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Design of Robust PID Power System Stabilizer for Multimachine Power System Using HS Algorithm

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Abstract In this paper, the design of a proportional, derivative and integral (PID) based power system stabilizer (PSS) is carried out using a new Meta heuristic harmony search algorithm (HSA) to optimize the parameters. The design of proposed PID controller is considered with an objective function based on eigenvalue shifting to guarantee the stability of nonlinear plant for a wide range of conditions using HSA. The HSA optimized PIDPSS (HSPIDPSS) controller is applied to the standard IEEE ten-machine thirty nine-bus test power system model in decentralized manner and the performance is compared with a robust fuzzy controller. The robustness is tested by considering four plant conditions with change of active power, active load and faults at different buses of the power system to establish, the superior performance with HSPIDPSS over the FPSS.

Keywords: *Harmony Search Algorithm optimized PID Power System Stabilizer (HSPIDPSS), Fuzzy Power System Stabilizer, IEEE ten-machine thirty nine-bus test power system, proportional-derivative and integral controller*

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1. Introduction

Power systems are complex multi-component dynamic systems in which the system characteristics fluctuate with varying loads and varying generation schedules. These power systems suffer by low frequency oscillations on sudden changes in load or occurrence of fault. The transfer of bulk power across weak transmission lines is hindered due to continuous persistence of such a low frequency oscillation (0.2–3.0 Hz) [1].

In early 1960s, the fast acting, high-gain automatic voltage regulators (AVR) were applied to the generator excitation system which in-turn invites the problem of low frequency electromechanical oscillations in the power system. To reduce the low-frequency oscillations, the PSS adds a stabilizing signal to AVR that modulates the generator excitation to damping electrical torque component in phase with rotor speed deviation, which increases the generator damping. The uniformly adopted type of PSS is known as conventional PSS (CPSS), which consists with the lead-lag type components. The recent development in CPSS design is carried out in [2], using Support vector machine and Harmony search algorithm for IEEJ Western Japan ten-machine power system. Similar to CPSS a Proportional, Integral Derivative (PID) controller many be connected to modulate the signal of the AVR to damp-out the small signal oscillations. The tuning of the PID gains is based on the conventional methods such as Zeigler/Nichols method, gain and phase margin method, Cohen/Coon pole placement, gain scheduling and minimum variance methods. However, these methods suffer with some limitations as (a) extensive methods to set gains, (b) difficulty to deal with gains for a large, complex and nonlinear power system, and (c) poor performance in a closed loop because of changing conditions [3].

To mitigate the shortcomings of these conventional methods; many optimization based algorithms have been proposed. The methods available in literature are as Tabu search [4], Evolutionary algorithm [5], Differential Evolution (DE) algorithm [6], Simulated Annealing, Genetic Algorithm [7], Fuzzy logic [8-11], Interval type-2 fuzzy logic [12,13], Artificial Bee Colony (ABC) [14], Particle swarm optimization [15], iterative linear matrix inequalities algorithm [16]. The above optimization methods works well but fails with the objective function as highly epistetic with large number of parameters. To such objective function, these methods may give degraded results with large computational burden.

The Harmony Search (HS) Algorithm is proposed by Geem in [17], is inspired from the process of the improvisation used by musicians to achieve the harmony. The HS algorithm [18,19] is a meta-heuristic optimization algorithm which is similar to the PSO [20] and GA [21]. It has been implemented extensively in the fields of engineering optimization [18], in recent years. It became an alternative to other heuristic algorithms like PSO [20]. It is a derivative free, meta-heuristic optimization (which doesn't use trial-and-error), inspired by the way musicians improvise new harmonies, and it uses higher-level techniques to solve problems efficiently [22]. HS can be classified as a population-based evolutionary algorithm such as GA and the PSO algorithm [23].

The article in [2]; presents the application of support vector machines (SVM) to adaptive PSS design in a multi-machine power system based on the HSA. In SVM, data from power system model as input and the SVM parameters along with model features optimized by harmony search based on the k-fold cross-validation technique. It presents a hybrid technique to use SVM and HSA in the design of PSS for IEEJ Western Japan ten machine power systems. However, the paper incorporate some limitations as (i) The parameters of CPSS are optimized to satisfy the D-stability region with damping ratio as 0.02 which is not an effective way of damping because the preferred damping ratio is always more than 0.1 as per dynamics of generators in small signal stability analysis as in [20,24] for New England ten multi-machine power system, for single-machine infinite-bus power system as in [25] and considered as even 0.2 in [26]. However, the paper has not demonstrated the plot of eigenvalue for all electromechanical modes of oscillations on s-plane concerning to all generators. Furthermore, the proposed EMOs are ($-0.2989 \pm j4.1377$, $\zeta = 0.0720$; $-0.2713 \pm j3.4281$, $\zeta = 0.0788$; $-0.3719 \pm j3.4837$, $\zeta = 0.1062$; $-0.1331 \pm j2.3868$, $\zeta = 0.0557$; $-0.1129 \pm j3.8358$, $\zeta = 0.0294$; $-0.0753 \pm j3.1278$, $\zeta = 0.0241$) very weak in nature. As per these EMOs, it is very clear that the location is very near to imaginary axis of the s-plane, which cannot be suggestive to guarantee the stability of the power system (ii) It is observed that some of the results for speed variation are settling at about 50 seconds, which is due to lesser damping factor selection otherwise the settling time should be around 5-10 seconds as in [20,25] and clearly mentioned in [26] (iii) No quantitative analysis of the response such as the performance indices (ITAE, IAE and ISE) are calculated for the proposed and the comparing responses. (iv) The power system considered in this article is IEEJ Western Japan ten-machine power system which is lesser a complex system as compared to the IEEE New England ten-machine thirty nine-bus power system model in terms of interconnection and design as well. As per above limitations, it seems that a very basic model of harmony search algorithm may be used to tune the CPSS parameters of the power system model.

The limitations observed as above are mitigated in this article by plot of dominant electromechanical mode of oscillation on the s-plane and verifying in D-shape sector drawn with maximum value of real part of EMO as -1 ($\sigma < -1$) and minimum value of damping factor as 0.1 ($\xi > 0.1$). The robustness is tested by considering four plant conditions with change of active power, active load and faults at different buses of the power system to establish, the superior performance with HSPIDPSS over the FPSS. The superiority of HSPIDPSS is validated in terms of settling time and the performance indices (ITAE, IAE and ISE) as lesser in magnitude as compared to FPSS.

In the organization of paper, the problem is formulated in section 2. A review on test system, PID based PSS design fundamental and the objective function are introduced in this section. An overview on Harmony Search Algorithm which is used to optimize the PID controller parameters is introduced in section 3. The performance analysis is carried out in section 4 for IEEE ten-machine thirty nine-bus test power system model. Lastly the analysis is concluded in section 5, followed by references.

2. Problem Formulations

2.1. Test System Representation

The general representation of a power system using nonlinear differential equations can be given by

$$\dot{X} = f(X, U) \tag{1}$$

Where, X and U represents the vector of state variables and the vector of input variables. As in [21], the power system stabilizers can be designed by use of the linearized incremental models of power system around an operating point. The system representation based on differential equations and used data is given in [13,27]. The state equations of a power system can be written as

$$\Delta\dot{X} = A\Delta X + BU \tag{2}$$

Analysis of ten-machine thirty nine-bus power system as in Figure 1 can be carried out by simultaneous solution of equations consisting of prime movers, synchronous machines with excitation systems, transmission line network, dynamic and static loads, and other devices like static VAR and HVDC converters based compensators. The dynamics of generator rotors, excitation, prime movers, and other related devices are being represented by differential equations. Thus, the complete multi-machine model consists of large numbers of ordinary differential equations (ODE) and algebraic equations. These are linearized about an operating point (nominal) to derive a linear model for the small signal oscillatory behaviour of power systems [28,29]. The range of variation in operating point can generate a set of linear models corresponding to each operating point/condition.

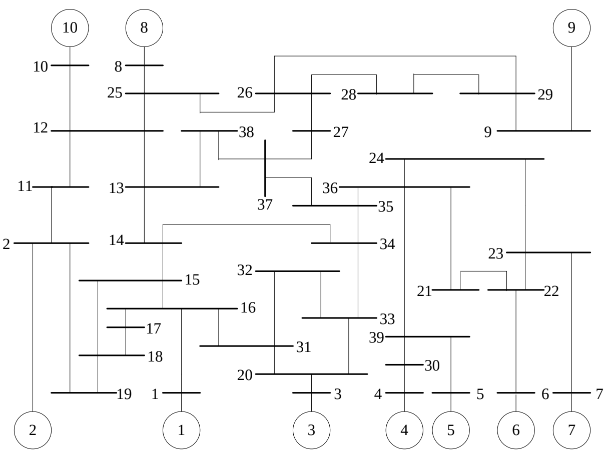

Figure 1. Line diagram of New England 39 Bus test Power System

The state equations of a power system, consisting 'N' number of generators and N_{pss} number of power system stabilizers can be written as in Eqn. (2). Where, A is the system matrix with order as $4N \times 4N$ (40×40) and is given by $\partial f / \partial X$, while B is the input matrix with order $4N \times N_{pss}$ (40×10) and is given by $\partial f / \partial U$. The order of state vector ΔX is $4N \times 1$ (40×1), the order of ΔU is $N_{pss} \times 1$

(10×1). Here, the well known Heffron-Phillip linearized model is used to represent the large multimachine power system as in Figure 2.

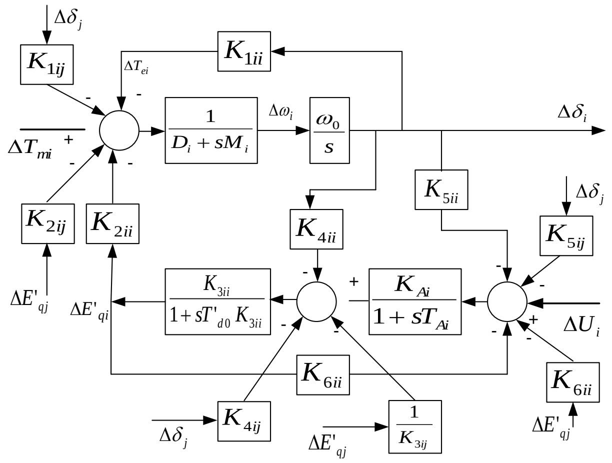

Figure 2. Heffron-Philips Model for Multimachine Power System

2.2. PID tuning Scheme

Since last 60-70 years, the Proportional, Integral and derivate (PID) controller is most popularly known and used feedback controller in the field of complex process industries. It can provide excellent robust control performance over a wide range of operating conditions of a power system because of its three different modes of operation [1,16]. The proportional controller mode can reduce the rise time but unable to reduce the steady-state error of the response. The higher value of proportional gain may cause the system to become an unstable but lower value make in-sensitive or lesser sensitive to even large value of error [1]. The derivative control mode improves the system stability by reducing overshoot and improving transient response. The integral control mode of operation may eliminate the steady-state error but may worsen the transient response of the system. The lower value of integral gain value makes a system sluggish while the higher value causes the random increase in the overshoot [4,16]. Therefore, to design the PID controller, all three gains require special attention to get the control signal by the trial-and-error method based on the experience and plant behaviour. The block diagram representation of PID controller for a closed-loop system is shown in Fig. 3 and mathematically represented by Eqn. (3).

$$Upid = K_p \Delta\omega(t) + K_i \int_0^{T_{SIM}} \Delta\omega(t)\, dt + K_d \frac{\partial \Delta\omega(t)}{\partial t} \tag{3}$$

2.3. Objective Function

To increase the system damping over a wide range of operating conditions and configuration of a power system, a robust tuning must be incorporated. Therefore, PSS design is formulated as an eigenvalue-based objective function. The two sub-objective functions based on minimization of real part of eigenvalue and maximization of damping factor are taken into consideration for optimization of PID parameters [24,26].

The optimization constraints are the limits/bounds on the optimized parameters such as gain and the time constants. Thus, the optimization problem is subjected to.

$$\begin{cases} K_p^{min} \le K_p \le K_p^{max} \\ K_d^{min} \le K_d \le K_d^{max} \\ K_i^{min} \le K_i \le K_i^{max} \end{cases} \tag{4}$$

Typical ranges of the optimized parameters are selected as -5.00 to 50.00 for K_p, K_d and Ki. Considering one of the above objectives, the proposed approach employs HS algorithm to solve this optimization problem for an optimal set of PSS parameters. Considering ith eigenvalue representation as $\lambda_i = \sigma_i \pm j\omega_i$ and the associated damping ratio expression as $\xi_i = -\sigma_i / \sqrt{\sigma_i^2 + \omega_i^2}$ [26].

$$J = \sum_{i=1}^{n} (\sigma_0 - \sigma_i)^2 + \alpha \sum_{i=1}^{n} (\xi_0 - \xi_i)^2 \tag{5}$$

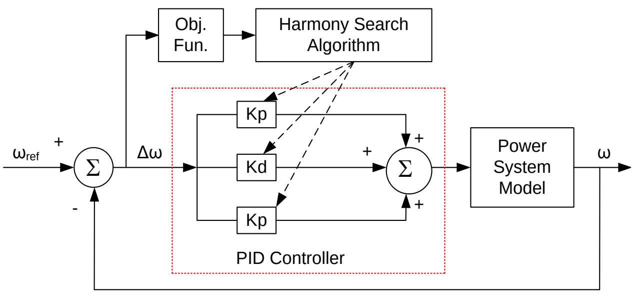

Figure 3. PID controller tuned by Harmony Search Algorithm

3. Overview of Tuning Methodology: HSA

This algorithm is an evolutionary meta-heuristic which is inspired by a natural phenomenon. It is inspired by the method used by musicians to improvise new optimal harmonies. In this algorithm, an analogy in between optimization and improvisation is designed such that to mimic the process used by musicians to get the note that results to a finest pleasing harmony, whenever, musicians are synchronized with other musicians [30,31].

3.1. Procedural Steps of HS Algorithm

Each row of harmony memory (HM), consists of *N* decision variables and the fitness score *w* ([x^1, x^2… *w*]). The HM is initialized with HMS randomly generated solution vectors [32,33].

Step 1: Initialization Process: Let in an optimization problem, the objective function is represented by Minimization of *F(x)* which is subjected to $x_i \in X_i$, *i=1, 2, 3 … N*. Where, x is the set of design variables (x_i), ($x_i^L \le x_i \le x_i^U$), and N is the count of design variables.

1. Define the variable limits as lower (x_i^L) and upper (x_i^U) or $x_i^L \le x_i \le x_i^U$.

2. Deciding the value of harmony memory size (HMS), from the range $10 \leq HMS \leq 100$.

3. Decide value of HMCR (harmony memory consideration rate) within the range $0.0 \leq HMCR \leq 1.0$

$$x'_1 \leftarrow \begin{cases} x'_i \quad l\{x_i^1, x_i^2, ..., x_i^{HMS} & : prob.\ HMCR \\ x'_i \in X_i & : prob.\ (1-HMCR) \end{cases} \quad (6)$$

4. Decide the value of PAR (pitch adjustment rate) from the range $0.0 \leq PAR \leq 1.0$

$$x_j^i = x_j^L + rand(0,1) \times (x_j^U - x_j^L) \quad (7)$$

$$x'_i \leftarrow \begin{cases} yes & with\ probability\ PAR \\ no & with\ probability\ (1-PAR) \end{cases} \quad (8)$$

5. Compute the step size (b_i) as $b(i) = (x_i^U - x_i^L)/N$

6. Specify the maximum limit of iteration number.

Step 2: HM Initiation: The HM matrix as in Eqn. (9) is filled with randomly generated possible solution vectors for HMS and is sorted by the values of the objective function f(x).

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \Rightarrow \begin{bmatrix} f(x^1) \\ f(x^2) \\ \vdots \\ f(x^{HMS-1}) \\ f(x^{HMS}) \end{bmatrix} \quad (9)$$

Step 3: Improvisation Process: A New Harmony vector $x' = (x'_1, x'_2, ..., x'_n)$ is generated based on three criteria: random selection, memory consideration, and pitch adjustment.

Random Selection: To decide the value of x'_1 for the New Harmony $x' = (x'_1, x'_2, ..., x'_n)$, the HS algorithm randomly selects a value from range with a probability of "*1 - HMCR*".

Memory Consideration: To decide the value of x'_1, the HS algorithm randomly selects a value x_1^j from the HM with a probability of "*HMCR*", where *j = 1, 2,…, HMS*. It can be represented as in Eqn. (9).

Pitch Adjustment: Each element of the New HM vector $x' = (x'_1, x'_2, ..., x'_n)$ is subjected to determine whether it should be pitch-adjusted or not. The selected x'_i is further adjusted by adding an amount to the value with a probability of PAR. The PAR parameter is called the probability of pitch adjustment and is represented by Eqn. (8).

The *'no'* with probability *'1 - PAR'* represents that the probability of not adding any amount. On the other hand, if the pitch adjustment decision for x'_i is yes, then x'_i is replaced by $x'_i \leftarrow x'_i \pm bw$; where, *bw* is distance bandwidth in case a continuous variable. The pitch adjustment is performed on every variable of the New HM vector.

Step 4: Updating the HM: Let the HM vector is $x' = (x'_1, x'_2, ..., x'_n)$, which is resolved by minimization of objective function is better than the worst harmony present in the HM. Therefore, the New Harmony is inserted into the HM, while, the worst harmony is removed from the HM.

Step 5: Checking the stopping criterion: If the maximum count of improvisations is reached and the stopping criterion as maximum number of iterations is satisfied, then the process of computation is terminated. Otherwise, go to steps 3 and 4 to repeat the process. The HS algorithm is shown in the Figure 4.

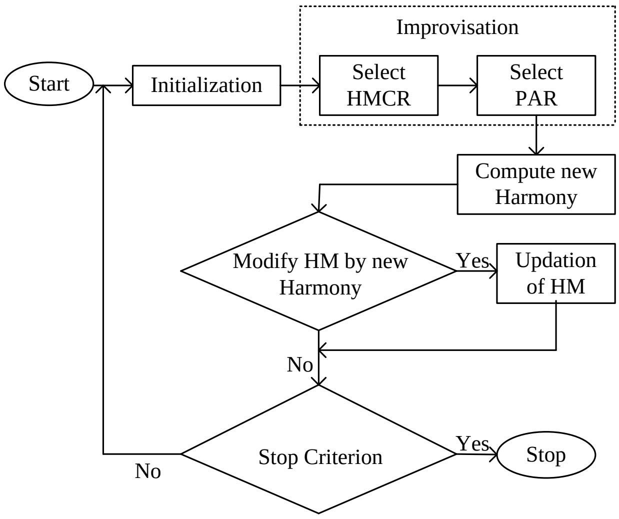

Figure 4. Harmony Search Algorithm

4. Results and Discussions

4.1. Experimental Plant Creation

The line diagram of ten-machine thirty nine-bus power system (New England thirty nine bus test system) as in Figure 1, while the system data are as in [21]. A linear representation of the system without PSSs is formed around a nominal point and the power system models (plants) are generated by applying change in active power, active load and fault at different bus numbers as in Table 1. The plants generated are subjected to operate without PSS (i.e. under open loop) and the speed responses of generators (ten in number) in each plant are recorded. It is clear that none of generator of any plant is showing stable operation. The proposed HSPIDPSS and FPSS would be implemented on these plants and the performance analysis is carried out.

4.2. HSA Optimized PID Parameters

The above generated plants as in Table 1 are equipped with the PID controller as in Figure 3 and optimized by Harmony Search algorithm subjected to the objective function (as in section 2.3) with the parametric bounds such as $-5 \leq K_p \leq 50$, $-5 \leq K_d \leq 50$ and $-5 \leq K_i \leq 50$. The optimized parameters of controllers connected to generators for plant-1 are enlisted in the Table 2. The performance of the HSA during optimization for 200 iterations is shown in Figure 5 under function minimization and in terms of fitness function value. This figure incorporates the maximum function value at starting as 0.0018 and minimum at the end of 200 iterations as 9.4803×10^{-4}.

Table 1. Ten-machine thirty nine-bus power system plants

Plant	Active Power	Fault Location
1	[5.519816;10.00; 6.5000; 5.080; 6.3200; 6.500; 5.60000; 5.400; 8.3000; 2.500]	Bus No. – 16, Base case for active power and active load
2	[5.519816; 10.0; 6.6000; 5.08000; 6.1200; 6.5000; 5.60000; 5.4000; 8.30000; 2.5000]	Bus No. – 13, Active power of Gen -3 and 5 are changed., Active load of Gen -1 and 2 are changed.
3	[5.419816; 10.10; 6.4000; 5.18000; 6.32000; 6.5000; 5.60000; 5.4000; 8.3000; 2.50000]	Bus No. – 11, Active power of Gen – 1, 2, 3 and 4 are changed, Active load of Gen -2 and 4 are changed.
4	[5.519816; 10.0; 6.5000; 5.08000; 6.32000; 6.5000; 5.50000; 5.5000; 8.3000; 2.50000]	Bus No. – 9, Active power of Gen – 7 and 8 are changed, Active load of Gen -8 and 9 are changed.

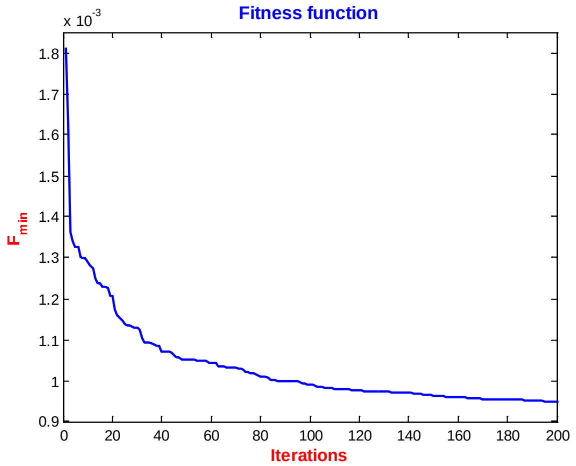

Figure 5. Plot of fitness function with iterations

Table 2. The harmony search tuned PID parameters for ten generators of plant 1-4

Generators	Kp	Kd	Ki
Gen-1	49.9948	15.5289	38.1243
Gen-2	48.9951	49.9127	49.2617
Gen-3	46.9101	23.3802	48.6788
Gen-4	36.2787	48.5096	46.2030
Gen-5	49.2328	35.6628	46.8553
Gen-6	48.6677	39.2584	49.7246
Gen-7	45.7080	11.1073	49.6559
Gen-8	47.4491	33.3796	44.4684
Gen-9	46.3637	13.7397	43.7974
Gen-10	46.9797	19.5897	45.1682

The initializing parameters of the harmony search algorithm to optimize the controller parameters are as the number of variables (NVAR) is 20, maximum number of iterations as 200, memory size (HMS) as 40 (equal to the order of the plant matrix), harmony consideration rate (HMCR) as 0.9, minimum pitch adjusting rate (PAR_{min}) as 0.2, maximum pitch adjusting rate (PAR_{max}) as 0.5, minimum (bw_{min}) and maximum (bw_{max}) value of bandwidth as 0.0001 and 1, respectively.

4.3. Eigenvalue Analysis

The test system without PSS and equipped with HSPIDPSS is subjected to linear mode for determination of connected eigenvalue for different plant conditions as mentioned in Table 1. The nonlinear simulation of the test system without PSS reveals that none of the generators are giving a stable response; therefore, the related damping factor is negative and the plot of the eigenvalue is incorporated in Figure 6 with circular red colour for all four plant conditions. The eigenvalue of the test system with the HSPIDPSS associated to different plant conditions are represented in Figure 6 and tabulated in Table 3. The eigenvalue plot of the system with HSPIDPSS satisfies the d-shape sector condition ($\sigma < -1$ and $\xi > 0.1$) as mentioned in section 2.3. No eigenvalue having real part (σ) as > -1 and associating damping factor (ξ) as < 0.1 can prove system stability within the D-shape sector. The test system without PSS has 20 electromechanical modes of oscillations (EMOs) out of total 40 eigenvalue. On application of HSPIDPSS, one eigenvalue to the real axis of s-plane is added for a generator, and the EMO is being adjusted to giving stable operation of the generators. Therefore, the total eigenvalue of the test system becomes as 50 with HSPIDPSS. On the other hand, application of conventional PSS as in [2] adds one extra EMO and one eigenvalue at real axis, making total eigenvalue as 60.

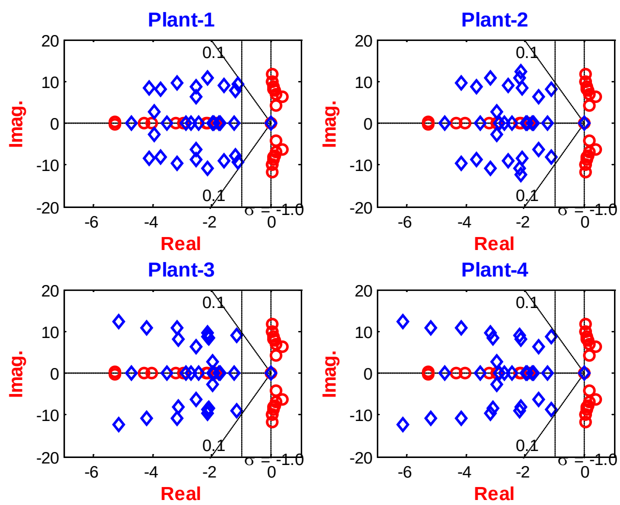

Figure 6. Plot of dominant EMOs for plant 1 to 4 of test system without PSS and with HSPIDPSS

4.4. Speed Response Analysis

Since the objective of the paper is to optimize the PID controller parameters using Harmony Search Algorithm, therefore, the system responses without PSS, with FPSS as in [19] and with HSPIDPSS are compared. Since four plants consists forty generator responses, therefore, it is not possible to show generator wise response analysis in graphical form. It is clear that the speed response with HS optimized PIDPSS is quickly settling as compared to the response with fuzzy PSS for all generators. To be considerate of space constraint, the speed response with FPSS and with HSPIDPSS for plant 1, 2, 3 and 4 are shown in Fig. 7(a), 7(b), 8(a), 8(b), 9(a), 9(b), 10(a), and 10(b), respectively. However, to four plants in terms of settling time with FPSS and with HSPIDPSS is provided in Table 4. The oscillations are damped out much faster of the power system with HSPIDPSS as compared to system equipped with FPSSs. This illustrates the potential and superiority of the proposed design approach to obtain an optimal set of PID parameters using HSA (HSPIDPSS).

Table 3. Representation of least damped EMOs with damping factor and frequency in Hz of all ten generators for plant 1 to 4

Gen	Plant-1	Plant-2	Plant-3	Plant-4
1	-1.1300+9.3983i [0.1194, 1.4958]	-2.1302 +12.3967i [0.1694, 1.9730]	-5.1302 +12.3956i [0.3824, 1.9728]	-6.1316 +12.3960i [0.4434, 1.9729]
2	-1.1869 + 7.9126i [0.1483, 1.2593]	-2.1843 +10.9059i [0.1964, 1.7357]	-4.1876 +10.9123i [0.3583, 1.7367]	-5.1861 +10.9142i [0.4292, 1.7370]
3	-2.1620 +10.7767i [0.1967, 1.7152]	-3.1619 +10.7789i [0.2815, 1.7155]	-3.1626 +10.7747i [0.2816, 1.7149]	-4.1610 -10.7757i [0.3602, 1.7150]
4	-3.1536 + 9.7621i [0.3074, 1.5537]	-4.1542 + 9.7615i [0.3916, 1.5536]	-2.1535 + 9.7610i [0.2154, 1.5535]	-3.1542 - 9.7666i [0.3073, 1.5544]
5	-1.5712 - 9.1341i [0.1695, 1.4537]	-2.5717 + 9.1386i [0.2709, 1.4545]	-1.1706 + 9.1343i [0.1271, 1.4538]	-2.1716 - 9.1336i [0.2313, 1.4537]
6	-2.5303 - 8.8194i [0.2758, 1.4037]	-3.6301 + 8.8220i [0.3805, 1.4041]	-2.1320 + 8.8187i [0.2350, 1.4035]	-1.1298 - 8.8204i [0.1270, 1.4038]
7	-3.7228 - 8.1134i [0.4170, 1.2913]	-1.1231 + 8.1171i [0.1371, 1.2919]	-3.1223 + 8.1169i [0.3590, 1.2919]	-2.1230 - 8.1138i [0.2531, 1.2914]
8	-4.1008 - 8.3493i [0.4409, 1.3288]	-2.1014 + 8.3562i [0.2439, 1.3299]	-2.1010 + 8.3492i [0.2440, 1.3288]	-3.1015 - 8.3544i [0.3480, 1.3296]
9	-2.5359 - 6.3300i [0.3719, 1.0075]	-1.5355 + 6.3284i [0.2358, 1.0072]	-2.5367 - 6.3356i [0.3717, 1.0083]	-1.5357 - 6.3290i [0.2358, 1.0073]
10	-3.9570 + 2.7781i [0.8184, 0.4422]	-2.9627 + 2.7840i [0.7287, 0.4431]	-1.9562 - 2.7756i [0.5761, 0.4417]	-2.9573 - 2.7791i [0.7287, 0.4423]

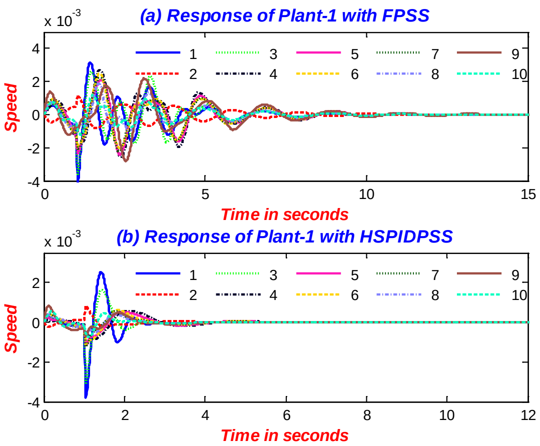

Figure 7. *Speed response of* ten *g*enerators for (a) Plant-1 with Fuzzy PSS, and (b) Plant-1 with HSA tuned PID based PSS

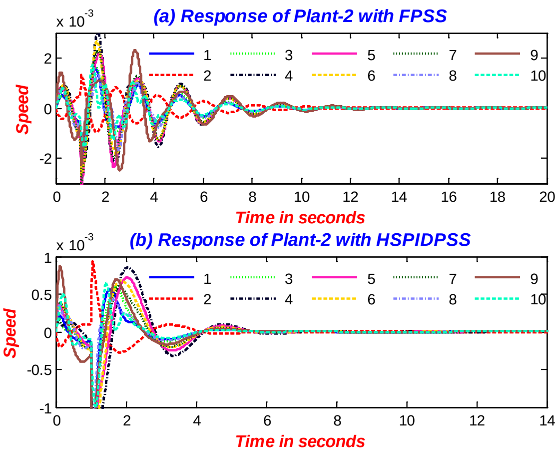

Figure 8. Speed response of ten generators for (a) Plant-2 with Fuzzy PSS, and (b) Plant-2 with HSA tuned PID based PSS

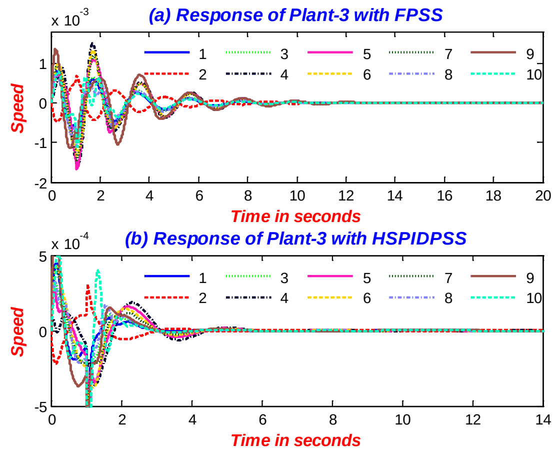

Figure 9. Speed response of ten generators for (a) Plant-3 with Fuzzy PSS, and (b) Plant-3 with HSA tuned PID based PSS

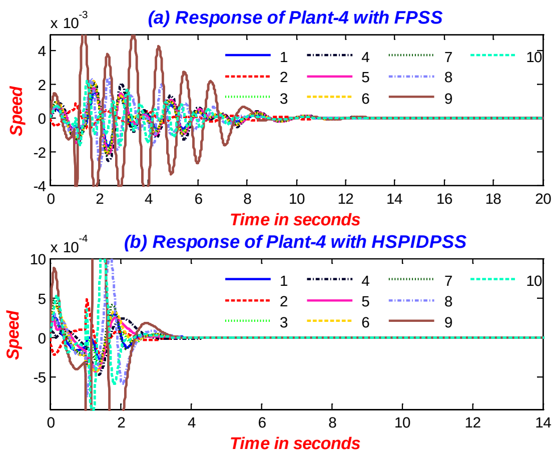

Figure 10. Speed response of ten generators for (a) Plant-4 with Fuzzy PSS, and (b) Plant-4 with HSA tuned PID based PSS

4.5. Performance Index Based Analysis

For completeness and clear perceptiveness about the system response for all the system conditions, three performance indices (PIs) that reflect the settling time and overshoot are introduced and evaluated. These indices are defined as.

ITAE: Integral of the Time-Weighted Absolute Error

$$ITAE = \int_{t=0}^{T=t_{sim}} t\left|\Delta\omega(t)\right| dt \quad (10)$$

ISE: Integral Square Error

$$ISE = \int_{t=0}^{T=t_{sim}} \left|\Delta\omega(t)\right|^2 dt \quad (11)$$

IAE: Integral of the Absolute Error

$$IAE = \int_{t=0}^{T=t_{sim}} \left|\Delta\omega(t)\right| dt \quad (12)$$

where, t_{sim} is the simulation time of the system. The performance indices as ITAE calculated for speed response of plants 1 to 4, without PSS (open), with FPSS and with HSPIDPSS are mentioned in Table 5. Here, it should be cleared that the least value of performance index represents the best performance of the system. As in plant 1 to 4, the PIs with HSPIDPSS as compared to without PSS (open) and with PIDPSS are least. The response with least value of performance index as compared to others represents best speed response performance.

Table 4. Settling time of Speed response of different generators of different plants 1-4

Generators of a plant	Plant-1		Plant-2		Plant-3		Plant-4	
	With FPSS	With HSPIDPSS	With FPSS	With HSPIDPSS	With FPSS	With HSPIDPSS	With FPSS	With HSPIDPSS
Gen-1	9.80	2.73	9.05	4.18	8.27	1.62	10.8	2.50
Gen-2	11.60	4.30	12.60	4.54	9.22	3.02	11.82	2.94
Gen-3	9.71	3.64	11.46	3.84	8.32	4.14	10.97	2.80
Gen-4	12.52	4.47	12.74	5.54	10.37	5.60	13.04	2.83
Gen-5	11.98	4.32	13.10	5.17	10.61	4.24	13.28	2.45
Gen-6	10.85	4.38	11.52	4.53	11.67	3.13	14.15	2.64
Gen-7	11.78	4.26	13.89	4.40	12.66	5.06	13.24	2.58
Gen-8	11.85	4.43	11.45	4.30	10.71	1.86	11.09	3.26
Gen-9	11.75	4.11	13.83	4.28	12.62	2.14	13.36	2.96
Gen-10	9.54	3.54	10.34	4.11	9.31	2.09	10.14	2.42

Table 5. Performance indices (ITAE, IAE & ISE) based analysis of test system with controllers (FPSS, HSPIDPSS) & with No-PSS

Power System Model	Performance Index	No-PSS	FPSS	HSPIDPSS
Plant-1	ITAE	10.1103	0.1835	0.0162
	ISE	33.7468	7.0380E-06	6.0821E-06
	IAE	14.2518	1.0153E-02	9.7441E-03
Plant-2	ITAE	9.1624	0.1763	0.0205
	ISE	28.0987	5.4935E-06	4.1689E-06
	IAE	12.8673	1.0022E-02	1.0918E-03
Plant-3	ITAE	8.7297	0.0656	0.0063
	ISE	26.3265	1.0135E-06	1.0039E-06
	IAE	12.0369	4.3459E-03	3.3941E-04
Plant-4	ITAE	9.9514	0.2134	0.0114
	ISE	33.0254	6.8345E-06	95.2511E-06
	IAE	14.1362	8.5675E-03	7.7710E-04

5. Conclusions

In this paper, the proportional integral derivative based power system stabilizer is designed for IEEE ten-machine thirty nine–bus test power system model. The constants of PID controller are optimized by using Harmony Search Algorithm with an objective function based on eigenvalue shifting. The speed response of the generator for the multimachine power system without PSS, with fuzzy PSS and with the harmony search algorithms based optimized PIDPSS are compared. It is found that the response with FPSS can stabilize the system under adverse operating conditions (under several faults) with prolonged settling time as compared against a few of seconds with HSPIDPSS. The superior performance of HSPIDPSS is further illustrated by using performance indices associated to speed response as the value is least as compared to the system without PSS and with FPSS. The linear mode of the test system with HSPIDPSS is analyzed to guarantee system stability in D-shape sector on s-plane.

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