the contingency cases, respectively.

KEYWORDS: Power System Stabilizer (PSS), Firefly Algorithm (FFY), Genetic Algorithm (GA), Unified Power Flow Controller (UPFC), Pseudo Spectrum Analysis, Contingency.

1. INTRODUCTION

In general, the power system is operating with number of generators and number of loads interconnected and it makes the system as complex system. The operation of the system with more stability is the important factor that must be concentrated. The compensating equipment design will ensure the enhancement of stability of the system. To design the multi machine system with more effective and economical, it is advisable to design the compensating devices like power system stabilizers which will provide the compensating signal. The PSS is designed by the optimization techniques [1-4].

By using the regulators which will regulate the voltage and high-speed excitation systems with better ceiling voltage, the stability may be improved. The regulators and fast excitation systems will not supply the damping torque which is able to ensure the stability improvement [5, 6]. In some operating conditions the stable system will operate with negative damping characteristics. These voltage regulators will improve the performance by supplying the negative damping but it may lead to result the instability of the multi machine system [7]. The FACT devices may also be located for power flow problems [8].

At the time of low-frequency variations, the current induced in the damper windings is less hence the effect of damper windings is negligible. The direct axis and quadrature axis armature windings of the alternators can be explained by the algebraic equations. The field winding circuit of the machine is explained by the differential equations [9-11].

The considered multi machine power system contains the nonlinearity with the number of generators plants and also different types of machines like hydro, thermal plants [12-15]. The operation of various types of plants with different operating conditions will make the multi machine inter connected system as the nonlinear system with continuously varying operating conditions. The design and application of PSS by using various search algorithms will give the stable responses [16], [17].

The required supplementary stabilizing signals for stability enhancement are supplied by using the power system stabilizer to the multi machine system. It is ensuring the regulation of the damping torque for settling down the variations of the alternators [18-20] and also the relative variations which is very much essential to maintain the step between the interconnected machines. The power system stabilizer with a lead/lag compensator, stabilizer gain using the speed and/or accelerating power as input signal to give the supplementary stabilizing signals as output may be designed and applied. The parameters of the power system stabilizer were searched or designed by using different methods.

The search algorithms like GA, ANT colony, PSO, fuzzy logic approaches etc are used for the PSS parameter design. In this paper, the genetic algorithm and firefly algorithms are compared to ensure the stability of a multi machine power system. The firefly search algorithm is used to tune the PSS parameters which gives the more enhanced stability when compared to the genetic algorithm approach. Since the considered interconnected hydro thermal multi machine system is the replica of the nonlinear system operating with various operating conditions, the designed PSS must ensure the improvement in the stability of individual and also the inter machine stability [21-23].

The dynamic stability is the important factor to be maintained within the acceptable range and also must be enhanced under typical faulty conditions [24], [25]. The practical power system will face the problem of low frequency oscillations frequently and the voltage instability will be caused by swinging rotor of the alternator and the problems of contingencies in the interconnected power system [26], [27]. The contingency analysis is used to estimate the effect of abnormal conditions, like line outages, failure of important equipment and the over loading conditions. The outage of lines will cause more severe problems in the power system.

The contingency analysis is done by calculating the maximum loading parameters of all possible location of the tested system. One line is identified and the analysis is done with the outage of that line. It is very much necessary for a rugged and stable system to maintain the enhanced stability even with the problem of line outage [28]. The increased stability of power system by damping out the low frequency dynamics and by controlling the variations in voltage and real and reactive power flows in multi machine system without contingencies is proposed in this article. A new methodology is proposed to determine parameters in the power system stabilizer by using the design and application of firefly algorithm-based stabilizer.

With the problem of line removal, the system will face more stability problem and also the regeneration and the redistribution of the power must be done in an effective manner. The unified power flow controller is designed by using the firefly algorithm and it is located in the optimal location by using the severity index. It is observed that after removal of a line between the two buses, the healthy and stable system will face the power flow and stability problems. The stability maintenance is disturbed and the power flows in the system also gets disturbed. The two important factors of regeneration and redistribution of the power flows is compensated by using the FACT device with the combined features of shunt and series compensator known as the unified power flow controller (UPFC). In this article in addition to the design and application of the PSS, the coordinated design and application of UPFC and PSS is proposed and the results are compared. From the results the better responses are observed with UPFC-PSS when compared to the mere application of PSS.

The pseudo spectrum analysis is done from the obtained Eigen values. By using the proposed methodology, the responses and the Eigen values with and without contingency cases, it is obtained that the proposed UPFC-PSS ensures the improved stability of the multi machine system for normal and contingency cases.

2. MODELING OF THE TESTED SYSTEM

The three machine nine bus system which contains the synchronous operation of two thermal and one hydro generator is considered for the analysis of stability.

The single line diagram of the tested system is shown in Fig. 1. The block diagram model with an exciter for 'i' number of machines is shown in Fig. 2.

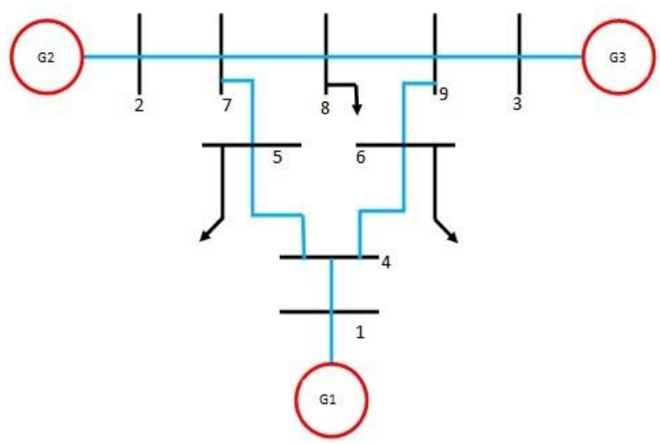

Fig. 1. Line Diagram of multi machine system.

To get the state space modeling by using the 'K' constant approach [6] the step wise procedure is mentioned below:

1. Form the Y-Bus matrix.
2. Calculate the load flow results by using the Newton Rapson method.
3. Derive the initial conditions of the machines from the load flow results and the reduced Y-bus matrix.
4. Find the 'K' constant matrices from the initial conditions.

Table 1. Machine Data of three machine system.

Parameters	Machine 1 (Hydro)	Machine 2 (Thermal)	Machine 3 (Thermal)
H(secs)	23.64	6.4	3.01
X_d (pu)	0.146	0.8958	1.3125
$X_d^{\prime}$(pu)	0.0608	0.1198	0.1813
X_q(pu)	0.0969	0.8645	1.2578
$X_q^{\prime}$(pu)	0.0969	0.1969	0.25
$T_{do}^{\prime}$(pu)	8.96	6.0	5.89
$T_{qo}^{\prime}$(pu)	0.31	0.535	0.6

s

By following the steps mentioned in section. 2, the 'K' constant matrices from 'K_1 to K_6' are obtained as:

$$K_1 = \begin{bmatrix} -1.2666 & 0.7526 & 0.5141 \\ 0.2109 & 1.3991 & -1.6100 \\ 0.2876 & -1.4817 & 1.1941 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 0.4924 & 2.2572 & 1.8379 \\ -2.2952 & 5.0584 & -1.8453 \\ -2.0490 & -1.4591 & 4.2565 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} 0.8030 & -27.4920 & -10.7108 \\ -0.8432 & 0.1981 & -0.4568 \\ -0.4345 & -0.3444 & 0.1465 \end{bmatrix}$$

$$K_4 = \begin{bmatrix} 0.2662 & -0.1243 & -0.1419 \\ 1.3513 & 0.1238 & -1.4750 \\ 1.4986 & -2.3899 & 0.8913 \end{bmatrix}$$

$$K_5 = \begin{bmatrix} -0.1972 & 0.0930 & 0.1042 \\ -0.5166 & 0.4888 & 0.0278 \\ -0.5711 & 0.1981 & 0.3730 \end{bmatrix}$$

$$K_6 = \begin{bmatrix} 0.8219 & 0.0388 & 0.0771 \\ -0.3665 & 0.4287 & 0.2527 \\ -0.2426 & 0.4781 & 0.1843 \end{bmatrix}$$

The state space equations are written from the block diagram shown in Fig. 2 and written in the following form and it results the state matrix 'A_m'

$$\dot{x}_m = A_m x_m + B_m u \tag{1}$$

The state vector matrix 'x_m' contains the states of three generators interconnected system as $\Delta\omega_i, \Delta\delta_i, \Delta e_q{}'_i, \Delta e_{FD\,i}$ of each generator where $i=1, 2,3$.

$$\Delta\omega_i = \frac{1}{M_i s + D_i}(\Delta T_{mi} - \Delta T_{ei}) \tag{2}$$

$$\Delta\delta_i = \frac{2\pi f}{s}\Delta\omega_i \tag{3}$$

$$\Delta E_{qi}^{'} = \left[\frac{K_{3ii}}{1+sT_{d0}^{'}}\right]\left[-K_{4ii}\Delta\delta_i - K_{4ij}\Delta\delta_j - \left[\frac{1}{K_{3ij}}\right]\Delta E_{qj} + \Delta e_{FDi}^{'}\right] \tag{4}$$

$$\Delta e_{FDi} = \frac{-K_A}{1+sT_A}\left(\Delta V_i - U_i\right) \tag{5}$$

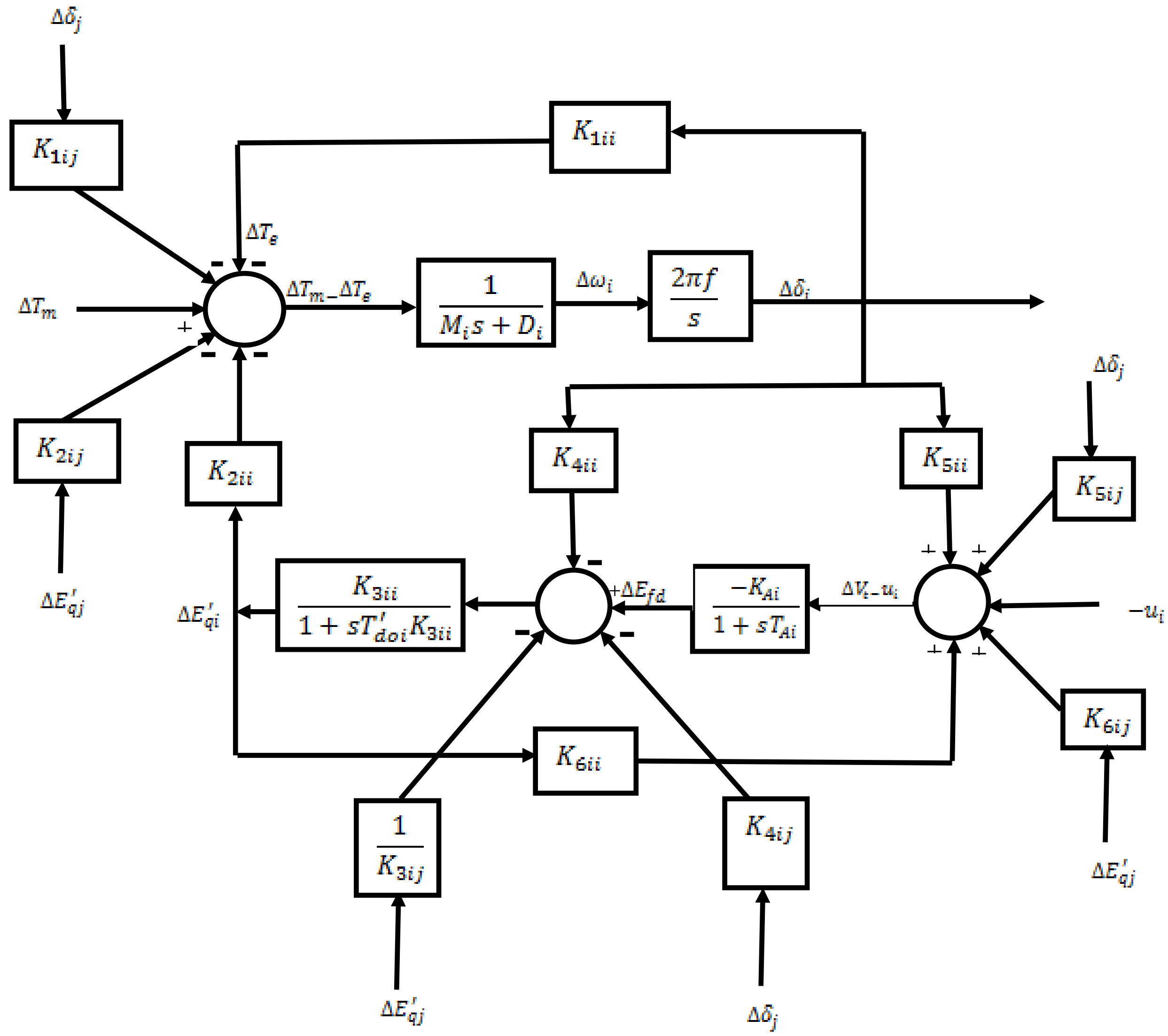

Fig. 2. Generalized block diagram of multi machine system.

By using the 'K_1 to K_6' matrices and the state equations derived from the block diagram of the tested three machine system, the system matrix 'A_m' and the control matrix 'B_m' are derived.

The system matrix 'A_m' without PSS is obtained as

$$A_m = \begin{bmatrix} -0.1 & 10.1039 & -3.9278 & 0 & 0 & -6.0032 & -18.006 & 0 & 0 & -4.1007 & -14.6609 & 0 \\ 376.99 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.027 & -0.139 & 0.1116 & 0 & 0.0139 & 0.0041 & 0 & 0 & 0.0158 & 0.104 & 0 \\ 0 & 19.7200 & -82.1896 & -5.0000 & 0 & -9.2991 & -3.8782 & 0 & 0 & 10.4209 & -7.7082 & 0 \\ 0 & -6.2109 & 67.5995 & 0 & -0.2000 & -41.2080 & -148.9830 & 0 & 0 & 47.4189 & 54.3475 & 0 \\ 0 & 0 & 0 & 0 & 376.9911 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.2252 & 0.1977 & 0 & 0 & -0.0206 & -0.8412 & 0.1667 & 0 & 0.2458 & 0.3648 & 0 \\ 0 & 51.6607 & 36.6495 & 0 & 0 & -48.8803 & -42.8705 & -5.0 & 0 & -2.7804 & -25.2671 & 0 \\ 0 & -18.0134 & 128.3141 & 0 & 0 & 92.7887 & 91.3763 & 0 & -3 & 74.7753 & 266.5539 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 376.9911 & 0 & 0 & 0 \\ 0 & -0.2544 & 0.3908 & 0 & 0 & 0.4058 & 0.4929 & 0 & 0 & -0.1513 & -1.1590 & 0.1698 \\ 0 & 57.1118 & 24.2596 & 0 & 0 & -19.8080 & -47.8053 & 0 & 0 & -37.3038 & -18.4267 & -5.000 \end{bmatrix}$$

$$B_m = \begin{bmatrix} 0 & 0 & 0 & 100 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 \end{bmatrix}^T$$

From the state matrix 'A_m' it is observed that the Eigen values of this open loop system are located in the unstable region. Hence the need of the supplementary stabilizing signal is known to be essential.

3. POWER SYSTEM STABILIZER

To improve the stability of the unstable system, the power system stabilizer has to be designed. The PSS is designed and applied to the three machines. The equation of the PSS with the parameters is written in the following equation. The stable Eigen values of the tested system are obtained by tuning the PSS parameters using the genetic search algorithm and firefly algorithms. To formulate the problem, the objective function is designed to get the stable Eigen values by minimizing it [5].

$$J = \max \operatorname{Re}(\lambda_{(k,i)});\ k = 1,2,3......., N; i = 1,2,3,......., N \tag{6}$$

The size of the state matrix 'A_m' is increased from $12X12$ to $15X15$ with the inclusion of the stabilizer. The equation of the stabilizer is written as:

$$G_{pi}(s) = \frac{K_{si}(1+sT_{1i})}{(1+sT_{2i})} \tag{7}$$

The new state equation with the power system stabilizer is written as

$$\dot{x}_{mp} = A_k x_{mp} + B_{mp} u \tag{8}$$

The unknown parameters of the PSS are designed by using Firefly algorithm and the genetic Algorithm approach [2]. For tuning the PSS parameters, Genetic search algorithm approach the population size and is selected as 200 and the desired stable system was obtained for 1000 number of generations. For the firefly search algorithm approach the stabilizer, parameters are obtained for 200 number of generations and the population size is 50. The analysis of stability of the multi machine system for the cases like without any controller, with stabilizer is done and the Eigen values are tabulated.

4. GENETIC SEARCH ALGORITHM

The genetic algorithm approach is used in this article to tune the PSS parameters which ensure the improved stability. A set of parameters are to be searched is selected called as population and is a set of chromosomes. The initial population is applied through the genetic operators for the successive generation of new population. Only the fittest organisms are used for the reproduction. The global optimum result is obtained by minimizing the objective function and also by following the constraints until the convergence point is obtained. In this process, the genetic operators like reproduction, crossover and mutation are used to get the next set of PSS parameters.

5. STEPS OF FIRE FLY ALGORITHM:

The flash signal of the firefly is the signal and it attracts the neighboring fireflies. The communication of attraction between the fireflies depends on the brightness of the individual fireflies. The firefly having the more brightness attracts the firefly with less brightness. The optimization problem is formulated by starting from the local optimized solution with various starting points. The objective function is designed in such a way that it has to find the brightness of the firefly. The solution for the iterative process of the mathematical optimization problem with the constraints will give the best parameters of the power system stabilizer. These obtained parameters are resulting the stable Eigen poles for the multi machine system. The procedure of firefly algorithm is mentioned in the form of flow chart shown in the Fig.3.

Table 2. Designed controller (PSS) parameters.

GA PSS	K_{S1}=-0.93358	T_{11}=-88.54158	T_{12}=0.00026
	K_{S2}=163.3920	T_{12}=0.0076950	T_{22}=1126.62
	K_{S3}=193.8942	T_{13}=-0.008603	T_{23}=2298.87
FFY PSS	K_{S1}=-0.9353	T_{11}=-88.50	T_{12}=0.00029
	K_{S2}=163.3316	T_{12}=0.00716	T_{22}=1126.32
	K_{S3}=193.1943	T_{13}=-0.00875	T_{23}=2298.07

From the Table.3 it is observed that the Eigen values without any controller are having the positive real part and with the PSS, all the Eigen values are obtained as stable values having the negative real parts.

From the obtained Eigen values, the pseudo spectrum [27] is drawn for the cases of without PSS and with the GA and FFY PSS.

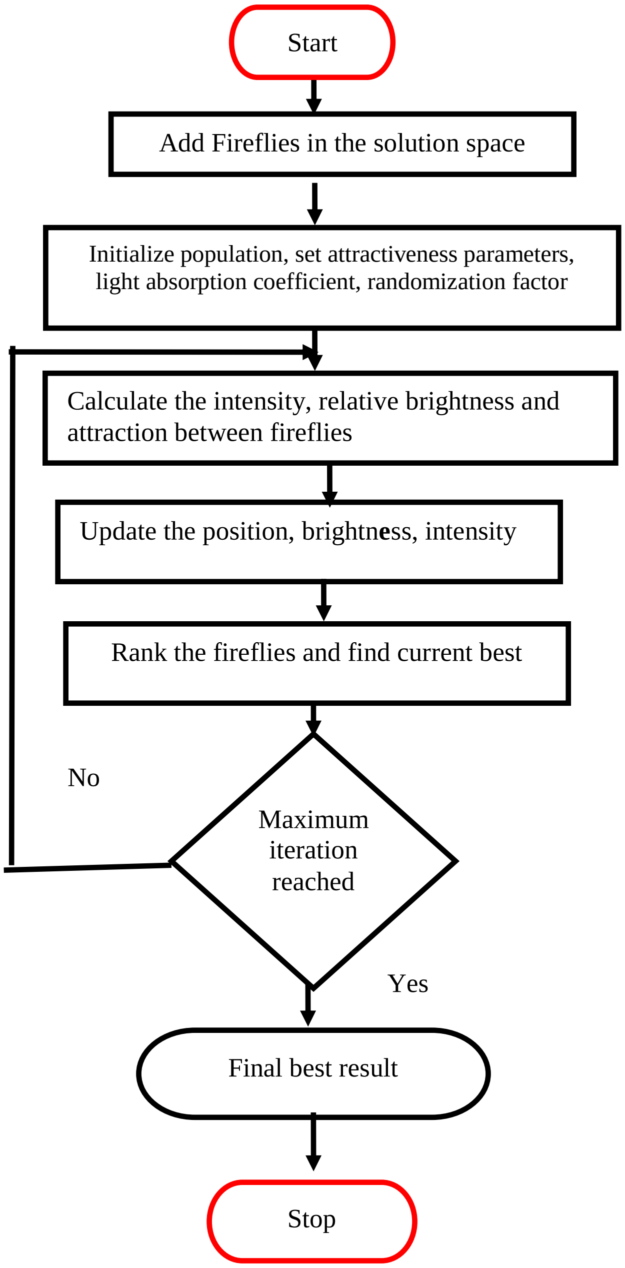

Fig. 3. Firefly search Algorithm flowchart.

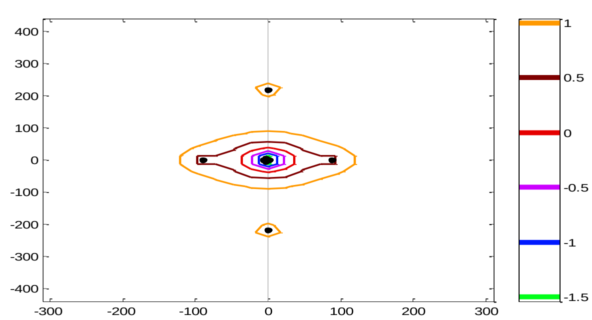

Fig. 4. The pseudo spectrum representation without controller.

Table 3. Eigen values for the test system without and with PSS.

Without any controller	With GA PSS	With FFY PSS
-0.0060 + 2.1836i	-3.3778 + 0.0002i	-3.7223 + 0.0005i
-0.0060 – 2.1836i	-0.0002 + 0.0043i	-0.0019 + 0.0043i
0.8769 + 0.0003i	-0.0002 – 0.0043i	-0.0019 – 0.0043i
-0.8879 + 0.0003i	-0.0011 + 0.0041i	-0.0021 + 0.0042i
-0.0240 + 0.0566i	-0.0011 – 0.0041i	-0.0021 – 0.0042i
-0.0240 – 0.0566i	-0.0003 + 0.0021i	-0.0007 + 0.0021i
-0.0700 + 0.0011i	-0.0003 – 0.0021i	-0.0007 – 0.0021i
-0.0253 + 0.0244i	-0.0005 + 0.0001i	-0.0060 + 0.0001i
-0.0253 – 0.0244i	-0.0005 – 0.0001i	-0.0060 – 0.0001i
0.0148 + 0.0005i	-0.0002 + 0.0001i	-0.0021 + 0.0001i
0.0012 + 0.0007i	-0.0002 – 0.0001i	-0.0021 – 0.0001i
-0.0008 + 0.0000i	-0.0006 + 0.0002i	-0.0008 + 0.0004i
-----	-0.0006 – 0.0002i	-0.0008 – 0.0004i
-----	-0.0031 + 0.00001i	-0.0017 + 0.0003i
-----	-0.0031 + 0.00001i	-0.0017 – 0.00003i

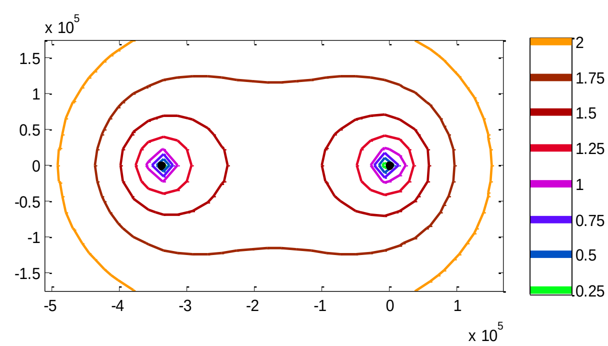

Fig. 5. The pseudo spectrum representation with GA based stabilizer.

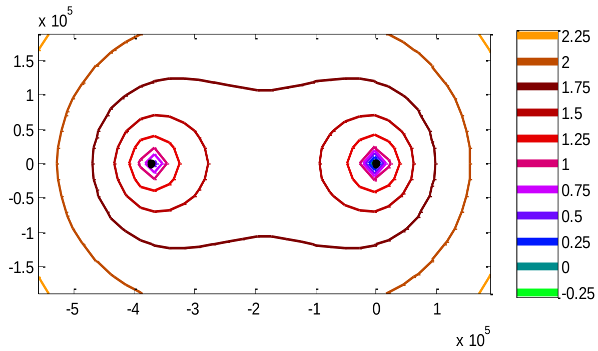

Fig. 6. The pseudo spectrum representation with Firefly based stabilizer.

From pseudo spectrum analysis as shown in Fig. 4 to Fig. 6 by using the PSS with the proposed method is giving the Eigen values on to the more stable side of the complex plane.

For checking the inter machine stability, the variations in the speed deviations between the set of machines 1-2; 2-3 and 1-3 are plotted. In case of the variations in the speed, the machines are settled at zero position as fast as possible, it is clear that the interconnected system will retain in Step under the disturbances also.

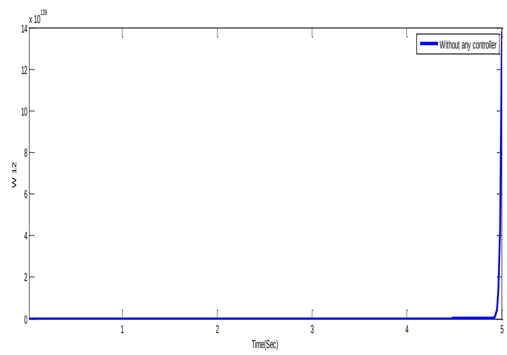

Fig. 7. Response of ω_{12} without controller.

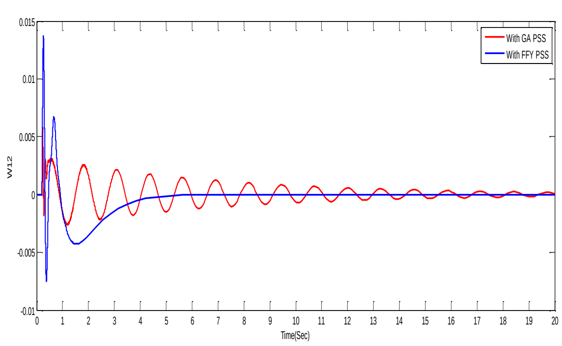

Fig. 8. Response of ω_{12} with GA PSS and FFY PSS.

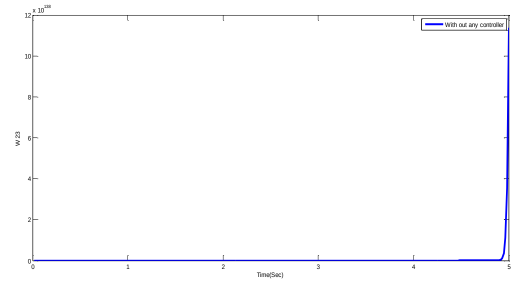

Fig. 9. Response of ω_{23} without controller.

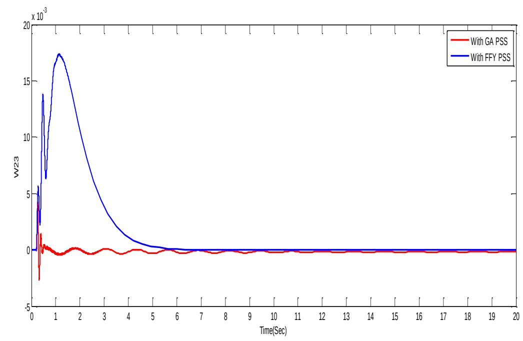

Fig. 10. Response of ω_{23} with GA PSS and FFY PSS.

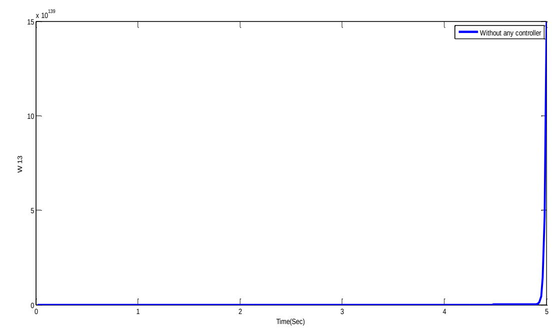

Fig. 11. Response of ω_{13} without controller.

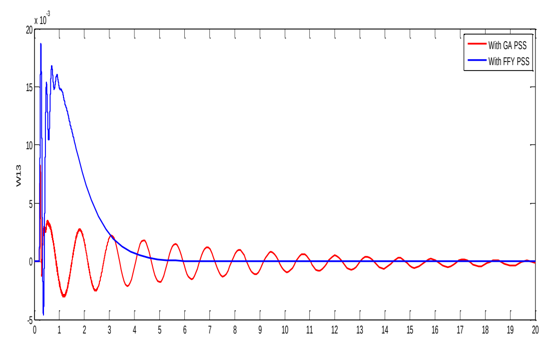

Fig. 12. Response of ω_{13} with GA PSS and FFY PSS.

Table 4. Parameters of the responses of angular velocities of Multi Machine system without and with PSS.

Angular Velocities		Without PSS	With GA PSS	With FFY PSS
ω_{12}	Settling Time (Sec)	----	20.1	4.9
	Max. Overshoot (rad)	14E28	0.004	0.014
	Max. Undershoot (rad)	----	-0.007	-0.003
ω_{23}	Settling Time (Sec)	----	8.5	5.2
	Max. Overshoot (rad)	12E100	4E-3	16E-3
	Max. Undershoot (rad)	----	-2.5	----
ω_{13}	Settling Time (Sec)	----	19.8	5.1
	Max. Overshoot (rad)	5E60	8E-3	18E-3
	Max.Undershoot (rad)	----	-3.5	-4.8

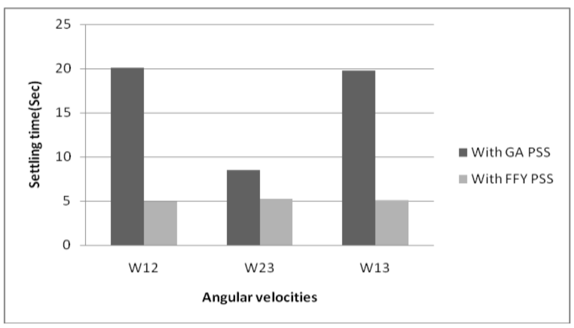

Fig. 13. Settling Times of the Responses of ω_{12}, ω_{23}, ω_{13} with GA and FFY PSS.

By observing the maximum overshoot, undershoot and the settling times of the responses in the, it is noted that the designed stabilizer is having the considerable effect on the stability improvement.

6. CONTINGENCY ANALYSIS OF MULTI MACHINE SYSTEM

The stability is getting affected due to the problem of contingencies in the interconnected power system. The need of stabilizer is evident for getting the disturbed system under contingency again in to the step with the existing system. It is proposed to design the PSS to give the stable Eigen values in the case of contingency. The tested system is analyzed with the contingency by finding the maximum loading parameters for all the possible location of the system.

From the obtained results the worst contingency case depending on the maximum loading parameter is determined and tabulated [28].

Table 5. Severity ranking for 3 machine-9bus system.

Order of severity	Line	Maximum loading parameter
1	4-5	0.8900
2	5-7	1.1086
3	7-8	1.1698
4	6-9	1.1764
5	8-9	1.4865
6	4-6	1.6617

From the above analysis, the line connected between the buses 4 and 6 is getting the maximum loading parameter. In the absence of the said line between the buses 4 and 6, the stability analysis is done as mentioned in the section.2.

From the initial conditions by following the procedure, the newly obtained 'K' constants are determined to form the new system matrix 'A_C' with contingency.

$$A_C = \begin{bmatrix} -0.1 & 2.5377 & -6.9276 & 0 & 0 & -7.3192 & -17.7978 & 0 & 0 & 4.7816 & -3.1031 & 0 \\ 376.99 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.0206 & 0.1326 & 0.1116 & 0 & 0.0108 & 0.0065 & 0 & 0 & 0.0098 & 0.004 & 0 \\ 0 & 13.3445 & -86.4456 & -5.0000 & 0 & -7.4458 & -5.4393 & 0 & 0 & -5.8988 & -2.7649 & 0 \\ 0 & -7.8896 & 55.7977 & 0 & -0.2000 & -43.7979 & -150.8301 & 0 & 0 & 51.6875 & 60.0091 & 0 \\ 0 & 0 & 0 & 0 & 376.9911 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.2183 & 0.1857 & 0 & 0 & 0.0444 & -0.8195 & 0.1667 & 0 & 0.1739 & 0.3815 & 0 \\ 0 & 45.9947 & 23.4299 & 0 & 0 & -67.2222 & -53.6905 & -5.0 & 0 & 21.2276 & -21.4971 & 0 \\ 0 & 43.8590 & 67.62 & 0 & 0 & 58.7690 & 29.0822 & 0 & -3 & -102.6279 & -189.3815 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 376.9911 & 0 & 0 & 0 \\ 0 & 0.0694 & 0.2170 & 0 & 0 & 0.3663 & 0.3758 & 0 & 0 & -0.4357 & -0.9024 & 0.1698 \\ 0 & 20.0270 & 6.5391 & 0 & 0 & -33.6717 & -59.7441 & 0 & 0 & 13.6447 & -40.1772 & -5.000 \end{bmatrix}$$

7. POWER SYSTEM STABILIZER FOR CONTINGENCY

The Eigen values under contingency case are getting on the Right side of the complex plane. Hence there is an essential need of the PSS to be observed. The new state equation with PSS is written as:

$$\dot{x}_{CP} = A_{CP}x + BC_{P}u \qquad (9)$$

The parameters of the stabilizer are tuned using the GA and FFY techniques and are tabulated.

Table 6. Designed controller (PSS) parameters under contingency condition.

GA PSS	K_{S1}=0.0555	T_{11}=0.1412	T_{12}=1.0945
	K_{S2}=-0.0371	T_{12}=-0.4331	T_{22}=37.1152
	K_{S3}=-0.0457	T_{13}=0.5725	T_{23}=2.4456
FFY PSS	K_{S1}=0.05	T_{11}=0.15	T_{12}=1.0962
	K_{S2}=-0.0371	T_{12}=-0.4684	T_{22}=37.1001
	K_{S3}=-0.0461	T_{13}=0.57684	T_{23}=2.4422

Table 7. Eigen values for the test system without and with PSS under contingency condition.

Without any controller	With GA PSS	With FFY PSS
-0.5761 + 228.0535i	-3.3204+ 227.5572i	-3.3650+ 227.5485i
-0.5761- 228.0535i	-3.3204- 227.5572i	-3.3650- 227.5485i
0.7566 + 48.5459i	-92.9312+ 0.0005i	-92.8765+ 0.0003i
0.7566 - 48.5459i	-11.6760+ 36.7777i	-12.7585 + 36.5797i
-14.2181+ 0.0007i	-11.6760- 36.7777i	-12.7585- 36.5797i
6.8388+ 0.0002i	-1.4796+ 26.4043i	-0.3946 + 27.5262i
-3.3717+ 1.7934i	-1.4796 - 26.4043i	-0.3946 - 27.5262i
-3.3717- 1.7934i	-21.5301+ 0.0008i	-21.4658+ 0.0003i
2.2823+ 0.0003i	-0.1764+ 9.35308i	-0.2498+ 8.5749i
-0.0991+ 0.0006i	-0.1764- 9.35308i	-0.2498- 8.5749i
-1.7968+ 1.7715i	-3.8672+ 0.0001i	-0.0593 + 2.4503i
-1.7968- 1.7715i	-0.1923+2.1965i	-0.0593- 2.4503i
----	-0.1923- 2.1965i	-3.8658+ 0.0001i
----	-0.1915+ 0.9235i	-0.2257+ 0.8703i
----	-0.1915- 0.9235i	-0.2257- 0.8703i

From the Eigen values, for the case of line outage as the problem of contingency the Pseudo spectrum representation is done for the case of contingency as mentioned below.

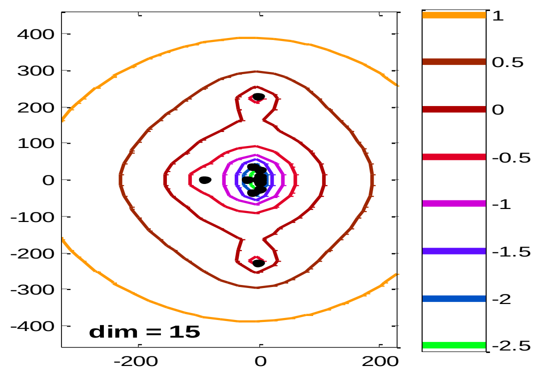

Fig. 14. The pseudo spectrum representation without any controller under contingency.

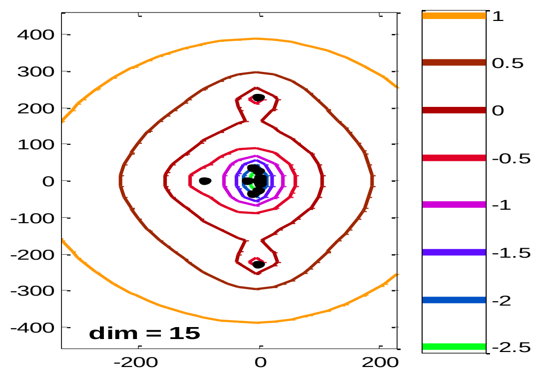

Fig. 15. The pseudo spectrum representation with GA-PSS under contingency.

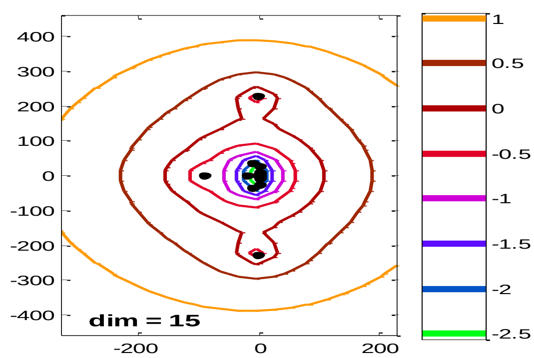

Fig. 16. The pseudo spectrum representation with FFY-PSS under contingency.

The step responses of the inter machine speed variations are plotted and the settling times are recorded.

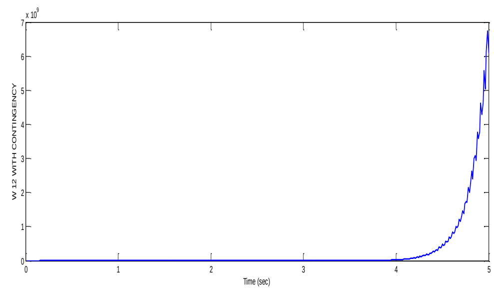

Fig. 17. Response of ω $_{12}$ with contingency and without any controller.

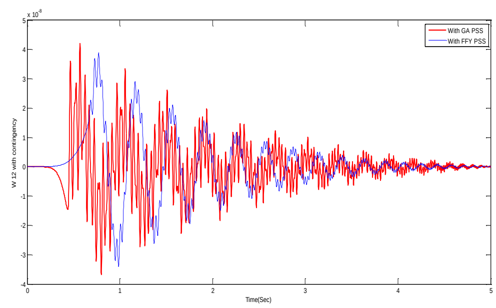

Fig. 18. Response of ω $_{12}$ with contingency and with GA, FFY PSS.

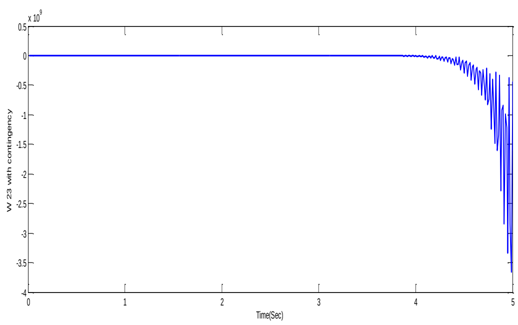

Fig. 19. Response of ω $_{23}$ with contingency and without any controller.

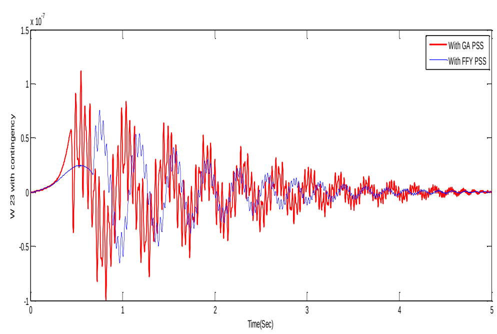

Fig. 20. Response of ω $_{23}$ with contingency and with GA, FFY PSS.

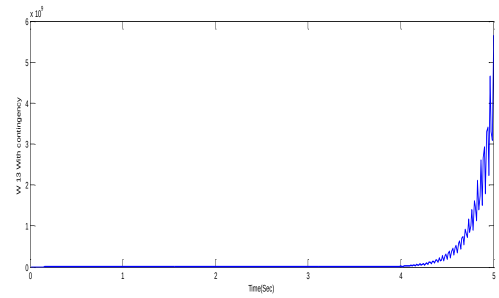

Fig. 21. Response of ω_{13} with contingency and without any controller.

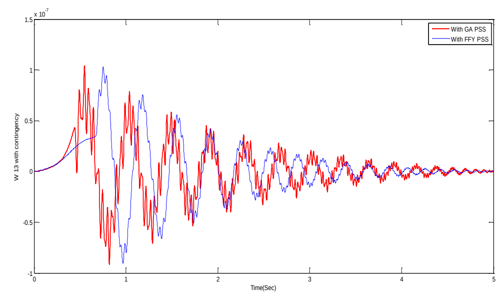

Fig. 22. Response of ω_{13} with contingency and with GA, FFY PSS.

From the responses shown above, the settling time for the various cases for comparison the effectiveness of the proposed method is determined and tabulated with the existing approach.

Table 8. Parameters of the responses of angular velocities of multi machine system without and with PSS under contingency.

Angular Velocities		With out PSS	With GA PSS	With FFY PSS
ω_{12}	Settling Time (Sec)	----	5.1	4.6
	Max. Overshoot (rad)	7E9	4.2E4	3.8E4
	Max. Undershoot (rad)	----	-3.9	-3.5
ω_{23}	Settling Time (Sec)	----	5.2	4.7
	Max. Overshoot (rad)	----	1.2E-7	0.6E-7
	Max. Undershoot (rad)	-4.0	-1	-0.6
ω_{13}	Settling Time (Sec)	----	4.9	4.1
	Max. Overshoot (rad)	6E9	1.1E-7	0.9E-7
	Max. Undershoot (rad)	----	-0.9	-0.8

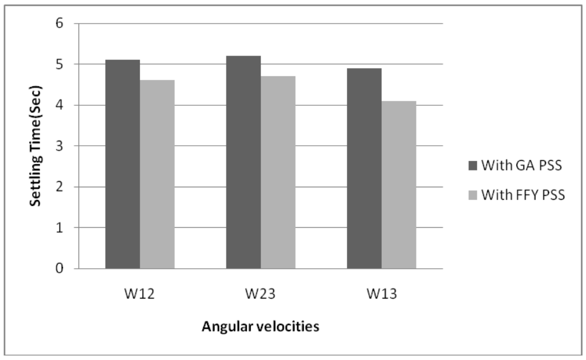

Fig. 23. Settling times of ω_{12}, ω_{23}, ω_{13} with GAPSS and FFY PSS under contingency.

From the pseudo spectrum and from the step responses, it is clear that the proposed FFY PSS is giving the more stabilized performance of the system under normal operating and also under the problem of contingency.

8. SMALL SIGNAL STABILITY AND PSEUDO SPECTRUM ANALYSIS OF MULTI MACHINE SYSTEM WITH UPFC

To regenerate and redistribute the electrical power, the unified power flow controller which is the combination of shunt and series power flow controller has to be designed and applied. The dynamic stability analysis was done by following the procedure mentioned in the section. 2 with UPFC.

In this paper to get the economic justification of using the fact device, the number of possible locations is reduced [8]. The device is located between two load buses and it is not having the shunt capacitors.
The equations for the power injection can be written as

$$P_{i,UPFC} = 0.02 r b_{se} V_i^2 \sin\gamma - 1.02 r b_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma)$$

$$P_{j,UPFC} = r b_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) \quad (11)$$

$$Q_{i,UPFC} = -r b_{se} V_i^2 \cos\gamma \quad (12)$$

$$Q_{j,UPFC} = r b_{se} V_i V_j \cos(\theta_i - \theta_j + \gamma) \quad (13)$$

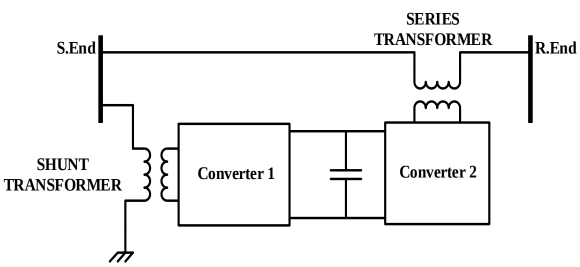

Fig. 24. Basic configuration of unified power flow controller.

The parameters of the unified power flow controller are r, γ, X_{se}, Q_{sh}. Where 'r' is the per unit magnitude and 'γ' is the phase angle of the voltage source converter connected in series. The UPFC is located by optimizing the device control parameters so as to minimize the severity function using the Firefly algorithm. The severity function proposed in the literature [8] is:

$$F_{Severity} = \sum_{i=1}^{N_{line}} \left(\frac{S_i}{S_i^{\max}} \right)^{2q} + \sum_{j=1}^{N_{line}} \left(\frac{V_{j,ref} - V_j}{V_{j,ref}} \right)^{2r} \quad (14)$$

Table 9. Severity index for all possible locations of three machine nine bus system.

Location Number	Location (From bus to bus)	Severity index with UPFC
01	4-5	58.3866
02	4-6	58.9735
03	5-7	58.1283
04	6-9	58.4060
05	7-8	59.1775
06	8-9	58.3533

From the six possible locations, the UPFC is located between the buses 5 and 7. The parameters of the UPFC are designed and tabulated.

Table 10. Parameters of the Unified power flow controller.

Xse	r	Gama	Qsh
0.0025	0.01431	72.6338	0.06007

With the placement of UPFC the system is formulated into the state space form as

$$\dot{x}_u = A_u x_u + B_u u \quad (15)$$

9. DESIGN OF POWER SYSTEM STABILIZER WITH UPFC

For the design and application of coordinated UPFC-PSS, the new state equations are added and the system is written in the state space form with increase in the size of system state matrix 'A_k' with 15x15.

$$\dot{x}_{up} = A_{up} x_{up} + B_{up} u \quad (16)$$

Table 11. Designed controller (PSS) parameters.

UPFC-GA PSS	K_{S1}=0.16901	T_{11}=-0.11628	T_{12}=0.82271
	K_{S2}=0.61061	T_{12}=0.240837	T_{22}=16.3807
	K_{S3}=-0.07762	T_{13}=1.635567	T_{23}=6.98268
UPFC-FFY PSS	K_{S1}=0.1978	T_{11}=-0.10123	T_{12}=0.85609
	K_{S2}=0.60466	T_{12}=0.21611	T_{22}=16.3992
	K_{S3}=-0.07250	T_{13}=1.6342	T_{23}=6.98453

Table 12. Eigen values for the test system without PSS, with only PSS and with UPFC-PSS.

Without any controller	With UPFC And GA PSS	With UPFC And FFY PSS
-0.0060 + 2.1836i	-1.2187 + 0.0006i	-1.1395 + 0.0007i
-0.0060 - 2.1836i	-0.0177 + 1.2784i	-0.0176 + 1.2784i
0.8769 + 0.0000i	-0.0177 - 1.2784i	-0.0176 - 1.2784i
-0.8879 + 0.0000i	-0.0248 + 0.4245i	-0.0265 + 0.4225i
-0.0240 + 0.0566i	-0.0248 - 0.4245i	-0.0265 - 0.4225i
-0.0240 - 0.0566i	-0.0015 + 0.2207i	-0.0087 + 0.2230i
-0.0700 + 0.0000i	-0.0015 - 0.2207i	-0.0087 - 0.2230i
-0.0253 + 0.0244i	-0.1132 + 0.0000i	-0.0998 + 0.0000i
-0.0253 - 0.0244i	-0.0035 + 0.0514i	-0.0008 + 0.0535i
0.0148 + 0.0000i	-0.0035 - 0.0514i	-0.0008 - 0.0535i
0.0008 + 0.0000i	-0.0027 + 0.0022i	-0.0028 + 0.0022i
-0.0008 + 0.0000i	-0.0027 - 0.0022i	-0.0028 - 0.0022i
-----	-0.0013 + 0.0022i	-0.0013 + 0.0001i
-----	-0.0013 + 0.0012i	-0.0013 + 0.0001i
-----	-0.0030 + 0.0012i	-0.0034 + 0.0005i

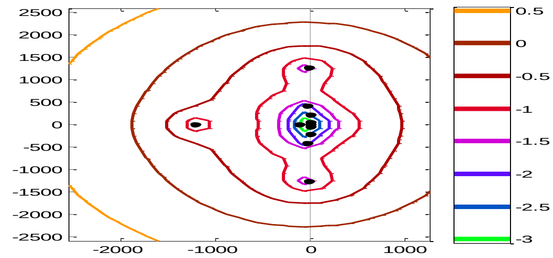

Fig. 25. The pseudo spectrum representation with UPFC-GA PSS GA.

From the observation of the Eigen values, it is evident that the proposed Firefly based UPFC-PSS is giving the more stabilized Eigen values. The pseudo spectrum analysis and the step responses are plotted for the cases with UPFC-PSS. By the application of the unified power flow controller, the power loss and the voltage deviations are calculated and tabulated.

Table 13. Comparison of voltage deviations and power loss.

Parameter	Without UPFC	With UPFC
Voltage deviation (p.u)	0.02298	0.02012
Power los(MW)	6.395044	4.641021474

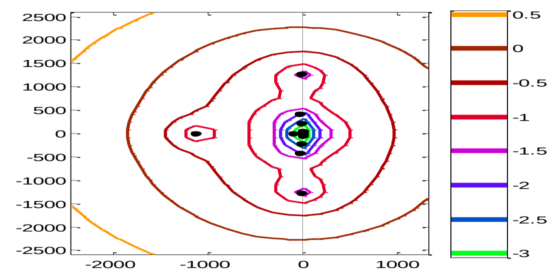

Fig. 26. The pseudo spectrum representation with UPFC-FFY PSS.

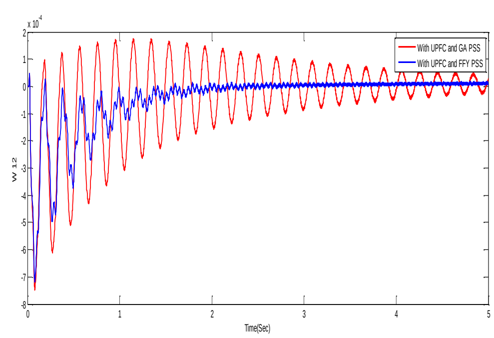

Fig. 27. Response of ω_{12} with UPFC GA PSS and UPFC FFY PSS.

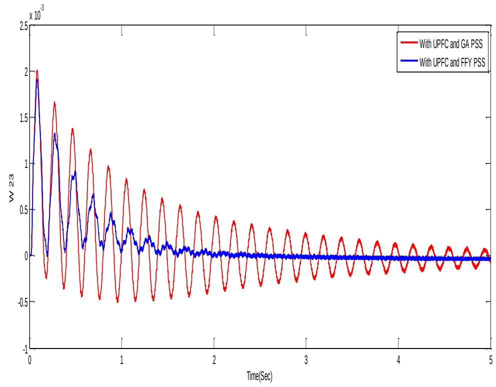

Fig. 28. Response of ω_{23} with UPFC GAPSS and UPFC FFY PSS.

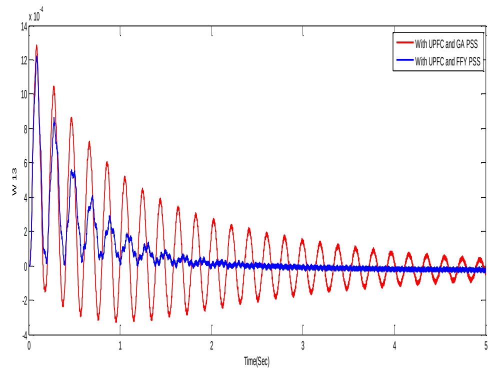

Fig. 29. Response of ω_{13} with UPFC GA PSS and UPFC FFY PSS.

Table 14. Parameters of the Responses of angular velocities of multi machine system with UPFC and PSS.

Angular Velocity		With UPFC and GA PSS	With UPFC and FFY PSS
ω_{12}	Settling Time (Sec)	5.9	2.8
	Max. Overshoot (rad)	1.8E-4	0.2E-4
	Max. Undershoot (rad)	-7.5	-7
ω_{23}	Settling Time (Sec)	5.98	1.9
	Max. Overshoot (rad)	2E-3	1.7E-3
	Max. Undershoot (rad)	-0.25	-0.01
ω_{13}	Settling Time (Sec)	5.8	2.0
	Max. Overshoot (rad)	13E-4	12E-4
	Max. Undershoot (rad)	-3.0	-0.1

It is observed that the settling times of the inter machine speed variations are getting less with the proposed UPFC-PSS designed using the Firefly approach.

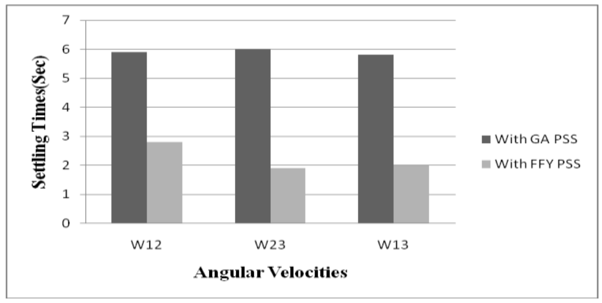

Fig. 30. Settling times of ω_{12}, ω_{23}, ω_{13} with UPFC GAPSS and UPFC FFY PSS.

10. SMALL SIGNAL STABILITY AND PSEUDO SPECTRUM ANALYSIS OF MULTI MACHINE SYSTEM WITH UPFC UNDER CONTINGENCY

With the application of the unified power flow controller, the contingency analysis is done by finding the maximum loading parameter.

Table 15. Severity ranking for 3 machine-9bus system with UPFC.

Order of severity	Line	Maximum loading parameter
1	4-5	0.7310
2	5-7	1.0963
3	7-8	1.1598
4	6-9	1.1703
5	8-9	1.4213
6	4-6	1.5592

Depending on the order of severity, it is observed that the line connected between the buses 4 and 6 is having the high loading impact in the system. Hence with the application of the unified power flow controller, also the line between 4 and 6 is creating the problem of contingency.

From the calculation of the initial conditions, the new 'K' constants are obtained to form the new system matrix 'A_Z' with application of the unified power flow controller and the problem of contingency.

By using the above 'K' constant with UPFC and contingency, the new system matrix 'A_Z' is written from the state space equations derived from the block diagram of the multi machine interconnected system. From the block diagram, the state equations are written in the form of:

$$\dot{x}_Z = A_Z x + B_Z u \qquad (17)$$

The system matrix 'A_Z' without PSS and with UPFC is obtained as

$$A_Z = \begin{bmatrix} -0.1 & -18188.57 & -7.2633 & 0 & 0 & 27257.89 & 1.6266 & 0 & 0 & -9069.31 & -0.17214 & 0 \\ 376.99 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.33693 & -0.13514 & 0.1116 & 0 & -0.9836 & 0.02430 & 0 & 0 & 0.64671 & -0.00181 & 0 \\ 0 & -215.43 & -84.9470 & -5 & 0 & 628.945 & -15.538 & 0 & 0 & -413.510 & 1.1579 & 0 \\ 0 & -730620.22 & 5291.59 & 0 & -0.2 & 5678666.15 & -8022.11 & 0 & 0 & -4948045.93 & -1288.69 & 0 \\ 0 & 0 & 0 & 0 & 376.99 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1.06799 & 0.3305 & 0 & 0 & 12.3555 & -0.57688 & 0.16666 & 0 & -11.2875 & -0.1239 & 0 \\ 0 & 98.9271 & -30.6158 & 0 & 0 & -1144.47 & -62.0017 & -5 & 0 & 1045.548 & 11.4830 & 0 \\ 0 & 676470.11 & -2022.02 & 0 & 0 & -13678385.93 & -1066.06 & 0 & -0.3 & 13001915.81 & -3766.82 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 376.99 & 0 & 0 & 0 \\ 0 & 0.1271 & -0.0365 & 0 & 0 & 11.3831 & -0..1840 & 0 & 0 & 11.2560 & -0.2691 & 0.1697 \\ 0 & -12.003 & 3.4540 & 0 & 0 & 1074.57 & 17.3767 & 0 & 0 & -1062.57 & -90.6185 & -5 \end{bmatrix}$$

The new state equation with PSS under contingency is written as:

$$\dot{x}_{ZP} = A_{ZP}\, x + B_{ZP}\, u \qquad (18)$$

Where, 'x_Z' *is the* state vector with stabilizer and u is the controlling signal.

Table 16. Designed controller (PSS) parameters under contingency with UPFC.

UPFC-GA PSS	K_{S1}=-0.0065	T_{11}=7.5877	T_{21}=20.8130
	K_{S2}=0.1369	T_{12}=0.2323	T_{22}=0.0036
	K_{S3}=0.1131	T_{13}=0.1716	T_{23}=0.0028
UPFC-FFY PSS	K_{S1}=-0.0065	T_{11}=7.58	T_{21}=20.7413
	K_{S2}=0.1353	T_{12}=0.2736	T_{22}=0.0037
	K_{S3}=0.1121	T_{13}=0.1618	T_{23}=0.0021

Table 17. Eigen values for the test system with UPFC-without PSS and with UPFC-PSS under contingency.

With UPFC & Without PSS	With UPFC & GA PSS	With UPFC & FFY PSS
83159.758 + 0.0004i	-3530129253.4+0.0012i	-4875468151.7 + 0.0001i
-83160.035 + 0.0004i	-2776278118.7+ 0.0004i	-2675429746.8 + 0.0002i
10953.784 + 0.0002i	-480391.22 + 0.0006i	-482051.89+ 0.0007i
-10954.031 + 0.0002i	-2.5540+ 205443.397i	-0.8148 + 221111.6i
-1.0299e-06 + 0.0011i	-2.5540- 205443.399i	-0.8148 - 221111.6i
-0.09344 + 0.0000i	-23.4355 + 74608.519i	-23.209 + 70946.86i
-2.5903 + 3.2946i	-23.4355- 74608.519i	-23.209 - 70946.86i
-2.5903 - 3.2946i	-2.6389 + 1657.093i	-4.1026+ 1312.54i
-2.6873 + 2.4871i	-2.6389 - 1657.093i	-4.1026 - 1312.54i
-2.6873 - 2.4871i	-4.1344 + 803.380i	-3.1879 + 1012.71i
-2.7042 + 1.4539i	-4.1344- 803.380i	-3.1879 - 1012.71i
-2.7042 - 1.4539i	-0.1862 + 0.0000i	-0.3731 + 0.0000i
----	-2.7834 + 0.0000i	-1.3584 + 0.0000i
----	-3.8052 + 93.850i	-4.5881 + 95.71i
----	-3.8052 - 93.850i	-4.5881 - 95.71i

From the obtained Eigen values, the pseudo spectrum analysis and the step response are plotted for the case of contingency with unified power flow controller.

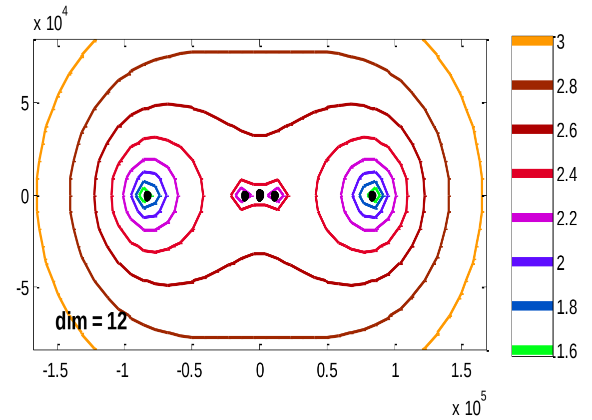

Fig. 31. The pseudo spectrum representation with UPFC and without controller under contingency.

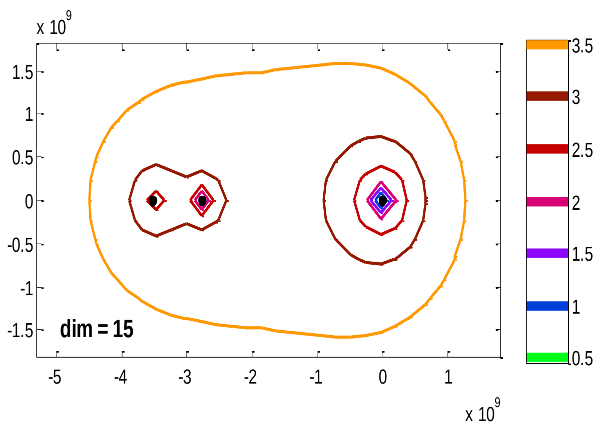

Fig. 32. The pseudo spectrum representation with UPFC and with GA based stabilizer under contingency.

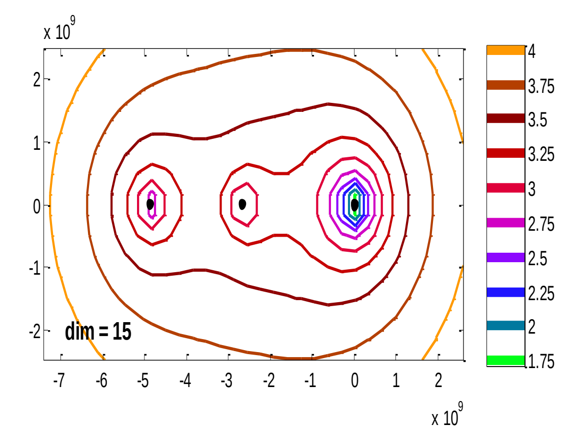

Fig. 33. The pseudo spectrum representation with UPFC and with FFY based stabilizer under contingency.

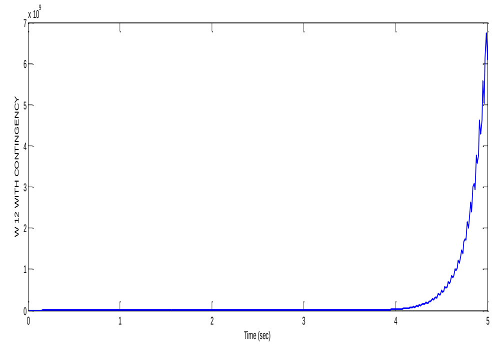

Fig. 34. Response of ω_{12} with UPF and without PSS under contingency.

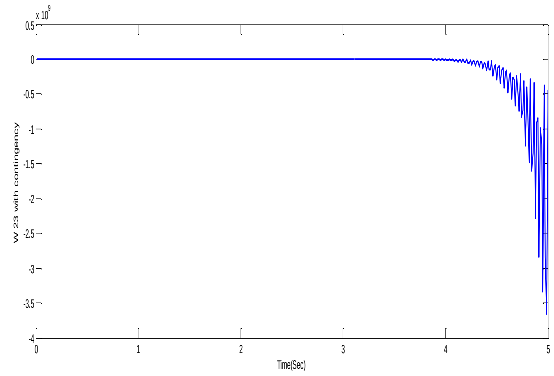

Fig. 35. Response of ω_{23} with UPFC and without PSS under contingency.

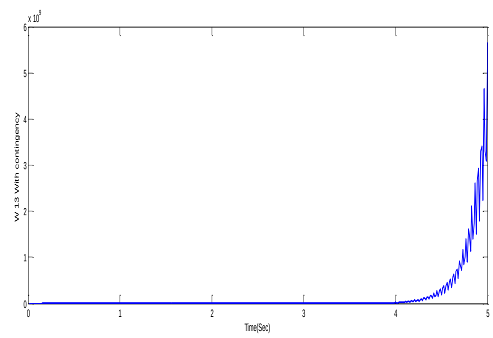

Fig. 36. Response of ω_{13} with UPFC and without PSS under contingency.

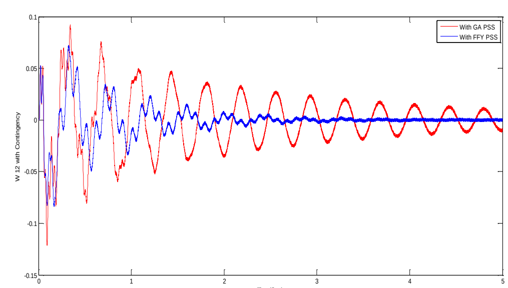

Fig. 37. Response of ω_{12} with UPFC-GA PSS and UPFC-FFY PSS under contingency.

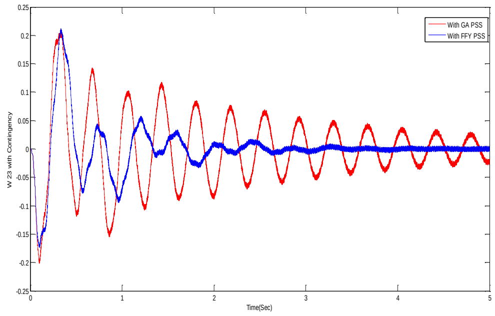

Fig. 38. Response of ω 23 with UPFC-GA PSS and UPFC-FFY PSS under contingency.

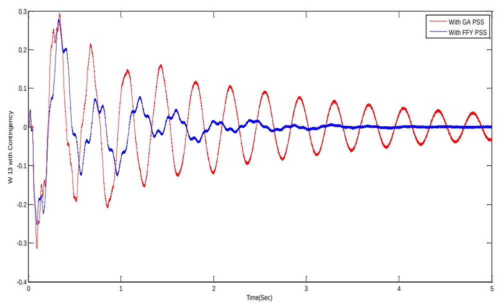

Fig. 39 Response of ω 13 with UPFC-GA PSS and UPFC-FFY PSS under contingency.

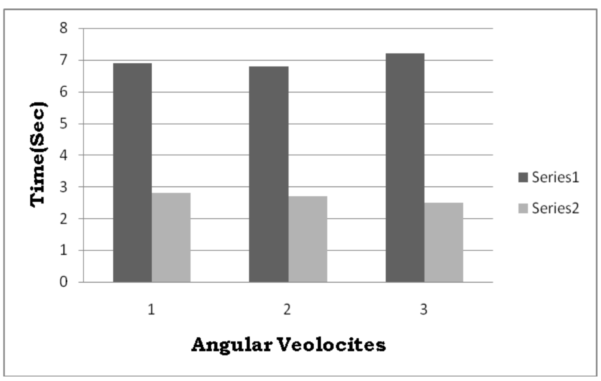

Fig. 40. Settling times of ω_{12}, ω_{23}, ω_{13} with UPFC-GAPSS and UPFC-FFY PSS under contingency.

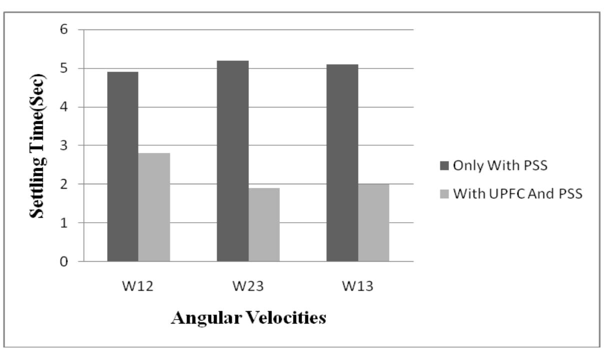

Fig. 41. Settling times of Angular velocities with only PSS and with UPFC-PSS.

Table 18. Parameters of the responses of angular velocities of multi machine system without PSS and with UPFC-PSS under contingency.

Angular Velocities		Without PSS	With UPFC-GA PSS	With UPFC-FFY PSS
ω_{12}	Settling Time (Sec)	----	6.9	2.8
	Max. Overshoot (rad)	7E9	0.1	0.06
	Max. Undershoot (rad)	----	-0.13	-0.07
ω_{23}	Settling Time (Sec)	----	6.8	2.7
	Max. Overshoot (rad)	----	0.2	0.2
	Max. Undershoot (rad)	-3.9	-0.2	-0.16
ω_{13}	Settling Time (Sec)	----	7.2	2.5
	Max. Overshoot (rad)	6E9	0.29	0.28
	Max. Undershoot (rad)	----	-0.31	0.27

Table 19. Settling times of the angular velocities of multi machine system with only PSS and with UPFC-PSS.

Angular Velocity		Only With PSS	With UPFC And PSS
ω_{12}	Settling Time (Sec)	4.9	2.8
ω_{23}	Settling Time (Sec)	5.2	1.9
ω_{13}	Settling Time (Sec)	5.1	2.0

Table 20. Settling times of the Angular velocities of Multi Machine system with only PSS and with UPFC-PSS under contingency.

Angular Velocities		With Only PSS	With UPFC And FFY PSS
ω_{12}	Settling Time (Sec)	4.6	2.8
ω_{23}	Settling Time (Sec)	4.7	2.7
ω_{13}	Settling Time (Sec)	4.1	2.5

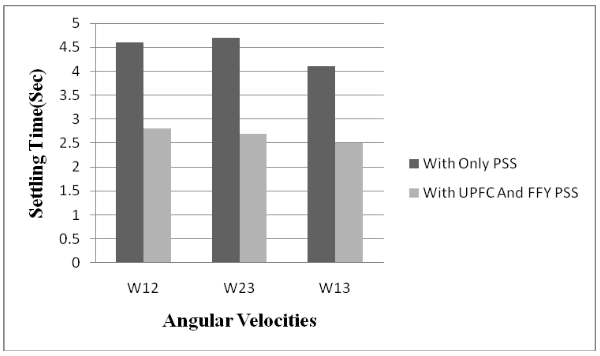

Fig. 42. Settling times of angular velocities with PSS and with UPFC-PSS under contingency.

11. CONCLUSIONS

After careful observation of the Eigen values, the pseudo spectrum analysis, and the settling times of various cases examined for the tested multi machine, the proposed new methodology for the design of PSS is giving more stable Eigen values. The variations of the inter machine parameters speed and the rotor angle in between the machines 1-2; 2-3; 3-1 are settling at faster rate. It is also observed that, in addition to get the stable Eigen values, the need of the settlement of the responses of the inter machines at zero position is the essential condition.

A contingency problem is solved in this article in the stability aspect. The important non linearity of contingency creation and the analysis with that contingency is done in this paper. The affected power flow and the voltage deviation, power losses are also controlled by using the unified power flow controller. The modeling of the multi machine system is changed for every case that is solved in this article. The stabilizer parameters are proposed for each case and obtained the better performance for the case of coordinated application of UPFC-PSS when compared with the mere application of the power system stabilizer. The searching technique firefly algorithm is giving the desired parameters of the power system stabilizer at less time duration when compared with the genetic algorithm technique. The pseudo spectrum analysis is done for all the cases and the stable Eigen values has the effect of the stability of the system. From the step responses, the proposed UPFC-PSS is giving the less settling time for the normal case and also for the contingency cases.

Therefore, from the step responses of the interconnected machines angular velocity and the load angles with the proposed UPFC-PSS, it is concluding that the proposed stabilizer is able to shift the unstable Eigen values to the stable side of the complex plane effectively. It is believed that the same methodology can be applicable to the larger inter connected multi machine systems.

12. NOMENCLATURE

System matrices Notations

A_m	System Matrix without controller for Multi machine system
B_m	Control Matrix without controller for Multi machine system
X_m	State vector of Multi Machine system without PSS
A_{mp}	System Matrix with controller for Multi machine system
B_{mp}	Control Matrix with controller for Multi machine system
X_{mp}	State vector of Multi Machine system with PSS
A_u	System Matrix without controller for Multi machine system with UPFC
B_u	Control Matrix without controller for Multi machine system with UPFC
X_u	State vector of Multi Machine system without PSS & with UPFC
A_{up}	System Matrix with controller for Multi machine system with UPFC
B_{up}	Control Matrix with controller for Multi machine system with UPFC
X_{up}	State vector of Multi Machine system with PSS & with UPFC
A_c	System Matrix without controller for Multi machine system under contingency
B_c	Control Matrix without controller for Multi machine system under contingency
Xc	State vector of Multi Machine system without PSS under contingency
A_{cp}	System Matrix with controller for Multi machine system under contingency
B_{cp}	Control Matrix with controller for Multi machine system under contingency
X_{cp}	State vector of Multi Machine system with PSS under contingency
A_z	System Matrix without controller for Multi machine system with UPFC under contingency
B_z	Control Matrix without controller for Multi machine system with UPFC under contingency

X_z	State vector of Multi Machine system without PSS & with UPFC under contingency
A_{zp}	System Matrix with controller for Multi machine system with UPFC under contingency
B_{zp}	Control Matrix with controller for Multi machine system with UPFC under contingency
X_{zp}	State vector of Multi Machine system with PSS & with UPFC under contingency
K_{si}	Stabilizer gain for each machine for *i*=1, 2, 3.
u	Control vector
T_{1i}, T_{2i}	Phase lead compensator time constants for each machine for *i*=1,2,3

System Parameters

K_A	Voltage regulator gain
T_A	Time constant of the voltage regulator
K_{1i} to K_{6i}	K Constants of the synchronous machine modeling
T'_{d0}	Direct axis transient open circuit time constant
T'_{q0}	Quadrature axis transient open circuit time constant
M	Inertia coefficient; 2H
D	Coefficient of damping

State Variables

ω_i	Angular velocity of i[th] number of machine, i=1, 2, 3.
δ_i	Load angle of i[th] number of machine, i=1, 2, 3.
e'_{qi}	q-axis component of voltage behind transient reactance of i number of machines=1, 2, 3.
e_{FDi}	Equivalent excitation voltage of i number of machines=1, 2, 3.
V_{Si}	Stabilizer output for three machines for *i*=1, 2, 3.
ω_{12}	Difference of angular velocities of machine1 & machine 2
ω_{23}	Difference of angular velocities of machine 2 & machine 3
ω_{13}	Difference of angular velocities of machine1 & machine
δ_{12}	Difference of Load angles of machine1 & machine 2
δ_{23}	Difference of Load angles of machine 2 & machine 3
δ_{13}	Difference of Load angles of machine1 & machine 3
$r + j x_e$	Line impedance
$G + jB$	Terminal load admittance

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