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Design and Optimization of Simultaneous FPSS Controller and H∞TCSC Controller to Eliminate Low Frequency Oscillations in a Wide Range of Power Systems

Pouya Derakhshan-Barjoei[1], Meysam Momenian-Koupaie[2]

[1]*Department of Electrical Engineering, Young Researchers and Elite Club, Naein Branch, Islamic Azad University, Naein, Iran*

[2]*Department of Electrical Engineering, Naein Branch, Islamic Azad University, Naein, Iran*

Abstract: *Low frequency oscillations are considered as the main causes of the reduction of security and stability for today's interconnected power systems. However, with the installation of a PSS on the generator, the damping of the oscillations is attenuated, but the improvement of the damping quality of these oscillations is still one of the most important issues. Today, with the advent of the FACTS, it is possible to reduce these fluctuations along the transmission lines. In this paper, in order to simulate low frequency oscillations, we have evaluated a proposed hybrid control method to overcome uncertainties in the power system. In this method, H∞ TCSC controller is used to control the uncertainty of the parameters. The coordinated evaluation of the FPSS controller and the H∞ TCSC controller to stabilize the low frequency oscillation of the single-machine power system with the presence of parameters uncertainty has been addressed. The Particle Swarm Optimization (PSO) and Harmony Search Algorithm (HSA) evolutionary algorithms are also used to optimize the parameters of controllers. By simulating and evaluating the results in MATLAB software, the selective controller is more suitable for using the HSA algorithm.*

Keywords: *Low Frequency Oscillations, Power System Stabilization, FACTS, Fuzzy Logic, Evolutionary Algorithms.*

1. INTRODUCTION

In recent years, regional power companies have been forced to exploit existing power networks with maximum capacity for economic, control and environmental reasons [1]. With the emergence of large power systems and their interconnection, low frequency oscillations were observed at a range of 0.3-3 Hz in the power system. These fluctuations may occur after they occur or remain in the system, increasing their amplitude and causing system instability [2]. Due to the reasons mentioned above, one of the concerns of designers and utilities of modern power networks is sustainability, and one of the challenging issues in terms of sustainability is low frequency oscillation (LFO). This oscillation, in the absence of sufficient damping, can cause an island phenomenon in the power system [3]. Although the Power System Stabilizer (PSS) is considered as one of the integral parts of the generator in order to dampen the oscillations in the power system, its function is influenced by various factors such as network structure changes, load variations, etc. [4], And it may not have enough damage to the system [5]. In order to improve PSS performance, various methods have been developed for designing them. In the reference [6], using a new fuzzy logic with multiple inputs in the single-ended power system and [7] and [8] respectively, using self-regulating fuzzy slider mode and sliding mode The adaptive fuzzy in the two-phase and four-power power system has been studied to optimize the parameters of the power system stabilizer. An intelligent search algorithm can be found for reference [9] to optimize the PSS parameters in large-scale multimode power systems. The authors in reference [10] have optimized PSS parameters by using the Coco algorithm in the nine-bus and three-machine power system. Baley et al. in a study to optimize a PSS based on a special structure allocation algorithm in the 68-bus power system [11]. In addition to the above mentioned methods, which are based on the PSS parameters based on the linearized power system model using some artificial intelligence methods, new nonlinear control methods such as direct linear feedback can be used[12] and a multifunctional optimization for setting PSS in reference [13] and other methods. Also, the design of two controllers of power system damping in various articles such as TCSC and PSS coordination using the active power sensitivity optimization method in the 68-bus system, in order to adjust the parameters of PSS and TCSC in reference [14], coordination SVC and PSS using the modified Fruit Fly Algorithm in a three-zone integrated power system with a wind farm in reference [15] and the coordination of PV-STATCOM and PSS in a dual-system and four-machine system that has a PV device The 150 MW solar power is connected to one of its intermediate transmission lines. It is presented in reference [16].One of the types of FACTS devices is the Control Series Capacitor or Thyristor (TCSC). The TCSC is placed in series in series to reduce the line serial impedance, which increases the impedance of the line throughput and thus improves system depth. Therefore, FACTS devices such as TCSCs have the ability to increase the flexibility of performance, controllability and stability of power systems. TCSC is usually installed in high-power transmission lines. Advantages of using the TCSC include streaming power organization, reducing asymmetric components, reducing offsets in the network, providing voltage regulation, limiting short circuit shortcomings, removing power fluctuations, and improving transient stability [17]. Due to the use of PSS to modulate the power fluctuations and improve transient stability, the PSS cannot provide enough damping for system fluctuations, so in this case it is performed for optimal performance with minimum oscillation fluctuations between PSS and TCSC [18].On the other hand, it should be noted that the controllers used to erode, although they have a simple design, but after extensive adjustment, there is no solidity in stability. A lot of research has been done in this regard. In all investigated methods, the uncertainty of system parameters and loading uncertainty are not considered. Therefore, the designed controllers cannot be guaranteed against the system uncertainty and the system may be out of range under different conditions [19]. In this paper, a reference method is suggested for stability of the power system and the achievement of a robust controller for performance in all conditions. In this method, fuzzy logic has been used to design the PSS controller. Also, a control loop called H∞ has been used to improve TCSC performance for oscillation. Using this simultaneous control, it is possible to operate very differently against uncertainties in the power system. Also, evolutionary algorithms are used to optimize fuzzy logic parameters.

2. ROBUST CONTROL

In all control systems, control engineers are trying to set up specific system outputs at specific values by applying appropriate feedback signals or tracking certain variables. In the robust control theory, the closed loop system has always been robust to the disturbances and uncertainties of the system under discussion. Therefore, due to the weakness of classical methods and even modern control methods in the analysis of associated systems with uncertainty as well as the design of controllers of these systems, robust control methods can be used as one of the most effective and important methods to ensure the stability and optimal performance of this system.

In this paper, a controller is designed with the help of a robust control method and is designed to improve the damping of inter-sectional modes. Controllers are designed in the traditional way to the point of the system work, and by changing the system's working point, there is no guarantee for the controller's optimal performance. For example, a damper controller for FACTS devices designed to compensate for the geometric phase of a special value and for the nameplate conditions of the line, may be due to low or high frequency and oscillatory system changes, sufficient phase compensation for controlling the input signal, which can lead to a weakening of the controller's performance; in this case, the controller is not robust to system disturbances. The design of controllable controllers for power systems has been widely considered in recent years through advanced multimodal design techniques including LQ, LQG, H2 and H∞ techniques. The main purpose of these control methods is to design controllers that are robust to various uncertainties in the process of modeling the power system, as well as various system disturbances, including changing operating conditions. Of all the robust design methods, the H∞ method is very much considered. Unlike the H2 and LQ methods that only allow for design based on the time domain functional criteria, the H∞ method allows the designer to tailor his needs based on the weighting functions in the frequency domain. The H∞ design method based on H∞ soft minimization is a cost function assigned to reflect the resiliency and robust stability criteria of the system [21]. Controllers designed by H∞ in recent years have received a great deal of attention from the researchers in controlling the design of H∞ power systems.

3. PROPOSED METHOD

In this section, the modeling of the system studied and the design of controllers used are discussed.The studied system consists of a synchronous machine connected to an infinite shin through a transmission line. The selected model is chose from the reference 2.The state space representation for the presented model is expressed as (1):

$$\begin{aligned} \Delta \dot{X} &= A.\Delta X + B.\Delta U \\ \Delta Y &= C.\Delta Y + D.\Delta U \end{aligned} \qquad (1)$$

Which $\Delta X = [\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}]^T$ is the state vector and $\Delta Y = [\Delta\omega]$ is output vector. $\Delta U = [\Delta U_{PSS}, \Delta U_{TCSC}]^T$ Specifies the control signals generated by the FPSS and H∞TCSC controllers, while the angular velocity ($\Delta\omega$) is used as an input signal. In this section, using the basics of fuzzy theory, the details of the fuzzy logic controller are described for applying the power system under study. In this paper, for fuzzy stabilizer design (FPSS), the Fuzzy Mamdani inference engine has been selected. This FIS editor consists of two input variables (velocity variations and velocity derivative changes), an output variable (voltage variation), and a membrane FLC block. Each of the inputs and outputs of the fuzzy controller has 7 membership functions. Of course, it is worth noting that in practice, only the oscillator velocity variations are available and the changes in the angular velocity derivative, namely angular acceleration, are obtained by measuring the velocity at two different moments and from equation (2):

$$\Delta\dot{\omega}(t) = \frac{\Delta\omega(t) - \Delta\omega(t-1)}{\Delta t} \quad (2)$$

The design of the fuzzy controller design requires 3 steps: fuzzification, fuzzy rules, and defuzzification.

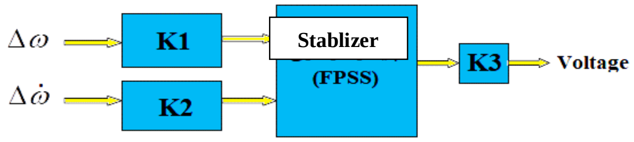

Figure 1. *Fuzzy Stabilization Structure (FPSS)*

Fuzzy rules are a set of rules that determine the relationships between inputs and the fuzzy controller output. These rules are defined using spelling phrases. When the controller has two inputs and one output, and there are seven speech variables assigned to each of the inputs and outputs, there are 49 rules that can be defined for the controller. Also, here the Mamdani method is used for fuzzy inference of the rules. The number of phrases used to describe a fuzzy or variable varies depending on the use of that variable. The fuzzification process is used to convert the velocity changes and velocity derivative changes to the fuzzy values. Seven phrases are assigned from a large negative to a large positive. Each phrase has its own membership function. The membership function determines the degree of membership that indicates the degree of attribution of the quantitative inputs or outputs to different fuzzy phrases from a fuzzy variable. Usually triangular membership functions are used to determine the degree of belonging. Therefore, to any input or output, a set of seven membership functions is attributed to the seven phrases. These membership functions for velocity and velocity inputs as well as the voltage output are shown in figure 2. Of course, it should be noted that using evolutionary algorithms, fuzzy rules, membership functions and constant coefficients of inputs and fuzzy controller output can be optimized.

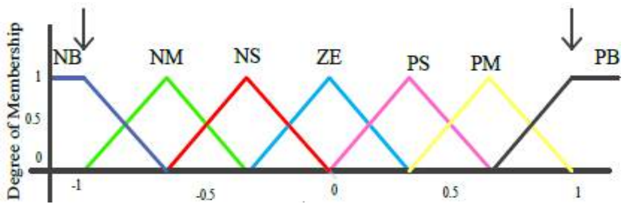

Figure 2. *Membership functions for fuzzy control variables [20]*

Finally, defuzzification should be done. At this stage, the fuzzy values derived from the inference engine are converted to specific values. The method of center of gravity is applied for defuzzification.

3.1. TCSC Controller design using H∞ method

In this paper, the controller design of the H∞ TCSC was performed using Glover-McFarlanemethod [22]. The TCSC controller design is based on the H∞ method, which is combined with the traditional loop, the transfer function of the loop as L = GK is defined as a function of the frequency. The control method for designing the H∞ TCSC controller uses a combination of loopback and robust stabilization in the proposed form. The first step is to select a late and former compensator W1 and W2. The second step is to calculate the normalized H∞ using the Glover-McFarlane method for the H∞ TCSC controller, as mentioned in reference 20.

In the presence of system uncertainties, the maximum margin ($1/\gamma_{\min}$) is determined by γ the lowest possible value. The value $\gamma_{\min}$ can be calculated by relation (3):

$$\gamma_{\min} = \sqrt{(1+\lambda_{\max}(XZ))} \quad (3)$$

Which $\lambda_{\max}(XZ)$ shows the largest amount of XZ . The minimum state space values of transfer function of Gs are (A, B, C, D), the values X and Z are unique positive deterministic solutions of the relation (4) :

$$\begin{aligned} &(A - BS^{-1}D^TC)^T X + X(A - BS^{-1}D^TC) \\ &\quad - XBS^{-1}X + C^T R^{-1}C = 0 \\ &(A - BS^{-1}D^TC)Z + Z(A - BS^{-1}D^TC)^T \\ &\quad - ZC^T R^{-1}CZ + BS^{-1}B^T = 0 \end{aligned} \quad (4)$$

In which:

$$R = I + DD^T, S = I + D^T D \quad (5)$$

γ provides good signs of robust stability to a wider range of device variations. The robust durability of the rated device is determined by the weight function selection, $\gamma_{\min} < 4$ as it is for most of the typical control system designs. If the condition $\gamma_{\min} < 4$ is not satisfied, then we must change the weighted function. The H∞ controller can be determined as follow:

$$H_\infty = \begin{bmatrix} A + BF + \gamma^2 (L^T)^{-1} ZC^T (C + DF) & \gamma^2 (L^T)^{-1} ZC^T \\ B^T X & -D^T \end{bmatrix} \quad (6)$$

$$\begin{aligned} F &= -S^{-1}(D^TC + B^TX) \\ L &= (1-\gamma^2)I + XZ \end{aligned} \quad (7)$$

$$\begin{aligned} F &= -S^{-1}(D^TC + B^TX) \\ L &= (1-\gamma^2)I + XZ \end{aligned} \quad (8)$$

With respect to the above relations, the controller H∞ TCSC, defined as K = W1 × K∞ × W2, is now found to satisfy the conditions stated in equation (9):

$$\left\| [I \ K_\infty]^T (I - G_S K_\infty)^{-1} [I \ G_S] \right\|_\infty < \gamma \qquad (9)$$

3.2. Harmonic Search Algorithm (HSA)

In this section, an algorithm is chosen to optimize the proposed method. The HSA algorithm has become the subject of many problems in recent years because of its applicability for discrete and continuous optimization problems, low mathematical calculations, simple concepts, low parameters, and easy implementation of one of the most used optimization algorithms, recently. This algorithm has less mathematical requirements than other meta-meta-methodologies, such as PSO, and can be adapted to various engineering issues with changes in parameters and operators. Unlike conventional population-based algorithms, which provide a number of answers for each problem, such as the PSO algorithm, one algorithm is found to be only one answer per repetition.

The Harmonic Search algorithm consists of five steps. [23]

The following parameters are set to the following:

• HMS: Harmonic memory size (number of resolution vectors in the harmonic memory),

• HMCR: Harmony Memory Considering Rate

• PAR: Pitching Adjust Rate The second stage of the algorithm is the creation and formation of harmonic memory, which is randomly constructed with solvers generators and functional functions, which will then play the role of memory. In the third step, the most important part of the Harmony Search algorithm is formed by making changes to the memory harmonics. At this point, the HMCR rate determines how far the new harmonics will be made directly from the harmonic memory, and the 1-HMCR indicates the possibility of a new harmonic randomization. In the remainder of this step, when a value is selected inside the memory, depending on the probability of the PAR, it may change, by adding a correct value to the value of the value that is called bandwidth. In the fourth step, if the new harmony is better than the worst harmony in memory, it will replace it and remove the worst-case harmony in memory. In the fifth step, the algorithm's completion condition is checked, and the number of iterations in the Harmonic Search algorithm is checked. In the event of the failure to establish the final condition, steps 3 and 4 are repeated again. The determination of the main parameters of the HSA (BW, PAR, and HMCR) algorithms has a great influence on the algorithm's performance; therefore, in the present work, in order to increase the accuracy and reduce the number of solving repetitions, a method (modified correction algorithm) is proposed to select these parameters. In order to correct the HMCR parameter, it is only necessary to suggest a random solution in the first tenth of the total repetition, and the HMCR parameter value is 0.7 to 0.95, and in the remaining 90% of the solution, the value of 1 is assigned to the HMCR parameter. This means that in the ninth, the rest of the variable solver is not randomly selected, and only the vector of the solutions in the memory is corrected. Of course, the oneteenth step can be changed.

To correct the PAR parameter, the maximum and minimum values are considered, and the problem solving starts with its minimum value. In the following, PAR is updated with each passing iteration according to equation (13):

$$PAR(Iter) = PAR_{MIN} + \left(PAR_{MAX} - PAR_{MIN}\right) \times \left(\frac{Iter}{MaxIt}\right) \qquad (10)$$

Where $Iter$ is the number of each iteration, and $MaxIt$ the total number of repetitions of the HSA algorithm. PAR_{MAX} is often considered between 0.9 and 1. But PAR_{MIN} will depend on the number of variables in the answer vector, which is equal to 0.1 for issues with a variable number of more than 10 variables.

To correct the BW parameter, the maximum and minimum values are considered, and the problem solving starts with its maximum value. In the following, BW is updated with each passing iteration according to equation (11):

$$BW\,(Iter) = BW_{MAX} \times \exp\left[Ln\left(\frac{BW_{MIN}}{BW_{MAX}}\right) \times \left(\frac{Iter}{MaxIt}\right)\right] \qquad (11)$$

The range of BW variations varies between 1% and 10% of variation variables. The material in reference to the revised Harmonic Search algorithm is found in Reference [23]. Also, to correct the harmonic memory, you can double the number of initial vectors, and select the HMS number after sorting by the cost function to increase the power of the HSA algorithm. As stated, the purpose of this paper is to install FPSS and H∞ TCSC in an electromagnetic system to minimize the system fluctuations after a randomized disorder in such a way as to ultimately improve stability. To determine the target function, there are different functions, but because our goal is to reduce the error signal and follow the output signal so that the response is improved by the time of reaching the stability state (ts) and the overshoot of the output signal (Mp), the target function can be defined:

$$J = ITAE = \alpha \times \int_0^t t \times |\omega(t)| dt \qquad (12)$$

In this equation t is the simulation time. The coefficient α is 10^6. On the other hand, J is minimized by setting the controller coefficients of FPSS and H∞ TCSC, which is the solution to this optimization problem using evolutionary algorithms.

4. SIMULATION AND ITS RESULTS

In this section, the results of simulation of the problem under study using MATLAB / SIMULINK software have been investigated in order to determine the effectiveness of the proposed model and the algorithm used. The block diagram of figure 4 is simulated using the MATLAB / SIMULINK software.

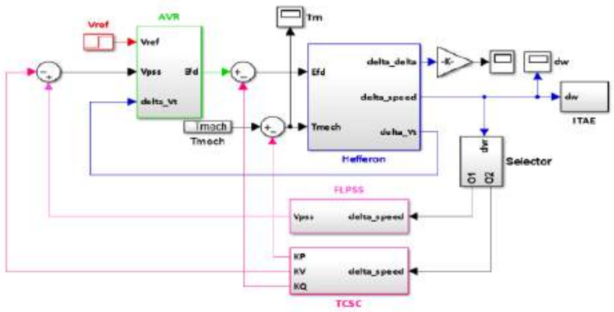

Figure 4. *The simulated HFR-simulation model in MATLAB*

As stated, the purpose of this paper is to optimize the parameters of the FPSS and H∞ TCSC controllers in such a way that the selected target function is minimized. The proposed method in this paper is the method presented in reference [20] but here optimization and improvement in target and result is considered. In the reference [20], FPSS controller membership functions are considered as constant, however, the parameters of the membership functions of the inputs and the output of this controller can also be optimized. Also, in this paper, the proposed method is used to design fuzzy rules, which is discussed below to optimize the FPSS and H∞ TCSC controllers, we first examine the optimization parameters that are:

- seven parameters to optimize fuzzy rules;
- two parameters to optimize the membership functions of each input;
- two parameters to optimize the membership of the output;
- thee parameters to optimize the FPSS controller coefficients K1, K2, and K3;
- KP, KQ and Kv, three parameters belonging to the H∞ TCSC controller.

A total of thirteen parameters are considered as the variables of the HSA algorithm as the initial vector. According to figure 2, for each input there are seven membership functions whose names are: NB, NM, NS, ZR, PS, PM and PB [24][25].

The technique used to optimize membership functions is that each input and output requires two parameters change and changing the vertex of the triangle.

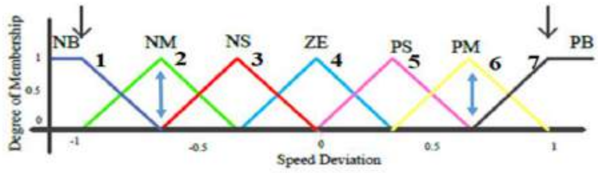

Figure 5. *optimize membership functions*

In table (2), the selected values of the parameters of the HSA algorithm are selected. Of course, one of the features of the HSA algorithm is to adjust the parameters correctly so that the optimal result is obtained at the lowest possible time. This requires the algorithm to be repeated for the optimization problem and determine its best values. In figure 6, the membership functions of the simulation are shown. In this article, the method of Mamdani is used. The centroid method is used to defuzzificate. In this method, the optimized values of the H∞ TCSC controller coefficients are KP = 198.5, KQ = 109.83, and KV = 1.5635, as well as the optimized values [K1, K2, K3] = [1.1,201.78,1.25].

Table 1. *Selectable Parameters of the HSA Algorithm*

Selected Value	Parameters Range	Prameters
50	100-20	HMS
0.9	0.95– 0.7	HMCR
Eq. 10	0.99 – 0.1	PAR
Eq. 11	%10-%1	Bandwidth

Table 2. *Optimized Fuzzy Rule Base with HSA Algorithm*

	NB	NM	NS	ZR	PS	PM	PB
NB	PB	PB	PB	NB	NM	ZR	ZR
NM	PB	PB	NB	NM	ZR	ZR	ZR
NS	PB	NB	NM	ZR	ZR	ZR	PM
ZR	NB	NM	ZR	ZR	ZR	PM	PB
PS	NM	ZR	ZR	ZR	PM	PB	NB
PM	ZR	ZR	ZR	PM	PB	NB	NB
PB	ZR	ZR	PM	PB	NB	NB	NB

It is worth mentioning that in the MATLAB / SIMULINK software, the mechanical input of the random input to the system was performed according to figure 7. The disturbances applied in the intervals of 0 and 10 seconds are 0.01 and 0.05 per unit, respectively. Figure 8 and 9 show the results of simulation. The velocity changes (Δω) in figure 8 and the angle variations (Δδ) are shown in figure 9. As can be seen, in a period when the mechanical power (ΔPm) is applied randomly to the system according to figure 9, the system has been able to prevent instability and minimize the changes in action as soon as possible, indicating the confirmation design is done. Different methods such as comparing the best answer, comparing the convergence rate, comparing the time of convergence, comparing the number of function evaluations and etc. are used to compare the evolutionary algorithms. In most articles and references, the frequency of calling the target function as a criterion for estimating optimization algorithms and an algorithm that achieves optimal response with less number of calls is a more appropriate algorithm to solve the problem.

Now we compare the method used in this paper with the reference method [20]. In Table 3, the results of the cost function derived from particle swarm optimization (PSO) and Harmonic Search algorithm (HSA) are shown. Of course, it should be noted that the cost function is expressed in equation (12), in which the coefficients of α were considered to be palpable from the cost function, which is considered to be 10^6. Therefore, according to Table (3), The proposed method is acceptable in this paper.

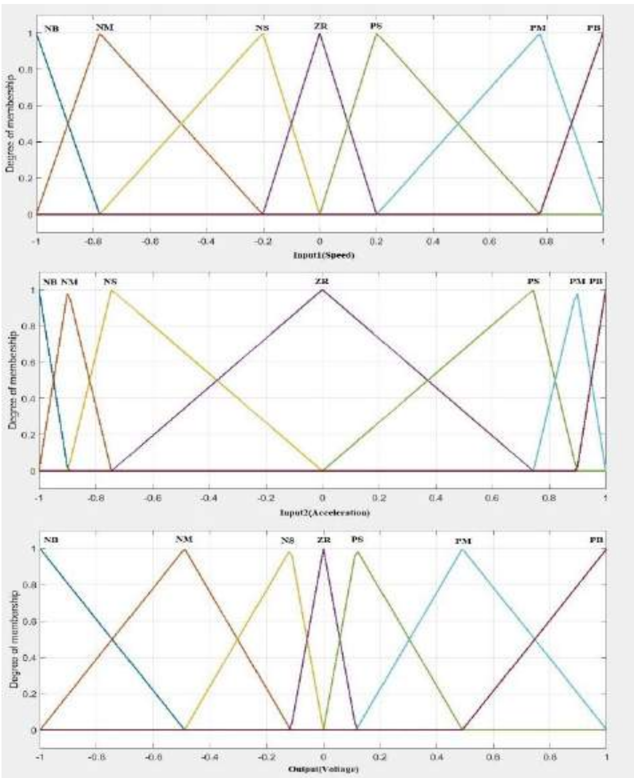

Figure 6. *optimized membership functions*

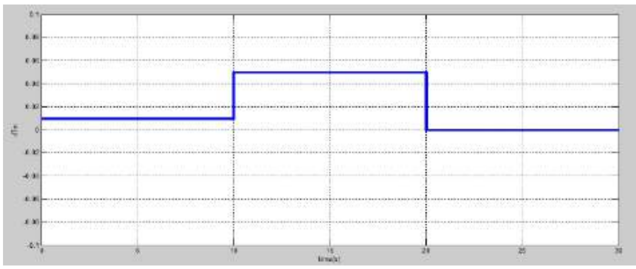

Figure 7. *Random input to the system (ΔPm)*

the cost function behavior is shown in figure 10, thecost for PSO and Harmonic Search (HSA) algorithms based on the proposed method. Therefore, according to figure 10, It was concluded that both PSO and HSA algorithms based on the proposed method, with the same number of recall, almost had the same performance. Of course, the HSA algorithm depends heavily on adjusting its parameters, and if they do not adjust properly, they will not get optimal response and there is a likelihood of encountering local convergence. For this reason, the modified HSA algorithm is used in this research.

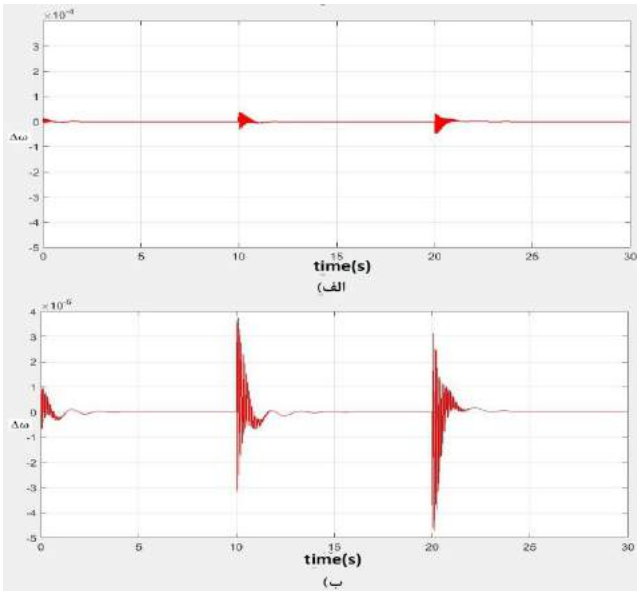

Figure 8. *Speed variation (Δω)*

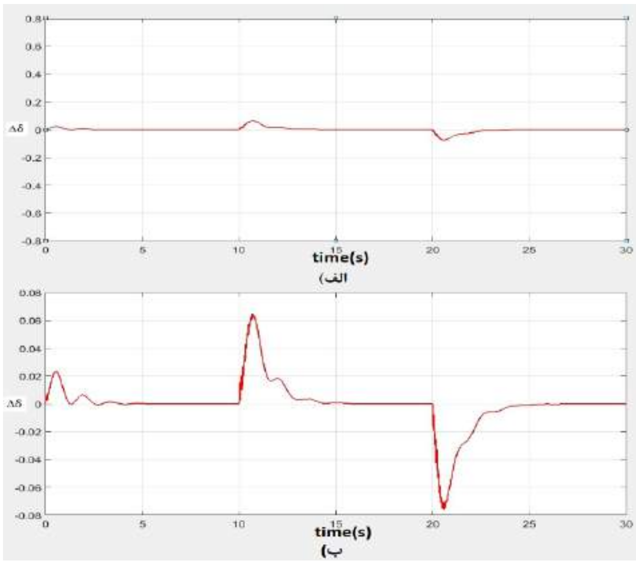

Figure 9. *Angle variations (Δδ)*

Table 3. *Comparison Table of Used Algorithms*

Selected Algorithm	Cost Function	Iteration
PSO based on [20]	500	100
Proposed PSO	416/7	100
Proposed HSA	411/9	100

In the end, it should be noted that for the present problem, the use of FPSS and H∞ TCSC controllers using the proposed method is quite reliable because the purpose of using evolutionary algorithms is to find the optimal solution close to the original one. Also, the HSA algorithm has a better trend in terms of memory and convergence speed to answer the problem, and has a shorter time to achieve the optimal response.

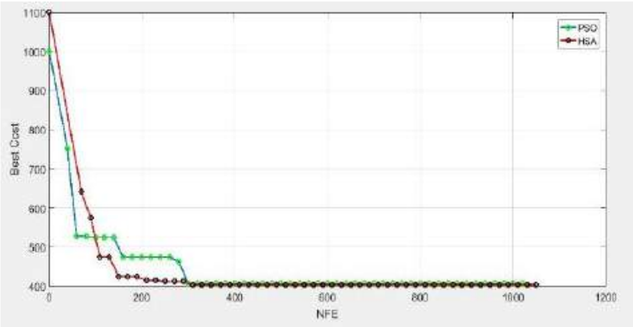

Figure 10. *Comparison of the cost functions*

5. RESULT

Flexible Transient Current Transmission Systems (FACTS) are considered as one of the effective methods for improving the system's controllability and power transmission constraints. Because of their rapid response, these controllers can be used to improve the stability of the power system by dampening low frequency oscillations. In this research, the stability of synchronous generator connected to infinite bus using FPSS and H∞ TCSC controllers was investigated. Using the proposed method and MATLAB software, it was simulated and using its results it can be concluded that the proposed method is completely accurate and reliable by using PSO and HSA. Also, the use of the modified HSA algorithm in terms of memory consumption and convergence speed is superior to other algorithms that require a primary population, such as GA and PSO.

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