Journal of Engineering Technology

Volume 7, Special Issue (Internet of Things),Oct. 2018, PP. 159-174

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Design of UPFC and Firefly PSS to Enhance the Stability of Hydro-Thermal Interconnected Multi Machine System

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Abstract. The complex interconnected power system is having the maintenance of dynamic stability as the predominant factor to be in synchronism with respect to all generators and loads that are connected to the system. The stability of each individual machine and also the stability of interconnected machines' parameters like relative speed variations gain more importance. Damping torque adjustment or sufficient supply of the damping torque to the synchronous machine which will increase the stability of the system is done by applying the power system stabilizer. This paper proposed a new methodology to design the power system stabilizer using the Firefly search Algorithm and with the application of unified power flow controller (UPFC) in the optimum location. The tested system is the interconnected system of hydrothermal generators. The enhanced stability of the multi-machine system with the proposed method was compared with the Genetic search Algorithm stabilizer with and without application of the unified power flow controller. From the results of step responses and pseudo spectrum representations, it is evident that the enhanced of the stability of the multi machine system is achieved by getting the stable Eigen values and faster-settled responses of relative angular velocity variations. The results are compared with mere application of power system stabilizer and for the combined application of unified power flow controller and power system stabilizer. The proposed methodology enhanced the dynamic stability of the interconnected system in an effective manner.

Key words: Power system stabilizer (PSS), Firefly Algorithm (FFY), Genetic Algorithm (GA), unified power flow controller (UPFC), Pseudo Spectrum Analysis.

1. Introduction

The power system includes the usage of the number of generators and loads connected and it makes the system as the complex system. The stable operation of the alternator gained more importance in the interconnected complex power system. For designing the system which is more effective and economical with more unit sizes and more per unit reactance in the transmission and generation equipment designs, it is advisable to design the compensating devices which will provide the compensating signal required to compensate the reduction in the margins of stability [1, 2, 3]. The problem of stability enhancement of multi machine interconnected system has gained more importance over the number of years and efforts are made to enhance the dynamic stability of the interconnected power system. The design of conventional regulators which will control the voltage and also high speed excitation systems with high ceiling voltage are used to increase the stability. But these regulators and excitation systems will not provide the sufficient damping torque which can able to affect the stability improvement. In some cases, the stable system may operate with negative damping characteristics. The voltage regulators will improve the situation by supplying the negative damping and it may lead to result the instability of the system [4,5] which is an undesirable condition.

To get the improved dynamic performance of the multi machine interconnected system it is very much essential to use supplementary stabilizing signals [6,7] which will improve the stability by increasing damping torque of each synchronous machine and further it improves the interconnected system stability also. From the past few years, many approaches are coming across in the literature for providing the damping torque required for the enhancement of the dynamic stability. The power system stabilizer contains a lead/lag compensator and gain will use the speed and/or power as an input signal to give the supplementary stabilizing signal [8] can be designed and applied. The parameters of the stabilizer were designed by applying different methods like to employ a linear optimal stabilizer [9] by using the concept of linear optimal regulators etc.

The multi machine power system is a highly complex system contains nonlinear with more number of generating plants and also different types of plants like hydro, thermal plants. This condition of operation of various types of plants with different loading conditions will make the combined multi machine system as a nonlinear system operating with continuously varying operating conditions [10, 11, 12]. The design and application of PSS by using different search algorithms will give the stable responses. But it could not get the fast and steady responses for the inert connected hydrothermal system. In addition to the design of power system stabilizer, the coordinated design of unified power flow controller and the PSS can give the better and faster responses when compared with the unique application of PSS.

From the literature, it is evident that the stabilizers designed based on the search algorithms like GA, ANT colony, PSO etc. can give the expected performance in improving the dynamic stability of the system [13]. In this proposed work the parameter search algorithms genetic algorithm and firefly algorithms are used to find the best PSS parameters which will ensure the stability of a multi machine power system. The genetic algorithm uses the genetic operators to search the optimal PSS parameters. Firefly search algorithm is also used to tune the PSS parameters. The considered interconnected hydrothermal multi machine system is complex which replica of the system operating with various operating conditions. By using the coordinated design of PSS and UPFC the dynamic stability of the multi machine system is improved at a faster rate than the GA by the design of PSS parameters using the Firefly search algorithm. However, the unique design of power system stabilizers using the genetic algorithm will not give the stable responses of relative angular velocities and relative torque angles of the interconnected system. The tested system for the study is a multi machine system working with one hydro and two thermal generators.

The dynamic stability [14, 15, 16, 17, 18] of the standard three machine nine system was tested by the application of UPFC and PSS tuned by genetic algorithm and also firefly algorithms. The results of the responses of relative parameters of the tested system are compared.

2. Interconnected multi machine system

The single line view of the interconnected hydrothermal multi machine system is shown in fig.1. The block diagram model of this ‘i’ number machine system with the voltage regulator, exciter is shown in fig.2. The linearised incremental model of this system is found in references [19, 20]. The linearised model equations of the given linearised incremental model of the machine shown in Fig.2 with an exciter and PSS are written in the form of state space equations which results in the state matrix ‘A’, the states that are considered for the analysis are written in the form of:

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$$\dot{x} = Ax + Bu \qquad \text{------- (1)}$$

The state vector matrix '*x*' includes the important states of every machine of the interconnected multi machine system as $\Delta\omega_i, \Delta\delta_i, \Delta e_q{'}_i, \Delta e_{FD\,i}$ of each generator where *i=1,2,3.* From the block diagram shown the equations for the twelve states of three machines are written as:

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

$$\Delta\delta_i = \frac{2\pi f}{s}\Delta\omega_i \qquad \text{----- (3)}$$

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

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

$$\Delta V_{Si} = K_{si}\frac{1+sT_{1i}}{1+sT_{2i}}\Delta\omega_i \qquad \text{----- (6)}$$

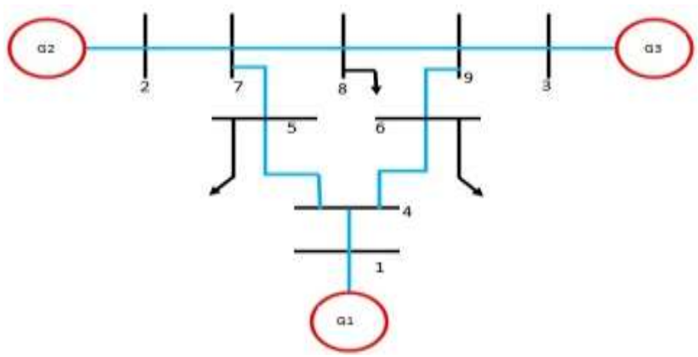

Figure .1 Line Diagram of Hydro Thermal Interconnected System

Table 1. Line Data of 3 machine 9 bus system

From Bus	To Bus	R(pu)	X(pu)	B(pu)
1	4	0.0	0.0576	0.0
4	5	0.01	0.085	0.176
4	6	0.017	0.092	0.158
6	9	0.039	0.17	0.358
5	7	0.032	0.161	0.306
2	7	0.0	0.0625	0.0
7	8	0.0085	0.072	0.149
8	9	0.0119	0.1008	0.209

3	9	0.0	0.0586	0.0

Table 2. Machine Data

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

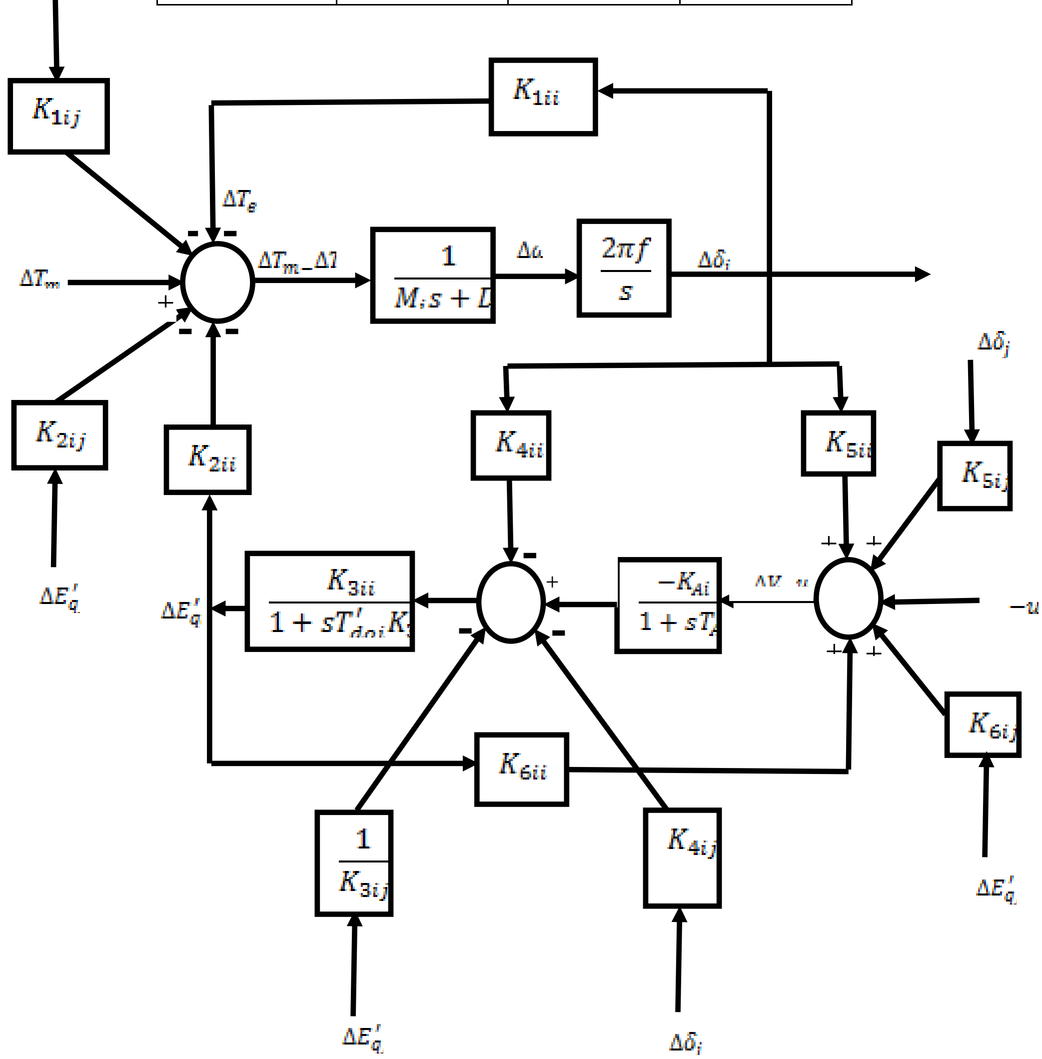

Figure. 2 Linearised model of synchronous machine with an exciter

3. Power System Stabilizer

To maintain the multi machine system as an ensured stable system the problem of stabilization can be solved by designing the PSS and application of PSS to all the three machines. For getting the stable Eigen values for the tested system, the parameters of power system stabilizer is tuned by using the genetic algorithm and firefly algorithms. For formulating the problem by using search algorithms, new state equations will be written, hence the size of the state matrix ‘A’ is increased from $12X12$ to $15X15$. By considering a lead circuit and the gain blocks as the structure of the stabilizer, the equation of transfer function of the stabilizer is written as:

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

4. Unified power flow controller (UPFC)

A unified power flow controller (UPFC) contains two potential sources resulting from the basic components of output voltages of converter transformers as shown in Fig.3. In this article to get the economic justification for using the fact device, the number of possible locations is reduced. The device is located between two load buses and it is not having the shunt capacitors. It is not placed in the line where the tap changer is located. By injecting the respective power at buses i and j and also by combining the series and shunt voltage models the mathematical modeling of UPFC is formulated. The equations for the power injection can be written as

$$P_{i,UPFC} = 0.02 rb_{se} V_i^2 \sin\gamma - 1.02 rb_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) \qquad \text{---- (8)}$$

$$P_{j,UPFC} = rb_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) \qquad \text{---- (9)}$$

$$Q_{i,UPFC} = -rb_{se} V_i^2 \cos\gamma \qquad \text{---- (10)}$$

$$Q_{j,UPFC} = rb_{se} V_i V_j \cos(\theta_i - \theta_j + \gamma) \qquad \text{----- (11)}$$

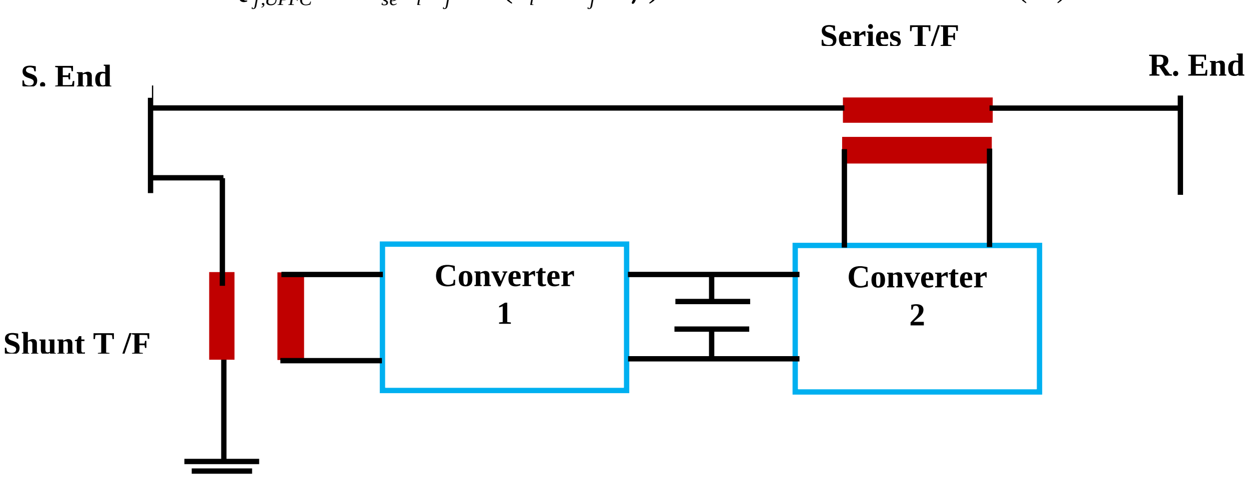

Figure.3 Basic configuration of unified power flow controller

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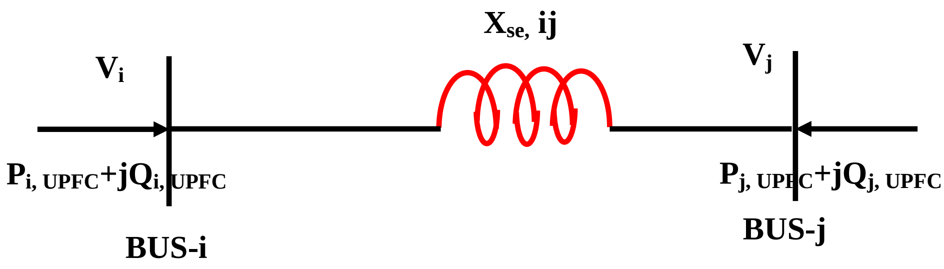

Figure.4 Power injection model of unified power flow controller

The parameters of the proposed UPFC 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 location of the UPFC is identified by optimizing the device control parameters so as to minimize the severity function by using the Firefly algorithm. The severity function proposed in the literature [21] is

$$F_{Severity} = \sum_{i=1}^{N_{line}} \left(\frac{S_i}{S_i^{\max}} \right)^{2q} + \sum_{j=1}^{N_{line}} \left(\frac{V_{j,ref} - V_j}{V_{j,ref}} \right)^{2r} \text{--------- (12)}$$

There are six possible locations are identified for locating the UPFC device. By minimizing the function by applying the overload and voltage violations as constrains the system severity index is calculated and tabulated in table.3.

Table 3

Severity index for all possible locations

Location (From bus to bus)	Severity index with UPFC
4-5	58.3866
4-6	58.9735
5-7	**58.1283**
6-9	58.4060
7-8	59.1775
8-9	58.3533

Hence the severity index is obtained as 58.1283 which is less among all possible locations of the three machine nine bus system. The UPFC parameters are designed and located in between the buses 5 and 7, which is treated as an optimized location. The values of the parameters are

Xse	r	Gama	Qsh
0.0025	0.01431	72.6338	0.06007

5. Proposed Method

To improve the stability of the multi machine system, tuning of the parameters of PSS and also in coordination with the unified power flow controller (UPFC) is done and it is the novel technique which will ensure the stability improvement. The device UPFC is installed between fifth and seventh buses of the three machine nine bus system. After installation of the UPFC device, the operating condition, and the power flow results of the system are changed. The new state matrix is obtained for this condition as shown in the following equation.

$$\dot{x}_k = A_k x + B_k u \qquad \text{-----} (13)$$

Where x_k *is the* state vector with stabilizer and u is the controlling signal.

The required condition for the more set of plants in the equation shown in (7) to be operated with the designed stabilizing signals is that the Eigen values of the newly formed closed loop system will lie on the stable side of the complex plane which is explained by using pseudo spectrum analysis.

To attain this desirable condition the approach followed to find the parameters K_{si} and T_{1i} *and* T_{2i} of the power system stabilizer for i=1,2,3 is proposed as to minimize the objective function[22] shown in the following equation.

$$J = \max \mathrm{Re}(\alpha_{i,k}),\ k = 1,2,3,\ ,i = 1,2,3$$

Where αk, i is the kth closed-loop eigen value of the ith plant. The designed parameters of the desired stabilizer Ksi, T1i, and T2i by applying the Firefly search algorithm will give the more stabilized poles for the multi machine system. The poles which are getting after application of the coordinated design of PSS and UPFC will be evident for the more stabilized relative variation of the hydrothermal interconnected system. The problem of optimization is resolved by using genetic search algorithms and firefly algorithms.

6. Steps of Genetic Algorithm

The genetic search algorithm is used in this work to determine the parameters of PSS which can ensure the stability. A set of points to be searched is selected and used initially is called as population and is a set of chromosomes. The initial population is applied through the operators of GA for further generation of a new population. Merely the fittest organisms will be used for reproduction, the weakest organisms will not be used for the next step. The global optimum result is obtained by following the said procedure up to the convergence point. In the process, the genetic operators: reproduction, crossover, and mutation are applied to get the new set of parameters of PSS. Evaluation and Genetic Operation are performed repeatedly until the convergence is achieved.

7. Steps of Fire Fly Algorithm:

The flash signal of a firefly is acting like a signal to attract the following fireflies. The attraction between the fireflies is depending on the brightness of the fireflies. If the brightness of one firefly is more, the firefly with less brightness is attracted by the first one having more brightness. A global optimization problem can be formulated by starting from the locally optimized solution from various starting points. The objective function is designed such that it will determine the brightness of the firefly. The iterative solution of a mathematical optimization problem by applying the constraints will give the best parameters of the power system stabilizer. These parameters are giving the stable Eigen poles for the multi machine system. The process of firefly algorithm is explained in the flowchart shown in the Fig.5

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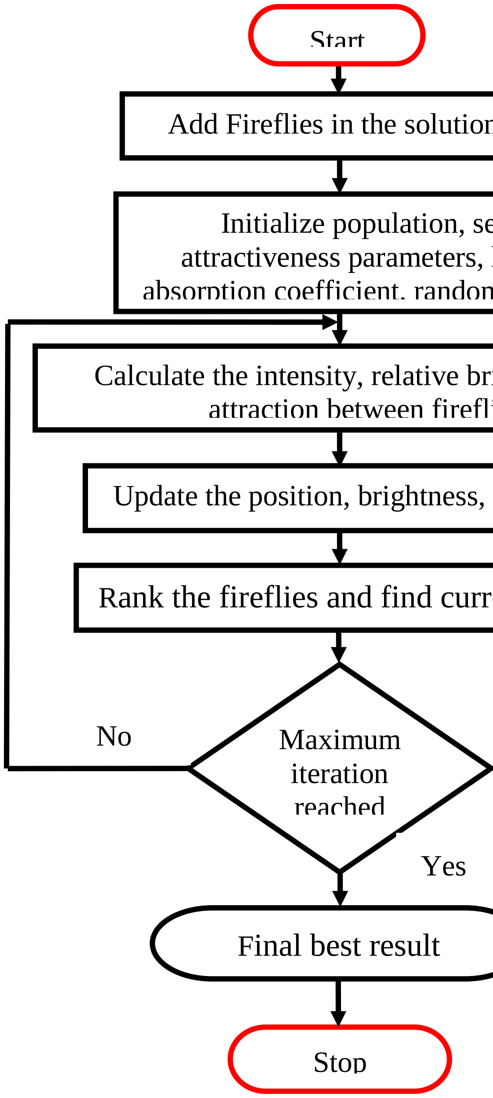

Fig 5. Firefly search Algorithm flowchart

8. Tested model of interconnected multi machine system

To analyze the process of improvement of stability of the interconnected multi machine system, a standard three generator nine bus system was considered. It consists of one hydro generator and two thermal generators. The tested system can be written in the form of state space as equation number (1). From the block diagram shown in Fig.2 the state equations [23] can be written in the form of

$$\dot{x} = Ax + Bu \quad \text{where} \quad x = \left[\Delta\omega_i \Delta\delta_i \Delta e_q{}'_i \; \Delta e_{FD\,i}\right]^T \; ; i=1,2,3. \qquad \text{--- (14) is the state vector.}$$

To derive the system matrix 'A', the load flow results from the N-R method are used. The initial conditions of the machines are calculated from the load flow results and the standard data of the three alternators. The 'K' constant matrices are obtained by following this procedure. By using the state equations mentioned in the section.2 the system matrix 'A' is obtained as

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

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

From the above system, the state matrix ‘A’ it is observed that the Eigen values of this open loop system are obtained as unstable poles that are which lies on the right hand side of the complex plane.

With 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 an increase in the size of system state matrix ‘Ak’ with 15x15.

$$\dot{x} = A_k x + B_k u$$

The required values of the PSS parameters gains and time constants are Ksi, T1i, and T2i; i=1, 2, 3 are searched by using the proposed method and Genetic Algorithm approach. The obtained results are applied to the matrix to check the locations of the Eigen values on the complex plane. For searching the PSS parameters with Genetic search Algorithm approach the population size is selected as 200 and the optimum result was obtained for 1000 number of generations. For the selection of stabilizer parameters with the Firefly search Algorithm approach the optimum stabilizer parameters are obtained for 200 generations and 50 population size. The designed parameters of PSS with Firefly and genetic algorithm, UPFC-PSS with Firefly and genetic algorithms are tabulated in table.4. The washout time constant of the PSS was considered as 2 sec within the acceptable range. The stability of the tested multi machine system for several conditions like without any controller, with stabilizer tuned by genetic algorithm and firefly algorithm, are tested and tabulated. The Eigen values of the various cases of the enhanced stability by the application of UPFC-PSS tuned by genetic algorithm and firefly algorithms are also determined and shown in table 5.

Table 4

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

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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 5

Eigen values for the test system without and with UPFC&PSS

Without any controller	**With GA PSS**	**With FFY PSS**	**With UPFC And GA PSS**	**With UPFC And FFY PSS**
-0.0060 + 2.1836i	-3.3778 + 0.0002i	-3.7223 + 0.0005i	-1.2187 + 0.0006i	-1.1395 + 0.0007i
-0.0060 - 2.1836i	-0.0002 + 0.0043i	-0.0019 + 0.0043i	-0.0177 + 1.2784i	-0.0176 + 1.2784i
0.8769 + 0.0000i	-0.0002 - 0.0043i	-0.0019 - 0.0043i	-0.0177 - 1.2784i	-0.0176 - 1.2784i
-0.8879 + 0.0000i	-0.0011 + 0.0041i	-0.0021 + 0.0042i	-0.0248 + 0.4245i	-0.0265 + 0.4225i
-0.0240 + 0.0566i	-0.0011 - 0.0041i	-0.0021 - 0.0042i	-0.0248 - 0.4245i	-0.0265 - 0.4225i
-0.0240 - 0.0566i	-0.0003 + 0.0021i	-0.0007 + 0.0021i	-0.0015 + 0.2207i	-0.0087 + 0.2230i
-0.0700 + 0.0000i	-0.0003 - 0.0021i	-0.0007 - 0.0021i	-0.0015 - 0.2207i	-0.0087 - 0.2230i
-0.0253 + 0.0244i	-0.0005 + 0.0001i	-0.0060 + 0.0001i	-0.1132 + 0.0000i	-0.0998 + 0.0000i
-0.0253 - 0.0244i	-0.0005 - 0.0001i	-0.0060 - 0.0001i	-0.0035 + 0.0514i	-0.0008 + 0.0535i
0.0148 + 0.0001i	-0.0002 + 0.0001i	-0.0021 + 0.0001i	-0.0035 - 0.0514i	-0.0008 - 0.0535i
0.0002 + 0.0001i	-0.0002 - 0.0001i	-0.0021 - 0.0001i	-0.0027 + 0.0022i	-0.0028 + 0.0022i
-0.0008 + 0.0000i	-0.0006 + 0.0002i	-0.0008 + 0.0004i	-0.0027 - 0.0022i	-0.0028 - 0.0022i
-----	-0.0006 - 0.0002i	-0.0008 - 0.0004i	-0.0013 + 0.0022i	-0.0013 + 0.0001i
-----	-0.0031 + 0.00001i	-0.0017 + 0.0003i	-0.0013 + 0.0012i	-0.0013 + 0.0001i
-----	-0.0031 + 0.00001i	-0.0017 - 0.00003i	-0.0030 + 0.0012i	-0.0034 + 0.0005i

From the above table.5, it is observed that the Eigen values without any controller are evident for the un stability of the system. The poles for the application of PSS and the coordinated application of UPFC-PSS will show the improved stability of the interconnected multi machine system [24]. The pseudo spectrum analysis was done for the Eigen values of different cases and it is observed that the Eigen values for without controller and with controllers cases [25]. The Eigen values are lying in the left hand side for the unstable system and lying on the right hand side for the stable system with respect to the complex plane. By using the DGs, solar PV systems and AI techniques the stability analysis and the robust controllers can be designed [26, 27, 28, 29]. It is also observed that the Eigen values of the coordinated design and application of UPFC-PSS case are lying on the more stable side of the S-plane when compared with the application of PSS alone. Hence the proposed method of coordinated design and application of UPFC-PSS are resulting in more stability for the tested system.

By analyzing the Eigen values obtained in table.5 by pseudo spectrum analysis as shown in Fig.6 to Fig.10 the proposed methodology to design the coordinated UPFC-PSS will give the stable poles which lie on the left hand side

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of the imaginary axis. In addition to the Eigen value placement, another important factor which receives more importance is the maintenance of zero speed variations between each machine.

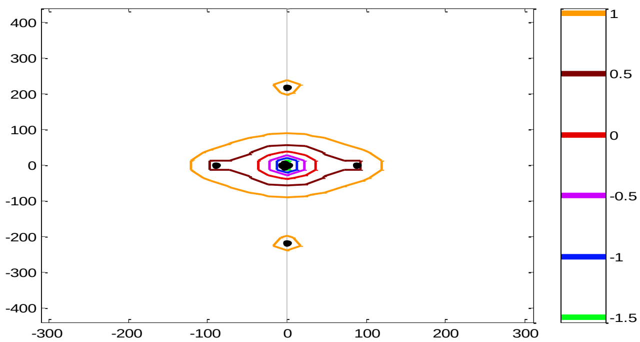

Figure.6 The pseudo spectrum representation Without any controller

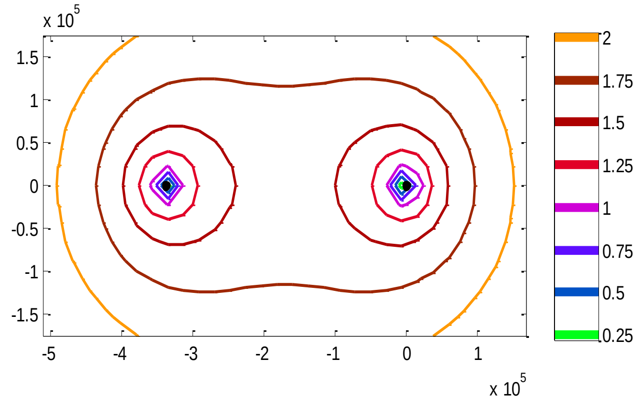

Figure.7 The pseudo spectrum representation with GA based stabilizer

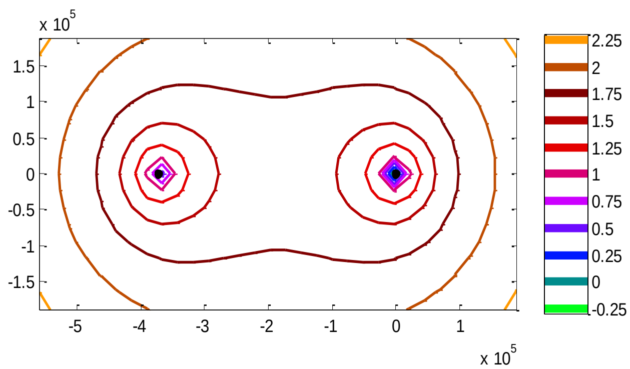

Figure.8 The pseudo spectrum representation with Firefly based stabilizer

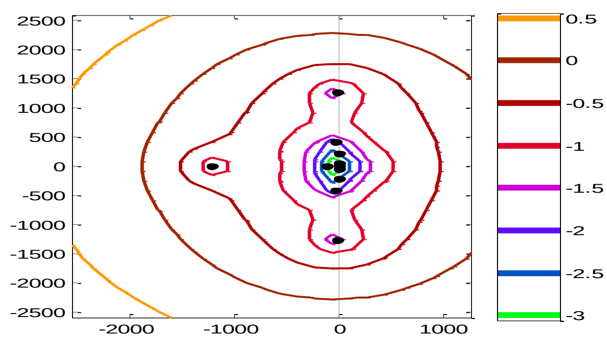

Figure.9 The pseudo spectrum representation with UPFC-PSS (GA)

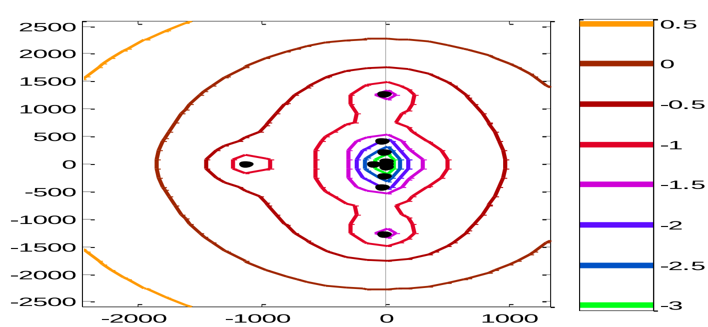

Figure.10 The pseudo spectrum representation with UPFC-PSS (FFY)

To check the maintenance of inter-machine stability is it very important to see that the variations in the speed deviations between the set of machines that is between 1-2; 2-3 and 1-3. If the speed variations between these mentioned set of machines settled at zero position as fast as possible it can be concluded that there is an inter-machine stability is maintained effectively.

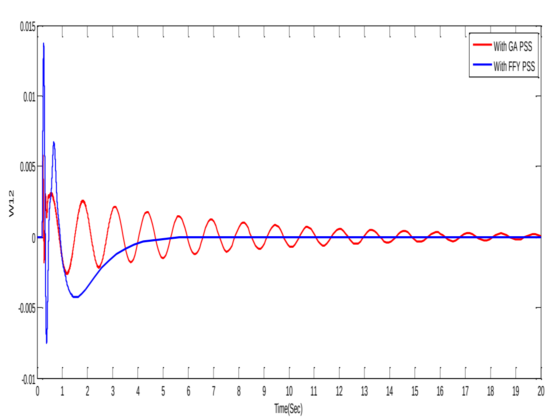

Figure.11 Response of ω $_{12}$ with GA PSS and FFY PSS

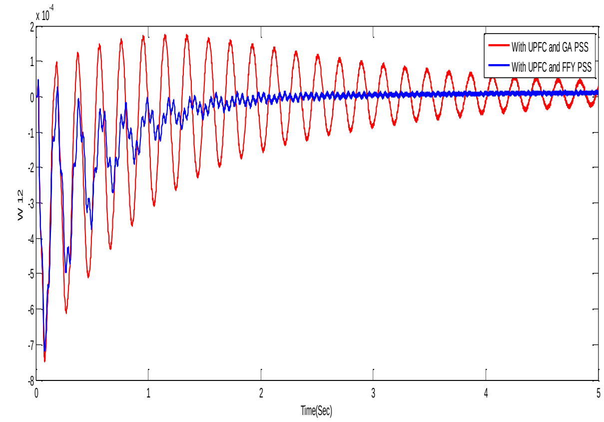

Figure.12 Response of ω $_{12}$ with UPFC GA PSS and UPFC FFY PSS

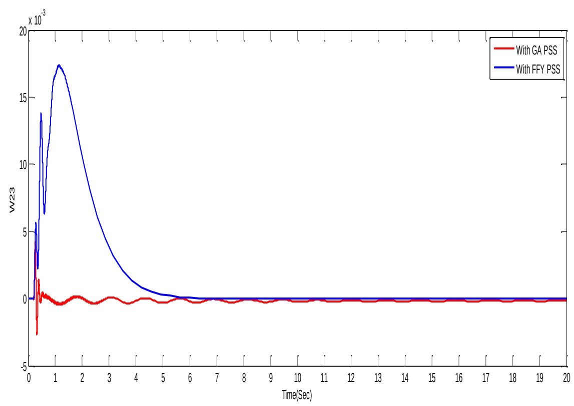

Figure.13 Response of ω $_{23}$ with GA PSS and FFY PSS

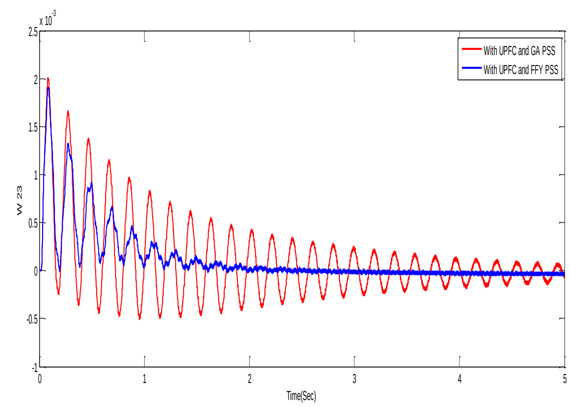

Figure.14 Response of ω $_{23}$ with UPFC GAPSS and UPFC FFY PSS

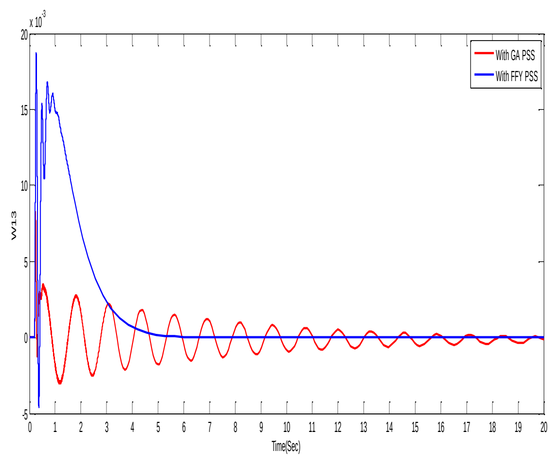

Figure.15 Response of ω_{13} with GA PSS and FFY PSS

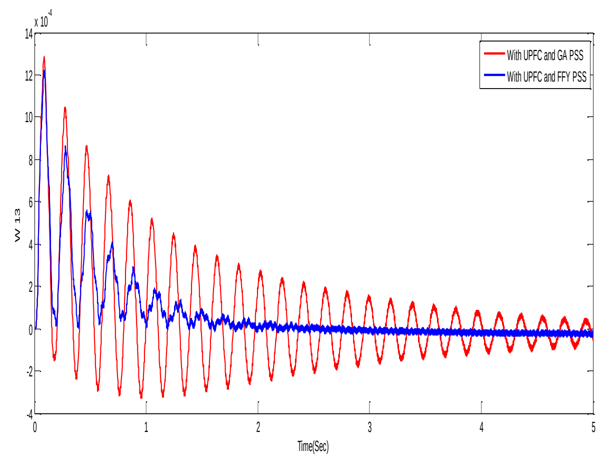

Figure.16 Response of ω_{13} with UPFC GAPSS and UPFC FFY PSS

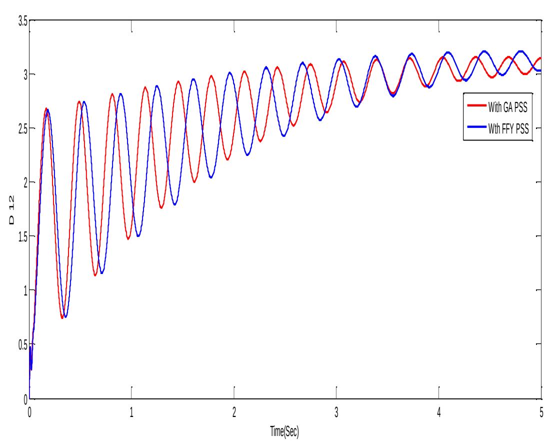

Figure.17 Response of δ_{12} with GA PSS and FFY PSS

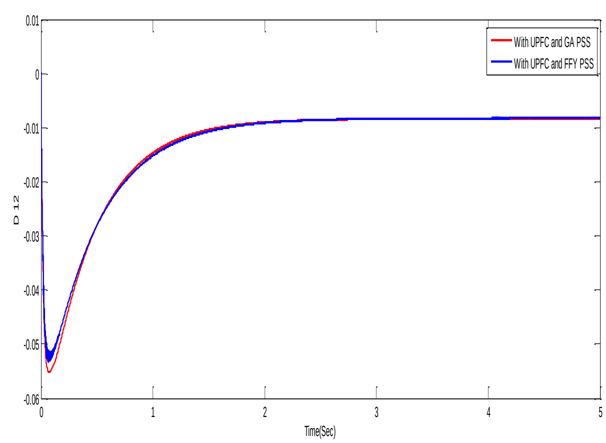

Figure.18 Response of δ_{12} with UPFC GA PSS and UPFC FFY PSS

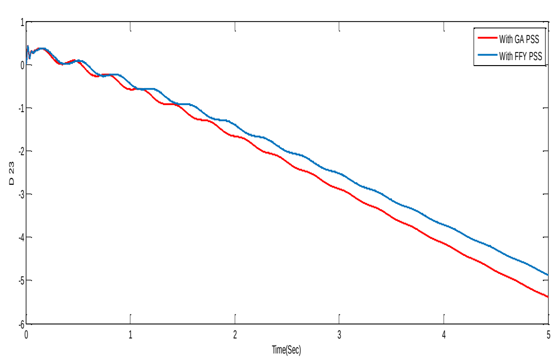

Figure.19 Response of δ_{23} with GA PSS and FFY PSS

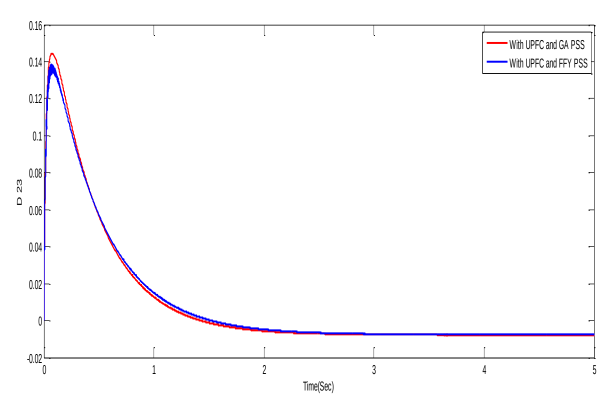

Figure.20 Response of δ_{23} with UPFC GAPSS and UPFC FFY PSS

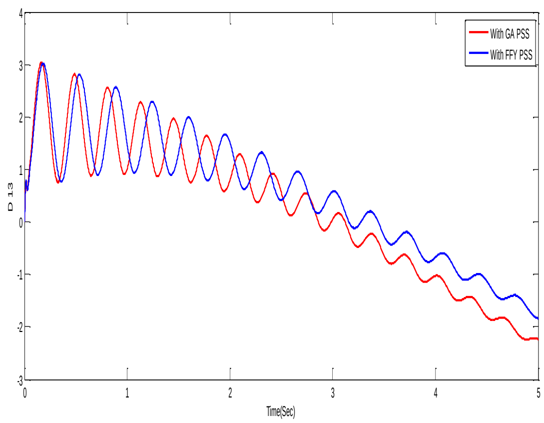

Figure.21 Response of δ_{13} with GA PSS and FFY PSS

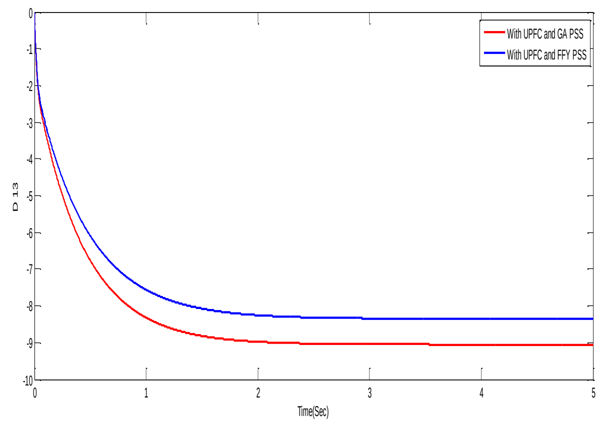

Figure.22 Response of δ_{13} with UPFC GAPSS and UPFC FFY PSS

After careful observation of the obtained Eigen values noted in table.5 and the pseudo spectrum representations shown from the Fig. 6 to Fig.10 it is noted that when compared with the GAPSS, FFYPSS cases the UPFC-FFYPSS is resulting in the more stable poles. By the design and application of the unified power flow controller, the power flow of the tested system is also changed into the efficient manner by reducing the power loss and voltage deviations. Further, the overall stability of the inert connected system is also maintained. To ensure the inter-machine stability the variations are plotted from Fig.11 to Fig.22.

9. Conclusions

A new methodology was proposed in this article for the ensured and improved stability of the hydrothermal interconnected multi machine system. By the design and application of coordinated designed UPFC-PSS tuned by firefly search algorithm to the multi machine system, the stability was improved. The pseudo spectrum representation and the step responses of relative speed variations of interconnected machines 1 to 2, 2 to 3 and 1 to 3 are observed for the application of stabilizer alone designed by GA and FFY and for the application of proposed UPFC-PSS tuned by using GA firefly algorithm. From the results, it is concluded that the proposed methodology of designing the UPFC-PSS results in the stable Eigen values and the step responses of inter-machine parameters are settled at faster duration when compared with the mere application of power system stabilizer. Its independent design allows implementing for the complex systems which will contain more number of machines and more numbers of buses and lines.

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Appendix

System Parameters & state variables		**System matrices notations**	
K_A	Voltage regulator gain	A	System Matrices without controller
T_A	Time constant of the voltage regulator	A_K	System matrix with controller
K_{1i} to K_{6i}	K Constants of the synchronous machine modeling	B	Control matrix
T'_{d0}	Direct axis transient open circuit time constant	x	State Vector without controller
M	Inertia coefficient	x_k	State vector with controller
D	Coefficient of damping	u	Control Vector
ω_i	Angular velocity of i number of machines=1, 2, 3.	K_{si}	Stabilizer gain for each machine for *i*=1, 2, 3.
δ_i	Torque angle of i number of machines=1, 2, 3.	T_{1i}, T_{2i}	Phase lead compensator time constants for each machine for *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.		