

ROBUST TUNING OF POWER SYSTEM STABILIZER PARAMETERS USING THE MODIFIED HARMONIC SEARCH ALGORITHM

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ABSTRACT: Power System Stabilizer is used to improve power system low frequency oscillations during small disturbances. In large scale power systems involving a large number of generators, PSSs parameter tuning is very difficult because of the oscillatory modes' low damping ratios. So, the PSS tuning procedure is a complicated process to respond to operation condition changes in the power system. Some studies have been implemented on PSS tuning procedures, but the Harmony Search algorithm is a new approach in the PSS tuning procedure. In power system dynamic studies at the first step system total status is considered and then the existed conditions are extended to the all generators and equipment. Generators' PSS parameter tuning is usually implemented based on a dominant operation point in which the damping ratio of the oscillation modes is maximized. In fact the PSSs are installed in the system to improve the small signal stability in the system. So, a detailed model of the system and its contents are required to understand the dynamic behaviours of the system. In this study, the first step was to linearize differential equations of the system around the operation point. Then, an approach based on the modified Harmony Search algorithm was proposed to tune the PSS parameters.

ABSTRAK: Penstabil Sistem Kuasa digunakan bagi meningkatkan sistem kuasa ayunan frekuensi rendah semasa gangguan kecil. Dalam sistem kuasa berskala besar yang melibatkan sebilangan besar penjana, penalaan parameter PSS adalah sangat sukar kerana nisbah corak ayunan redaman yang rendah. Maka, langkah penalaan PSS adalah satu aliran rumit bagi mengubah keadaan operasi sistem kuasa. Beberapa kajian telah dilaksanakan pada prosedur penalaan PSS, tetapi algoritma Harmony Search merupakan pendekatan baru dalam prosedur penalaan PSS. Dalam kajian sistem kuasa dinamik ini, langkah pertama adalah dengan memastikan status total sistem dan keadaan sedia ada diperluaskan kepada semua penjana dan peralatan. Parameter penalaan generator PSS biasa dilaksanakan berdasarkan titik operasi yang dominan di mana nisbah corak ayunan redaman dimaksimumkan. Malah PSS dipasang di dalam sistem bagi meningkatkan kestabilan isyarat kecil dalam sistem. Oleh itu, model terperinci sistem dan kandungannya diperlukan bagi mengenal pasti perihai sistem dinamik. Kajian ini, dimulai dengan melinear sistem persamaan pembezaan pada titik operasi. Kemudian, pendekatan berdasarkan algoritma Harmony Search yang diubah suai telah dicadangkan bagi penalaan parameter PSS.

KEYWORDS: power system stabilizer (PSS); power system; harmonic search algorithm

1. INTRODUCTION

Small-signal fluctuation stability is a major issue for power system security and reliability. These fluctuations affect the power system's natural damping [1]. PSS, if well-tuned, will have the ability to function properly in the system [2]. Although these stabilizers have a simple and robust structure, their configuration, even with computer simulation or field testing, involves a highly skilled process for system parameters [3]. These parameters are not readily available and may, during normal operation of the power system, change the values of the parameters [4]. These parameters cannot be measured directly so they should be well estimated [5]. Recently, several heuristic search algorithms have been proposed for tuning, PSS parameters, such as tab search [6] evolutionary programming [7], and Particle Swarm Optimization (PSO) [8] were suggested to evaluate the PSS Parameters. However, these methods failed to determine precise parameters when the system has a specific objective function with a large-scale number of parameters.

2. PROBLEM FORMULATION

The power system can be described using a set of first-order nonlinear differential equations[8]:

$$\dot{X} = f(x, u) \quad (1)$$

Where \dot{X} or x is the state variables vector, and u is the vector of input variables. The linearized models of a power system can be used to design the power system stabilizers. Therefore, the state equation of the power system with stabilizers can be written as [9]:

$$\Delta\dot{X} = A\Delta X + BU \quad (2)$$

$$\Delta y = C\Delta X + D\Delta U \quad (3)$$

where Δ represents small changes, X is the state vector of order n , y is the output vector of order m , U is the input vector of order r , A is a square matrix of states of size n , B represents a control matrix with size $n \times r$, C refers to the output matrix with size $m \times n$, D is the leading matrix with the size $m \times r$.

A traditional lead-lag compensator PSS is utilized in this study. The transfer function of the PSS is described by the following equation [10]:

$$V_i = K_i \frac{sT_\omega}{1+sT_\omega} \frac{(1+sT_{1i})}{(1+sT_2)} \frac{(1+sT_{3i})}{(1+sT_4)} \Delta\omega_i \quad (4)$$

where V_i is the output signal for PSS at i th machine, K_i The stabilizer gain, T_ω represents the time constant, $\Delta\omega_i$ speed deviation of i th machine from the synchronous speed.

3. OBJECTIVE FUNCTIONS

The Objective functions are formulated by tuning the PSS parameter and there are three different objective functions that have been used in many studies to set parameters, which will be discussed below:

a) The damping factor can be considered as the first objective as follows [11]:

$$\left(\max_{1 \leq q \leq n_q} \sigma_q \right)_y \quad (5)$$

$$\left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_y \quad (6)$$

$$\left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_1 + \left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_2 + \dots + \left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_{n_y} \quad (7)$$

$$MinF1 = \sum_{y=1}^{n_y} \left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_y \quad (8)$$

where, n_y are the all operating statuses of the test system, n_q denotes the number of eigenvalues under n_y , σ_q is the damping factor, σ_0 is damping factor constant. When the $F1$ (σ_q is defined as Damping factor) is less than or equal to zero, the response for the maximum damping factor ($\max_{1 \leq q \leq n_q}$) is less than or exactly equal to the expected value σ_0 , [12].

b) The damping ratio can be considered as the second objective as follows [13]:

$$MinF2 = \sum_{y=1}^{n_y} \left(\zeta_0 - \min_{1 \leq q \leq n_q} \zeta_q \right)_y \quad (9)$$

where ζ_0 represents the predicted damping ratio constant, and ζ_q represents the damping ratio. When $F2$ is less than or equal to zero, the response is the minimum damping ratio(s) ($\min_{1 \leq q \leq n_q} \zeta_q$) are more than or exactly the value of ζ_0 [14].

c) The damping ratio and damping factor can be considered as the third objective as follows [15]:

$$MinF3 = \sum_{y=1}^{n_y} \left(\max_{1 \leq q \leq n_q} \sigma_q - \sigma_0 \right)_y + \alpha \sum_{y=1}^{n_y} \left(\zeta_0 - \min_{1 \leq q \leq n_q} \zeta_q \right)_y \quad (10)$$

where α is the weight for combining both damping ratio and damping factor.

4. PROPOSED OBJECTIVE FUNCTION

The objective functions F1, F2, and F3 produce high frequency or low frequency, which may reduce the life of system devices [16]. Therefore, we can overcome the disadvantages mentioned earlier through the following equation [17]:

$$X = \frac{-(\sigma - \sigma_0)}{\sqrt{(\sigma - \sigma_0)^2 + \omega^2}} \times 100\% \quad (11)$$

$$MinF4 = \sum_{y=1}^{n_y} \left(X_0 - \min_{1 \leq q \leq n_q} X_q \right)_y \quad (12)$$

where

X: the constant value for the prospective damping scale

X_q: the damping scale for the qth eigenvalue

The following equations present the constraints of the PSS parameter design model [18]:

$$\left\{ \begin{array}{l} K_{min} \leq K \leq K_{max} \\ T_{1min} \leq T_1 \leq T_{1max} \\ T_{2min} \leq T_2 \leq T_{2max} \\ T_{3min} \leq T_3 \leq T_{3max} \\ T_{4min} \leq T_4 \leq T_{4max} \end{array} \right\} \quad (13)$$

5. THE PROPOSED ALGORITHM

Harmonic Search Algorithm is one of the simplest and most up-to-date methods, which is the process of finding the optimal solution to the problem. This method was used for the first time in 2001 [19]. Harmony search is inspired by the process of jazz musicians to find the optimal solution. In this algorithm, each solution is called a harmonic and is represented by a vector (N). This algorithm contains the following steps [20]:

a) Primary generation (Initial initialization)

In the first step, the optimization problem is indicated by the relationship. Also, at this step, the Harmony Memory size (HMS) is calculated.

$$Min: \{f(x) | x \in X\} \quad (14)$$

$$Subject\ to : g(x) \geq 0 \quad h(x) = 0 \quad (15)$$

where: $f(x)$ is the objective function, $h(x)$ and $g(x)$ are the functions of equal and unequal constraints respectively. Also in this step, the HS algorithm parameters are specified. These parameters are [21] :

- 1) Harmony Memory Size (HMS), or the number of solution vectors in the harmony memory.
- 2) Harmony Memory Considering Rate (HMCR), $HMCR \in [0,1]$.
- 3) Pitch Adjusting Rate (PAR) $\in [0,1]$.
- 4) Stopping criterion or number of improvisations (NI)

b) Primary Harmonic Memory Determination

At this step, the Harmony matrix (HM) is created from a large number of solution vectors that are created randomly[22].

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \quad (16)$$

c) New harmonic production based on improvisation

d) A new harmonic vector $x'(x'_1, x'_2, \dots, x'_N)$ is produced based on three rules that it describes as improvised:

- 1) Harmony Memory Considering Rate (HMCR)

- 2) sound regulation
- 3) random selection
- e) Updating Harmony Memory: If the new harmonic vector is better than the worst harmonic vector based on the selected target function, the new harmony is placed inside and the worst harmonic is left out of the set.
- f) Check the stopping criterion: when the termination criterion is satisfied, the calculations are completed, otherwise, steps 3 and 4 are repeated.

6. MODIFIED HARMONY SEARCH (MHS)

The disadvantages of the HS method are the use of PAR and Bandwidth, BW, constant values, which makes it difficult to set up these parameters. Another disadvantage of the HS is that the number of repetitions for which the algorithm needs to find the optimal solution is not appropriate [23]. If PAR is small and BW is large, the algorithm's performance is weak hence increased NI improvements are required to find that optimal solution Fig. 1.

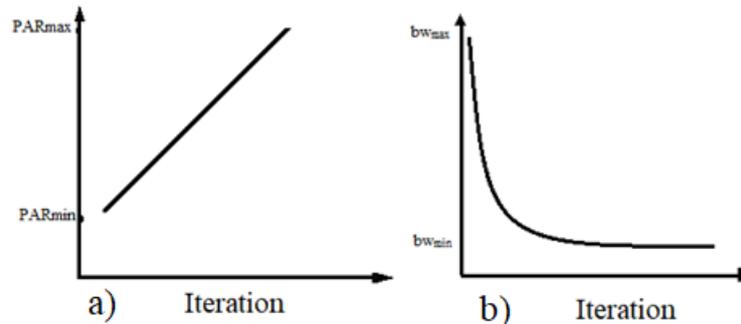


Fig. 1: a) change of PAR with iteration number,
 b) change of BW with iteration number 3-or 4.

The initial iteration of the HS has large BW and small PAR , which leads to increase the entire solution space of the search algorithm. These values are appropriate for subsequent replies in order to locally search. MHS is similar to HS, with a little difference in that PAR and BW parameter values are dynamically generated in each individual iteration according to the following relationships [24]:

$$PAR(gn) = PAR_{min} + \frac{PAR_{max} - PAR_{min}}{NI} \times t \quad (17)$$

where,

PAR(t) = Pitch Adjusting Rate for each iteration

PAR_{min} = Minimum Pitch Adjusting Rate

PAR_{max} = Maximum Pitch Adjusting Rate

NI = Number of solution vector Iteration

t = Iteration Number

$$bw(t) = bw_{max} \times e^{\left[\frac{1n \left[\frac{bw_{min}}{bw_{max}} \right] \times t}{N1} \right]} \quad (18)$$

where,

$bw(t)$ = Bandwidth for each iteration

bw_{min} = Minimum bandwidth

bw_{max} = Maximum bandwidth

7. PSS DESIGN AND SIMULATION RESULTS

In this study, the MHS algorithm is used to obtain the optimal design of the PSS parameters for the system of four generators shown in Fig. 2 [25] and compare results with other techniques (Harmony Search, Classic Approach).

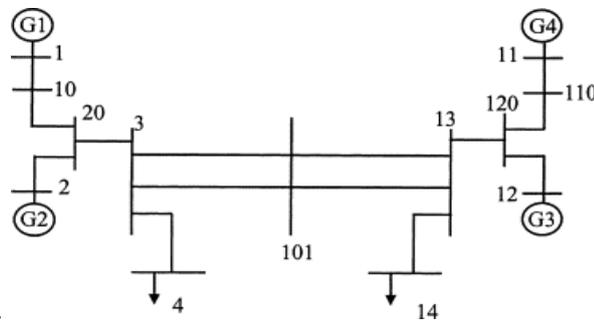


Fig. 2: Single-line diagram of the 4-generator system.

7.1 Case 1: The Stability of Four-Generators Without PSS

In this case, the system was tested after the fault at bus-3 without PSS to demonstrate the effect of PSS on the stability of this system. According to Table 1, the system is unstable. From Figures 3 and 4, it is observed that the rate of voltage changes and oscillation of the generator's speed are very high and the system is practically unstable.

Table 1: The Four-Generator data without PSS

Generators	Eigenvalues	Frequencies	Damping Ratios
1,2,3,4	$\pm 3.994j$	0.6354	-0.0134
3,4	$\pm 7.274j$	1.1577	0.0668
1,2	$\pm 7.323j$	1.655	0.0658

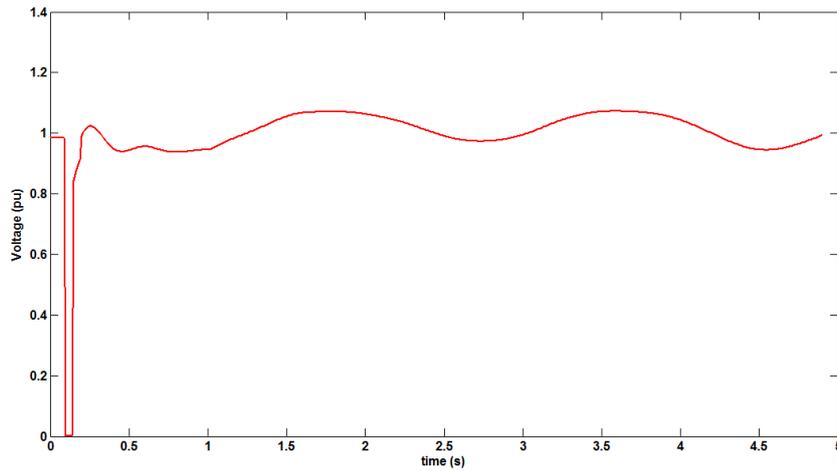


Fig. 3: The bus voltage changes after the fault at bus-3 without PSS

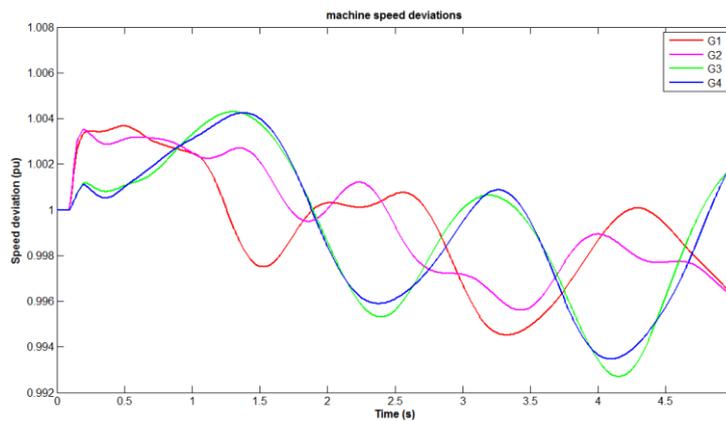


Fig. 4: Generator speed changes after the fault at bus-3 without PSS.

7.2 Case 2: The Stability of Four-Generators with PSS Based On (MHS)

In this case, PSS is installed on each generator which will guarantee stability of the system and restrain unwanted oscillations. Thus, the PSS parameter is set based on the (MHS) algorithm. The results of the modified harmonic search for the parameters are presented in Table 2. From Fig. 5 and Fig. 6 it is clear that the oscillations due to disturbances are completely repressed and the dynamic state of the system improved. All this happened only after installation of the PSS. Figure 7 explains the convergence of the objective function with MHSA and HSA. From this figure, it is clear that MHSA shows superior performance over HSA. The proposed method obtained the solution after 210 iterations while the HSA reached the solution after 300 iterations. This speed in finding the optimal solution is very important in the stability of the system.

Table 2: Optimal Designed Parameters of MHS

Generator	T ₄	T ₃	T ₂	T ₁	T _w	K
1	0.01	0.08	0.01	0.07	10	100
2	0.02	0.1	0.02	0.09	10	127
3	0.01	0.1	0.01	0.1	10	148
4	0.02	0.08	0.02	0.12	10	95

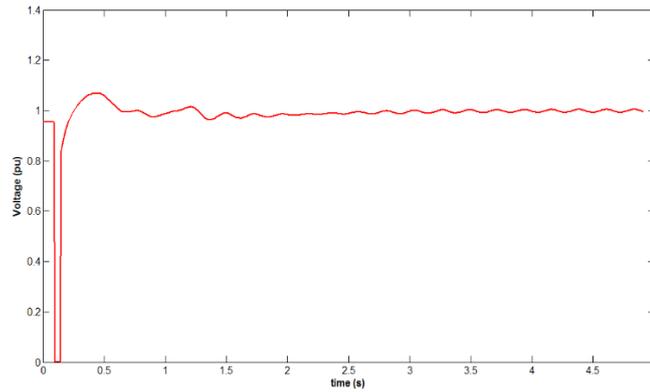


Fig. 5: Voltage changes on the bus number 3 with PSS.

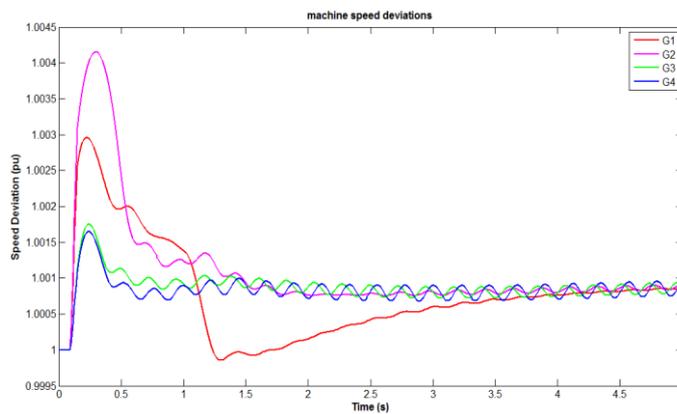


Fig. 6: Generator speed changes after the fault at bus 3 with PSS.

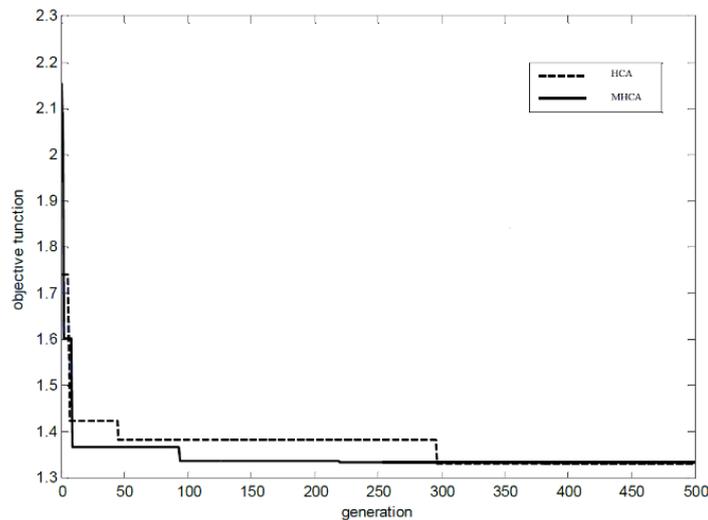


Fig. 7: Convergence characteristics of HSA and MHSA techniques.

Furthermore the above results are compared with those presented in [26] for the 4-generator system. In this reference, the parameters were obtained using the sensitivity analysis method. Table (3) shows the results of the special system values with stabilizer in the two studies. From Fig. 8-9 and Table 3, it is very clear that the performance of the PSS

designed using MHS is far better compared to the PSS designed using Sensitivity Approach (TSA) and Harmony Search.

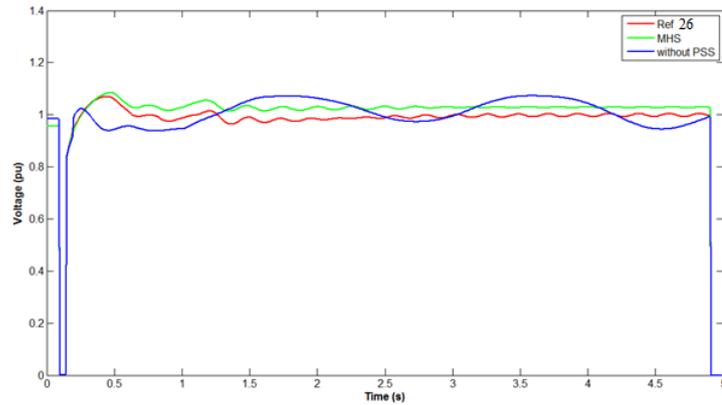


Fig. 8: Voltage changes at bus 3 after fault in the three-phase system.

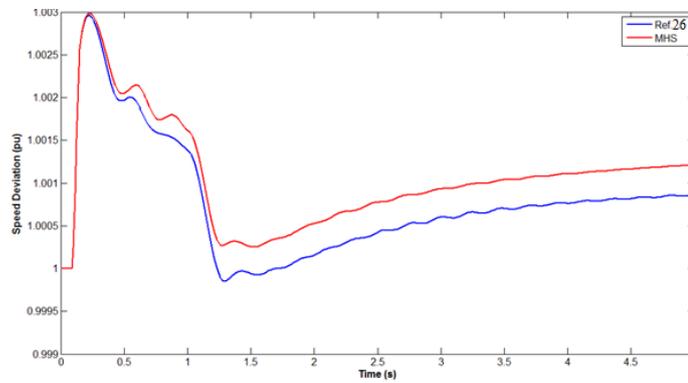


Fig. 9: the changes of the first generator speed.

Table 3: Eigenvalues of the System 4 Generators for Modified Harmony Search Method and Trajectory Sensitivity Approach

Generators	Eigenvalues	Frequencies	Damping Ratios
MHS	$-2.138 \pm j5.738$	0.856	0.397
	$-2.714 \pm j6.736$	0.891	0.391
	$-1.130 \pm j4.214$	0.637	0.268
Trajectory Sensitivity Approach (TSA)[26]	$-1.938 \pm j5.738$	0.913	0.319
	$-2.165 \pm j5.936$	0.945	0.343
	$-0.530 \pm j3.504$	0.558	0.149

8. CONCLUSION

Transient and small-signal stability are critical in power system operation and control studies due to their impact on consumers. Thus power system stabilizers could be used to solve this issue. A modified harmonic search algorithm was proposed to tune the PSS parameters to overcome the drawbacks of the previously suggested algorithms. The MHS results show that adjusted stabilizers have improved performance. The proposed method was applied to a system of four generators. The MHS algorithm results were compared

with the results of the sensitivity analysis method, which was previously suggested for this purpose. The comparison indicates the superiority of this algorithm to obtain the optimal parameters to set the stabilizer.

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