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STATE FEEDBACK CONTROLLER DESIGN FOR A SSSC USING IC-HS ALGORITHM

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Abstract- This paper presents a novel method for damping of low frequency oscillations (LFO) based on design of a state feedback controller for synchronous series compensator (SSSC) in a power system. The design problem of state feedback damping controller is formulated as an optimization problem to minimize a time domain based objective function by improved chaotic–harmony search (IC-HS) technique. Some modifications in harmony search algorithm are made for improvement of algorithm convergence. In fact, this paper focuses on coordinating of SSSC‘s inputs with together and coordination of power system stabilizer (PSS) with SSSC‘s inputs to find the best dynamic response. Single Machine Infinite Bus (SMIB) system has been considered to examine the operation of proposed controllers. Change of the input power of generator abruptly, is considered as a disturbance. The effectiveness of the proposed state feedback controller has been demonstrated by nonlinear time domain simulation studies. The results analysis show that the proposed controller can provide the excellent capability in fast damping of power system oscillations and improve greatly the dynamic stability of power system. In addition, the system performance analysis and surveys under various operating conditions demonstrate that the simultaneously coordination of SSSC‘s input controllers are superior to the PSS based damping controller.

Keywords: Power System Stability, Damping Oscillation, IC-HS Algorithm, SSSC, State Feedback.

I. INTRODUCTION

Flexible AC Transmission System (FACTs) is a novel integrated concept based on power electronic converters and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC system inter connections [1].Today's these devices in many power systems fields have founded. More of FACTS devices have been developed from switch-mode voltage source converter configurations. They are equipped with energy storage unit, such as DC capacitors [2]. The static synchronous series compensator (SSSC) is a kind of FACTS devices. SSSC is a member of FACTS family which is connected in series with a power system. It consists of a voltage source converter which injected a controllable alternating current voltage at fundamental frequency and DC capacitor as storage unit [3]. Although the main function of SSSC is to control of power flow but it can is used to control of dynamic stability of power system [4].

Several application fields for FACTs devices have been introduced. These fields consisting of congestion management, power flow controlling and improves dynamic stability of power systems. In some researches a comparative study between SSSC and other FACTs devices is carried out [5-7]. Active and reactive power flow control using SSSC and other FACTS devices were investigated in [8, 9], respectively. Congestion management is one of the most major aspects in the electricity markets. FACTS devices have been shown to be an effective tool to control of power flow, resulting in increased load ability and reduced system losses in [10-12]. Several controlling methods for FACTs devices have been introduced. Quadratic mathematical programming for the simultaneous coordinated design of a Power System Stabilizer (PSS) and a SSSC-based stabilizer was investigated in [13].

In this method, the gain and phase of a lead lag stabilizer can be simultaneously calculated. Fuzzy logic controllers are the other controlling methods that are designed. In [14] a novel design of a fuzzy coordinated SSSC controller for integrated power system is used. Recently optimization techniques for obtain parameters of controlling methods are used. These optimization techniques for achieved SSSC's controllers have been published in following literatures. Genetic algorithm (GA) and partial swarm optimization (PSO) in [15-17] references were investigated, respectively.

In this article a single machine infinite bus (SMIB) as a power system is considered and linearized around the operating condition with a disturbance in different loading situation and converted to optimizing problem. For solving these kinds of problem, several algorithms were recommended. In this paper improved chaotic-harmony search (IC-HS) technique is used. By considering available parameters ($\Delta\delta$, $\Delta\omega$) for state feedback gains this procedure is carried out. In this paper, two SSSC inputs and power system stabilizer applied independently and also through coordinated application connected to the state feedback gains. Finally the effectiveness of this work by results evaluation and comparison of performance indices has been shown.

The rest of the paper organized as follows: Modeling of the power system under study has been presented in Section II. Section III describes the linear model of the under study system. Section IV represents the state feedback controller for SSSC. Improved chaotic-harmony search algorithm and IC-HS based state feedback controller is described in section V and section VI respectively. The time domain simulation results for system under study are presented and discussed in Section VII. The paper ended with conclusions in Section VIII.

II. MODELING OF POWER SYSTEM UNDER STUDY WITH SSSC

Under study system in this article is a SMIB that between terminal voltage and transmission line SSSC installed. As well as two transmission line circuit is considered. In fact, the generator producing power through transmission lines and SSSC to the infinite bus delivers. The SSSC with two transmission line circuit is shown in Figure 1.

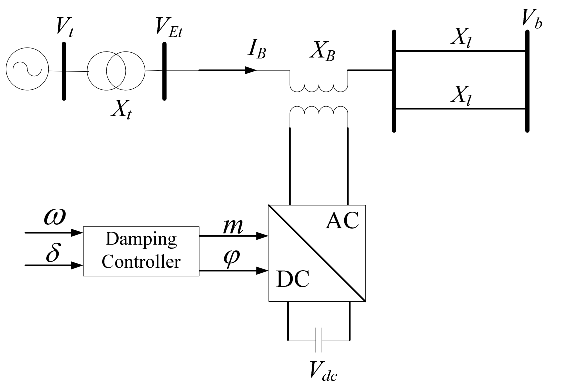

Figure 1. SMIB power system equipped with SSSC

For analysis and enhancing small signal stability of power system through SSSC, dynamic relation of system is needed. To have these relations through park transformation and ignoring resistance of boosting transformers can be achieve following equations [18, 19]:

$$\begin{pmatrix} v_{Bd} \\ v_{Bq} \end{pmatrix} = \begin{pmatrix} 0 & -X_B \\ X_B & 0 \end{pmatrix} \begin{pmatrix} i_{Bd} \\ i_{Bq} \end{pmatrix} + \begin{pmatrix} \dfrac{m.\cos\varphi.v_{dc}}{2} \\ \dfrac{m.\sin\varphi.v_{dc}}{2} \end{pmatrix} \quad (1)$$

$$\frac{dv_{dc}}{dt} = \frac{3m}{4C_{dc}} \left(\cos\varphi \quad \sin\varphi\right) \begin{pmatrix} i_{Bd} \\ i_{Bq} \end{pmatrix} \quad (2)$$

where, v_B, and i_B are the boosting voltage, and boosting current, respectively. The C_{dc} and V_{dc} are the DC link capacitance and voltage [18, 19]. The nonlinear model of the SMIB system as shown in Figure 1 has been introduced by following equations:

$$\frac{d\delta}{dt} = \omega_b(\omega - 1) \quad (3)$$

$$\frac{d\omega}{dt} = \left(\frac{P_m - P_e - D\Delta\omega}{M} \right) \quad (4)$$

$$\frac{dE'_q}{dt} = \left(\frac{E_{fd} + \left(X_d - X'_d\right) - E'_q}{T'_{do}} \right) \quad (5)$$

$$\frac{dE_{fd}}{dt} = \left(\frac{-E_{fd} + K_a\left(v_{ref} - v_t + U_{PSS}\right)}{T_a} \right) \quad (6)$$

$$T_e = E'_q i_q - \left(X_q - X'_d\right) i_d i_q \quad (7)$$

Using Figure 1, the following equations can be achieved:

$$v_t = v_{Et} + jX_t i_B \quad (8)$$

$$v_{Et} = v_b + v_B + j(X_B + X_l/2) i_B \quad (9)$$

$$v_t = v_{Bd} + jv_{Bq} \quad (10)$$

$$v_{Bd} = X_q i_{Bq} \quad (11)$$

$$v_{Bq} = E'_q - X'_d i_{Bd} \quad (12)$$

Using the aforementioned equations, the following relations can be achieved ($X = X_t + X_B + X_l/2$):

$$i_{Bq} = \left(\frac{1}{X + X_q} \right) \left[\frac{m.v_{dc}}{2} \cos\varphi + v_b \sin\delta \right] \quad (13)$$

$$i_{Bd} = \left(\frac{1}{X + X'_d} \right) \left[E'_q - \left(\frac{m.v_{dc}}{2} \sin\varphi + v_b \cos\delta \right) \right] \quad (14)$$

The output power of the generator can be acquired in terms of the d-axis and q-axis components of the armature current, i, and internal voltage, E'_q, as follows :

$$P_e = \left(X_d - X'_d\right) i_d i_q + E'_q i_q \quad (15)$$

By substituting (13) and (14) into (15), we have:

$$\begin{aligned} P_e = {} & \left(\frac{X_q - X'_d}{X_D X_Q} \right) \left[\frac{E'_q.m.v_{dc}}{2} \cos\varphi + E'_q v_b \sin\delta - \right. \\ & - \frac{m^2 v_{dc}^2}{4} \sin\varphi\cos\varphi - \frac{m v_{dc} v_b}{2} \sin\delta \sin\lambda - \\ & - \frac{m v_{dc} v_b}{2} \cos\delta\cos\varphi - v_b^2 \sin\delta\cos\delta + \\ & \left. + \frac{E'_q}{X_Q} \left[\frac{m v_{dc}}{2} \cos\varphi + v_b \sin\delta \right] \right] \end{aligned} \quad (16)$$

where, $X_D = X + X'_d$ and $X_Q = X + X_q$.

III. POWER SYSTEM LINEARIZED MODEL

General discussion of the stability of power systems, to better understand the nature of the issue and improve problem-solving methods is divided into two broad categories of stability under severe disturbances and stability under mild disturbances.

Traditionally stability under severe disturbances is related to transient situation. For analysis of this type of stability, network response to a severe disturbance such as short circuit transmission line, loss of production and suddenly applied load is evaluated.

In the first type of stability, fluctuations of many disturbances have a large size and linearization process around the operating conditions is not acceptable. In this situation nonlinear swing equation must be solved. Stability under mild disturbance or small signal stability to the network response against minor changes is related.

General stability properties of the oscillating modes not depend on the severity of the disturbance and therefore this stability analysis can be done using a linear model around equilibrium point. This point is expressed by the terms of an operating point (i.e., steady state).

By applying linearization process around operation point of under study system, state space model of the system can be achieved, as follows [18, 19]:

$$\dot{X} = AX + BU \tag{17}$$

where, the state vector X and the control vector U are defined, as follows:

$$X = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} & \Delta v_{dc} \end{bmatrix}^T \tag{18}$$

$$U = \begin{bmatrix} \Delta m & \Delta\varphi \end{bmatrix}^T \tag{19}$$

Linearizing the expressions of (2)-(6), yield the following linearized expressions:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{20}$$

$$\Delta\dot{\omega} = -\frac{\Delta P_e}{M} \tag{21}$$

$$\Delta\dot{E}'_q = \frac{\Delta E_{fd} - \left(X_d - X'_d\right)\Delta i_d - \Delta E'_q}{T'_{do}} \tag{22}$$

$$\Delta\dot{E}_{fd} = \frac{-K_A \Delta v_t - \Delta E_{fd}}{T_A} \tag{23}$$

$$\Delta\dot{v}_{dc} = h_1\Delta\delta + h_2\Delta E'_q + h_3\Delta E_{fd} + h_4\Delta v_{dc} + h_5\Delta m + h_6\Delta\varphi \tag{24}$$

where,

$$\Delta P_e = k_1\Delta\delta + k_2\Delta E'_q + k_3\Delta v_{dc} + k_4\Delta m + k_5\Delta\varphi \tag{25}$$

$$\Delta i_d = k_\delta\Delta\delta + k_{E'_q}\Delta E'_q + k_{v_{dc}}\Delta v_{dc} + k_m\Delta_m + k_\varphi\Delta\varphi \tag{26}$$

$$\Delta i_q = h_\delta\Delta\delta + h_{v_{dc}}\Delta v_{dc} + h_m\Delta_m + h_\varphi\Delta\varphi \tag{27}$$

$$\Delta v_t = \alpha X_q\Delta i_q + \beta\Delta E'_q - \beta X'_d\Delta i_d \tag{28}$$

where, $h_1 - h_6$, $k_1 - k_5$, k_δ, $k_{E'_q}$, $k_{v_{dc}}$, k_m, k_φ, h_δ, $h_{v_{dc}}$, h_m, h_φ, α and β are linearization constants. By substituting (20)-(24) into (17) and arranging it, the following matrixes for A and B can be achieved.

In this study, in order to evaluate the capability of each control inputs, they will be considered in both individually and combinational to enhance the system damping of low frequency oscillations.

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{k_1}{M} & 0 & -\frac{k_2}{M} & 0 & -\frac{k_3}{M} \\ \frac{-\left(X_d - X'_d\right)k_\delta}{T'_{do}} & 0 & \frac{1+\left(X_d - X'_d\right)k_{E'_q}}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-\left(X_d - X'_d\right)k_{v_{dc}}}{T'_{do}} \\ -\frac{K_A}{T_A}\left(\alpha X_q h_\delta - \beta X'_d k_\delta\right) & 0 & -\frac{K_A}{T_A}\beta\left(1 - X'_d k_{E'_q}\right) & \frac{-1}{T_A} & -\frac{K_A}{T_A}\left(\alpha X_q h_{v_{dc}} - \beta X'_d k_{v_{dc}}\right) \\ h_1 & 0 & h_2 & h_3 & h_4 \end{bmatrix} \tag{29}$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{-k_4}{M} & \frac{-k_5}{M} \\ \frac{-\left(X_d - X'_d\right)k_m}{T'_{do}} & \frac{-\left(X_d - X'_d\right)k_\varphi}{T'_{do}} \\ -\frac{K_A}{T_A}\left(\alpha X_q h_m - \beta X'_d k_m\right) & -\frac{K_A}{T_A}\left(\alpha X_q h_\phi - \beta X'_d k_\varphi\right) \\ h_5 & h_6 \end{bmatrix} \tag{30}$$

IV. STATE FEEDBACK CONTROLLER DESIGN FOR SSSC

In the state space model, a matrix plays a vital role because from it, modes or eigenvalues of system are obtained. These modes actually represents system stability situation when the system is suffering from a disturbance. Stability condition is defined, when all modes of system is on the left side of complex plane.

If one of these modes is on the right side of the complex plane or has a positive real part, the system is unstable. Usually to eliminate the instability of this case, there are many ways, for example methods of state feedback, output feedback, lead-lag controller and etc. So, this paper uses state feedback structure. A state feedback controller has the following structure:

$$U = -KX \tag{31}$$

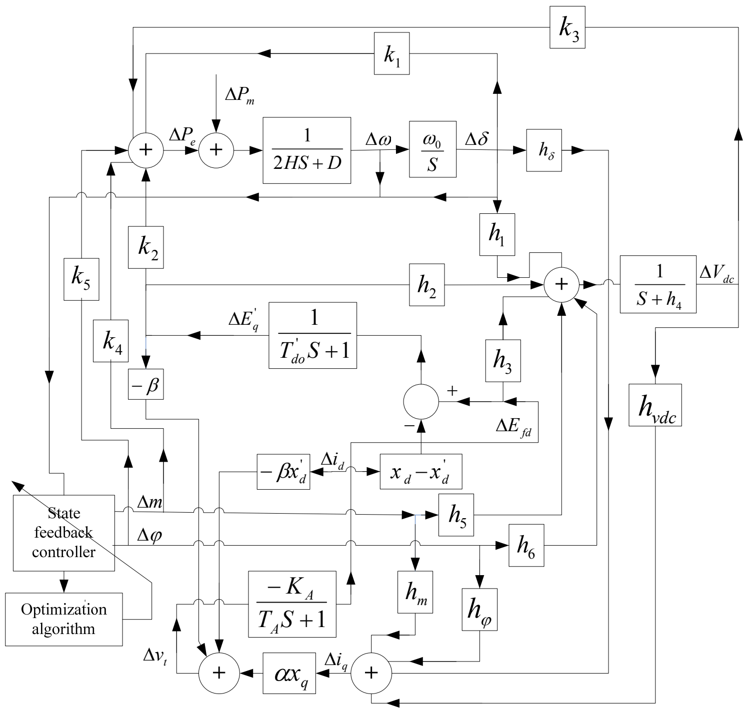

Figure 2. Linear model of SSSC with state feedback controller

In this paper, an optimal design of SSSC with state feedback consideration is given. In the matrix form, design equations can be represented, as follows:

$$\Delta U_{SSSC} = -\begin{pmatrix} k_1' & k_2' \end{pmatrix}\begin{pmatrix} \Delta\delta \\ \Delta\omega \end{pmatrix} \quad (32)$$

$$\begin{pmatrix} \Delta U_{1SSSC} \\ \Delta U_{2SSSC} \end{pmatrix} = -[T]\begin{pmatrix} \Delta\delta \\ \Delta\omega \end{pmatrix} = -\begin{pmatrix} T_1 & T_2 \\ T_3 & T_4 \end{pmatrix}\begin{pmatrix} \Delta\delta \\ \Delta\omega \end{pmatrix} \quad (33)$$

To obtain optimal values for coefficients K, which define as $\begin{pmatrix} k_1' & k_2' \end{pmatrix}$ for separately form and $[T]$ for combinatorial form, can move unstable eigenvalues of the system to the left complex plane and reached the proper performance of SSSC's controller. By changing the values of k, eigenvalues status of the system will change then, we can obtain desire values of k using the proposed algorithm, which have minimum error. This means that the system eigenvalues are conducted to the left complex plane. The SSSC controllers (i.e., m, φ) are two parameters, which help them, can reach the aforementioned goals but in this paper, the SSSC's controller inputs is considered in both separately (i.e., m, φ) and coordination with PSS [i.e., (m, PSS) and (φ, PSS)] under various operating conditions. Linear model of the SSSC around operating point with optimization algorithm has been shown in Figure 2.

V. IMPROVED CHAOTIC HARMONY SEARCH ALGORITHM (IC-HSA)

This section explains the performance of the improved chaotic-harmony search (IC-HS) algorithm. At first, the improved harmony search algorithm (IHSA) is explained and next its modification process is introduced. Eventually the proposed chaotic-harmony search algorithm is described. A brief review of the IHS and its effectiveness was shown in [20-23].

A. Improved Harmony search algorithm

Fundamental of this method is based on the concept in search of a suitable state in music. It means that how a musician can reach to its desired state with different search modes. To implement the above concepts in form of algorithm, several steps will ahead. This process generally will be implemented in the following five steps [22, 23].

Step 1. Initialize the problem and algorithm parameters.
Step 2. Initialize the harmony memory.
Step 3. Improvise a new harmony.
Step 4. Update the harmony memory.
Step 5. Check the stopping criterion.

Step 1: Initialize the problem and algorithm parameters

In this stage, initialization of all algorithm parameters will be carried out. These parameters can be defined by the following terms [23]:

HMS Harmony memory size or the number of solution vectors in the harmony memory
HMCR Harmony memory considering rate
PAR Pitch adjusting rate
NI Number of improvisations
N Number of decision variables

In addition to optimization process of an objective function $f(x)$, the boundary of the independent variables should be considered (x is the set of each independent variable).The value of x is restricted to $x_{Li} \le x_i \le x_{Ui}$ where, x_{Li} and x_{Ui} are the lower and upper limits of each variable.

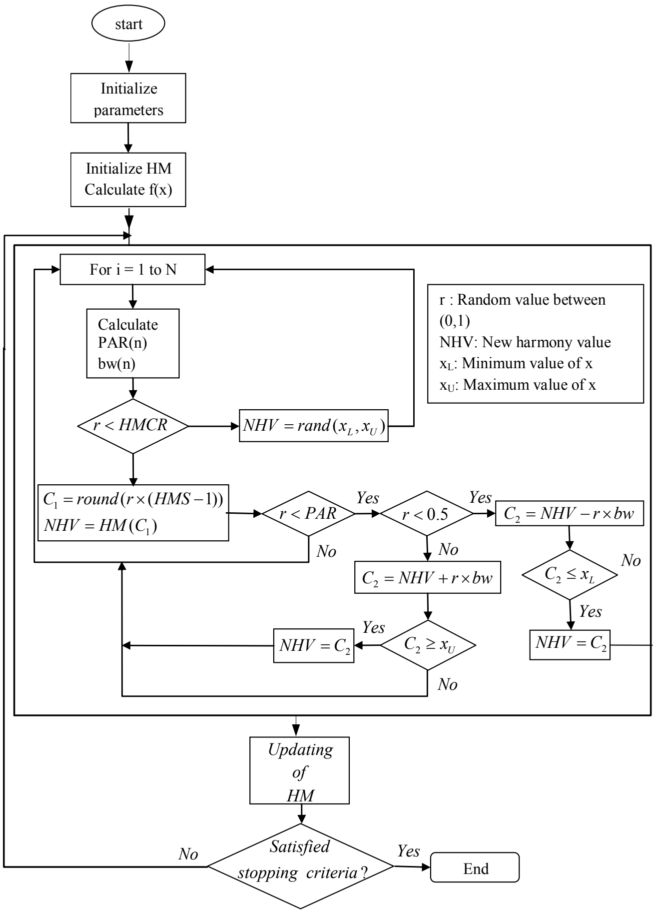

Figure 3. Flowchart of the IHS algorithm

Step 2: Initialize the harmony memory

The harmony memory (*HM*) is a matrix include of independent variables, which are selected randomly. Each row of this matrix indicates a solution to the problem.

$$HM = \begin{bmatrix} x_1^1 & \cdots & x_N^1 \\ \vdots & \ddots & \vdots \\ x_1^{HMS} & \cdots & x_N^{HMS} \end{bmatrix} \quad (34)$$

Step 3: Improvise a new harmony

Producing a new harmony is called improvisation. The new harmony vector $x' = \left(x_1', x_2', \ldots, x_N'\right)$ is achieved by three parameters: harmony memory consideration rate, pitch adjustment rate and random selection. The mentioned processes in flowchart form have been shown in Figure 3.

In the improved harmony search algorithm two parameters are changed in each iteration. These parameters are pitch adjustment rate (*PAR*) and bandwidth (*bw*). Changing form of these parameters is expressed, as follows:

$$PAR = PAR_{\min} + (PAR_{\max} - PAR_{\min}) / NI \quad (35)$$

where,

PAR: pitch adjusting rate of each generation
$PAR_{\min}$: minimum pitch adjusting rate
$PAR_{\max}$: maximum pitch adjusting rate
NI : number of solution vector generations
gn : generation number

$$bw(gn) = bw_{\max} . e^{\left(gn \frac{\ln\left(\frac{bw_{\min}}{bw_{\max}}\right)}{NI}\right)} \quad (36)$$

where,

$bw\,(gn)$: bandwidth of each generation
$bw_{\min}$: minimum bandwidth
$bw_{\max}$: maximum bandwidth

Step 4: Update the harmony memory

In the updating harmony memory stage, with replacing new values ($x' = \left(x_1', x_2', \ldots, x_N'\right)$) on the objective function, if the objective function value is better than the previous one it must be removed from memory and its new value will be replaced.

Step 5: Check stopping criterion

If the stopping criterion (maximum number of improvisations) is satisfied, computation is terminated. Otherwise, Steps 3 and 4 are repeated.

B. Modification of the Improved Harmony Search Algorithm

PAR and *bw* parameters in IHS algorithm in reaching optimum solution vectors is very important. The important these two parameters in determining the appropriate rate of convergence of the algorithm is identified. So that by choosing appropriate fixed values of their, algorithm can quickly be directed towards convergence. In the IHS algorithm for both *PAR* and *bw* parameters variable value is considered, it means that in each iteration of algorithm, their values will changed. This change to the parameter *PAR* is contrary *bw*. That is better for the parameter *PAR* value early in the algorithm is low, then ascending to find but bw at first has maximum value that in each iteration amount of it is reduced. In this paper, applying the same process of change is used but in this process after a certain repetition, bw value increases because the algorithm out of local minimum. At the recommended changing process, bandwidth parameter achieved from the following equations:

$$\beta = (\frac{1}{N_1})^{\alpha} \ln(\frac{bw_{\min}}{bw_{\max}}) \quad (37)$$

$$\theta(L) = k.\beta \left[\frac{-(L)^{\alpha} + (L+1)^{\alpha}}{N_2} \right] \quad (38)$$

$$bw(L,J) = bw_{\max} \left[e^{\beta(L^{\alpha}-1)} \right] e^{\theta(L)(J-1)} \quad (39)$$

where,
α: a control parameter
k: a control parameter
N_1: number of solution vector in first generation number
N_2: number of solution vector in second generation number
L: first generation number
J: second generation number
$bw(L,J)$: bandwidth of both L and J generation numbers
The variations of bandwidth parameter versus generation numbers have been shown in Figure 4.

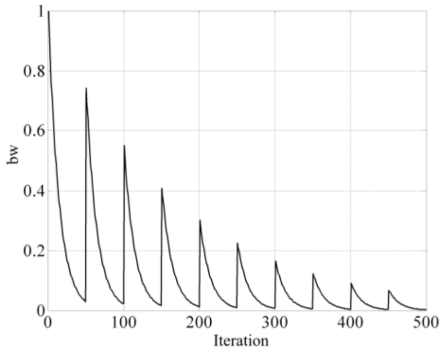

Figure 4. Variation of *bw* versus generation number

C. Proposed Method

In numerical analysis, sampling, decision making and especially heuristic optimization needs random sequences with some features. These features consist a long period and good uniformity. The nature of chaos is apparently random and unpredictable [24]. Mathematically, chaos is randomness of a simple deterministic dynamical system and chaotic system may be considered as sources of randomness [24]. A chaotic map is a discrete-time dynamical system which modeling in form of below equation:

$$x_{k+1} = f(x_k) \quad (40)$$

where, $0 < x_k < 1$ and (k = 0, 1, 2, …). The chaotic sequence can be used as spread-spectrum sequence as random number sequence. There are many methods for generating of random numbers but here used sinusoidal iterator for chaotic map [24]. It is represented by:

$$x_{k+1} = ax_n^2 \sin(\pi x_n) \quad (41)$$

when a = 2.3 and x_0 = 0.7 it has the simplified form represented by:

$$x_{k+1} = \sin(\pi x_n) \quad (42)$$

It generates chaotic sequence in (0, 1). Initial *HM* is generated by iterating the selected chaotic maps until reaching to the *HMS*. The procedure of the IC-HS algorithm has been shown in Figure 5. According to this figure, purpose of harmony search main loop is main loop of Figure 3, which is beginning after initialization of *HM*.

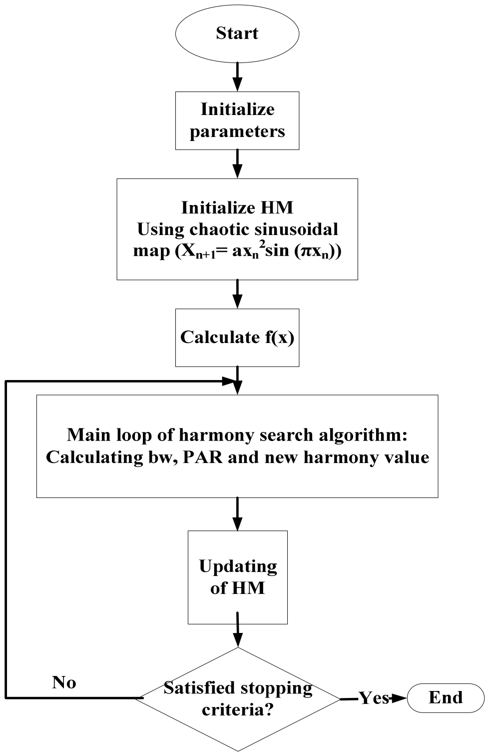

Figure 5. Flowchart of the chaotic-harmony search algorithm

VI. IC-HS BASED STATE FEEDBACK CONTROLLER

Actually, obtain values of controller parameters (K) for SSSC controller based on the optimization algorithm is a problem of optimization. In this study, for solving the optimization problem and reaching the global optimal values of coefficients k, IC-HS algorithm is used. By applying an impulse disturbance on input power of generator, its parameters and indicators will change. One of the important parameter is frequency. Speed deviation in form of Integral of Time Multiplied Absolute value of the Error (*ITAE*) as the objective function for the algorithm is selected. The objective function is defined as follows:

$$OF = \int_0^{tsim} t \left| \Delta\omega \right| dt \quad (43)$$

For each optimization problems a series of conditions and limitations exist. For this design, limitations of the controller parameters are the problem constraints. The following relations describe these restrictions:

$$k_1^{\min} \le k_1 \le k_1^{\max} \quad (44)$$

$$k_2^{\min} \le k_2 \le k_2^{\max} \quad (45)$$

$$T_1^{\min} \le T_1 \le T_1^{\max} \quad (46)$$

$$T_2^{\min} \le T_2 \le T_2^{\max} \quad (47)$$

$$T_3^{\min} \le T_3 \le T_3^{\max} \quad (48)$$

$$T_4^{\min} \le T_4 \le T_4^{\max} \quad (49)$$

In order to gain constraints, all oscillation of system under all operating conditions must be damped before machine inertia coefficient (M=2H). Criteria for this damping under condition of settling time with 5% of characteristic should be less than 2H value. Typical ranges of the optimized parameters are [0.01 5] values for k_1 and T_i (i = 1, 3) and for k_2 and T_i (i = 2, 4) values of [-120 120]. The proposed approach employs IC-HS algorithm to solve this optimization problem and search for an optimal set of state feedback controller parameters. The optimization of SSSC controller parameters is carried out by evaluating the objective cost function as given in Equation (43). The operating conditions are considered, as follows:

1- Normal load P = 0.80 pu, Q = 0.114 pu, x_L= 0.5 pu
2- Light load P = 0.2 pu, Q = 0.007, x_L= 0.5 pu
3- Heavy load P = 1.20 pu, Q = 0.264, x_L= 0.5 pu

In order to acquire better performance, the parameters of IC-HS algorithm have been shown in Table 1. It is necessary to note that in optimizing values of the controller parameters, algorithm must be repeated several times until finally a value for feedback control mode is selected. The optimal values of the controller parameters, which obtained for normal load, have been shown in Tables 2 and 3.

Table 1. Value of IC-HS algorithm constant parameters

parameters	HMS	$HMCR$	$PAR_{\min}$	$PAR_{\max}$	$bw_{\min}$	$bw_{\min}$
value	12	0.81	0.35	0.45	1e-6	1

Table 2. The optimal gain adjusting of proposed controllers

Controller	T_1	T_2	T_3	T_4
m and φ	0.9675	-89.29	0.1463	-97.68
PSS and φ	0.6243	95.10	0.2693	-97.12
PSS and m	0.5681	96.17	0.1879	-82.72

Table 3. The optimal gain adjusting of proposed controllers

Controller	φ	m	PSS
k_1	0.7821	0.7014	0.7943
k_2	-99.44	-97.59	96.94

VII. TIME DOMAIN SIMULATION

System performance with the values obtained for the optimal state feedback is evaluated by applying a disturbance at t = 1s for 6 cycles. The speed and delta deviation of generator at normal, light and heavy loads with the proposed controller based on the φ, m and PSS have been shown in Figure 6. For combinatorial states (i.e., coordination of SSSC's inputs together and with PSS), results simulation of speed and delta deviation at normal, light and heavy loads have been shown in Figure 7. From Figure 6, it can be seen that the m based damping controller, to achieve good performance is robust, provides premier adjustment and greatly increase the dynamic stability of power systems. From Figure 7, it can also be seen that the m and φ based damping controller are premier than the other types. From Table 4 and eigenvalues analysis, it can be received that the m based controller is premier to the φ and PSS based controller moreover, coordinated application of φ and m are premier to (φ, PSS) and (m, PSS) based controller. To show the efficiency and strength of the proposed method we use two indicators. The system performance characteristics evaluated based on the $ITAE$ and Figure of Demerit (FD) indices that defined as [19]:

$$ITAE = 1,000\int_0^5 t\left|\Delta\omega\right| dt \quad (50)$$

$$FD = \frac{1}{1,000}\left[\left(100\times OS\right)^2 + \left(300\times US\right)^2 + 50T_s^2\right] \quad (51)$$

where, ($\Delta\omega$) is the speed deviation, overshoot (OS), undershoot (US) and T_s is the settling time of delta deviation for the machine is considered for evaluation of the $ITAE$ and FD indices respectively. It should be noted that values of these indices for better performance in controlling of disturbance is reduced. Numerical results of strong performance for all system loading cases are listed in Table 5. It can be seen that the values of these system performance features for the state feedback m based controller are much smaller compared to state feedback φ and PSS based controller and in coordinated design, state feedback φ and m based controller are much smaller compared to state feedback (PSS, m) and (PSS, φ) based controller. This illustrates that the over shoot, undershoot and settling time of delta deviation are decreased by applying the proposed control method. Furthermore, these results can be received that the m and (φ, m) based controller at separately and coordinated situations are the most robust controller respectively.

VIII. CONCLUSIONS

The improved chaotic−harmony search algorithm was successfully used for the modeling of robust state feedback SSSC based damping controller. In fact, design of problem and obtain controller coefficients is converted into an optimization problem which is solved by IC-HS algorithm with the time domain objective function. In this design for each of the control signals from available state variables ($\Delta\omega$, $\Delta\delta$) have been used. The efficient of the proposed SSSC state feedback controller for improving dynamic stability performance of a power system are illustrated by applying disturbances under different operating points. Results from time domain simulations show that the oscillations of synchronous machines can be easily damped for power systems with the proposed method. To analyze performance of SSSC's controller two indicators have been used. These indices in terms of '$ITAE$' and 'FD' are introduced. These indices demonstrate that the state feedback m based damping controller is superior to the φ and PSS based damping controller. Moreover simultaneously coordination of (φ, m) based damping controllers are superior to (PSS, m) and (PSS, φ) based damping controllers.

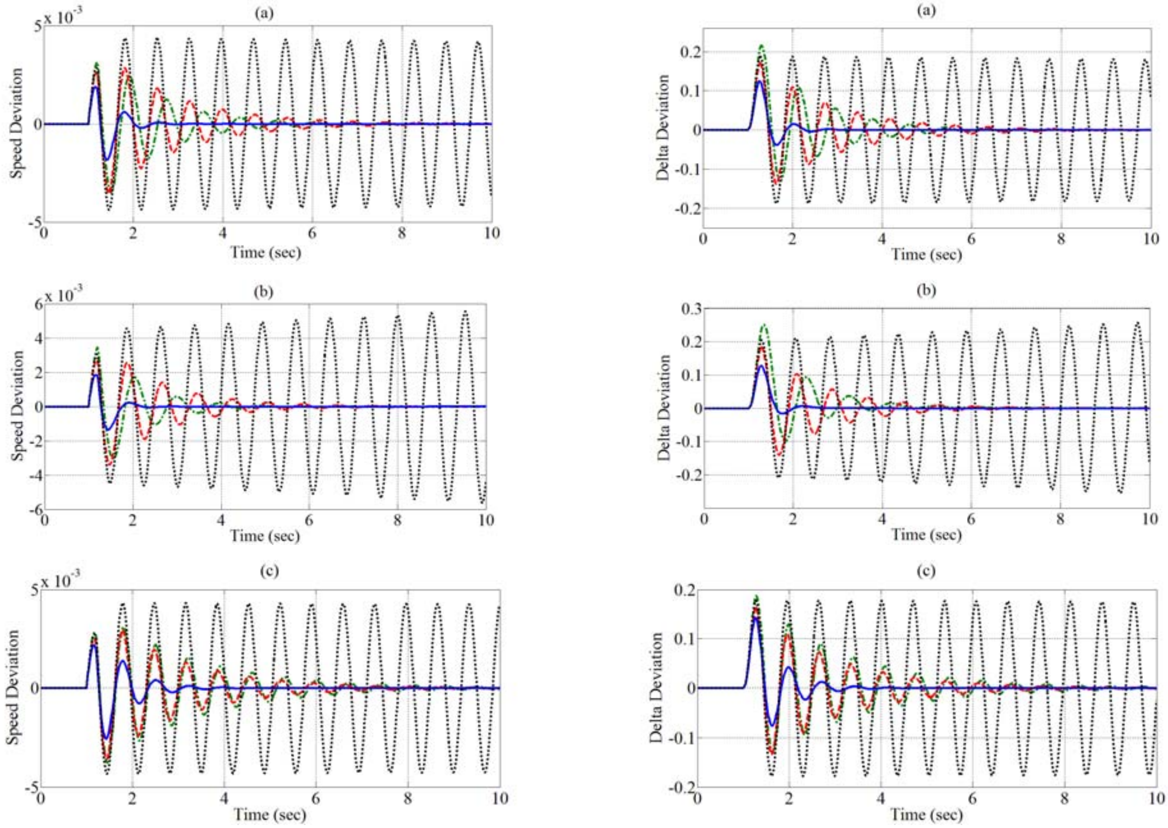

Figure 6. Dynamic responses of both speed and delta deviation with (a) normal, (b) heavy and (c) Light loads: Solid (*m* based controller), Dashed (*φ* based controller), Dot-Dashed (PSS based controller), and Dotted (Without controller)

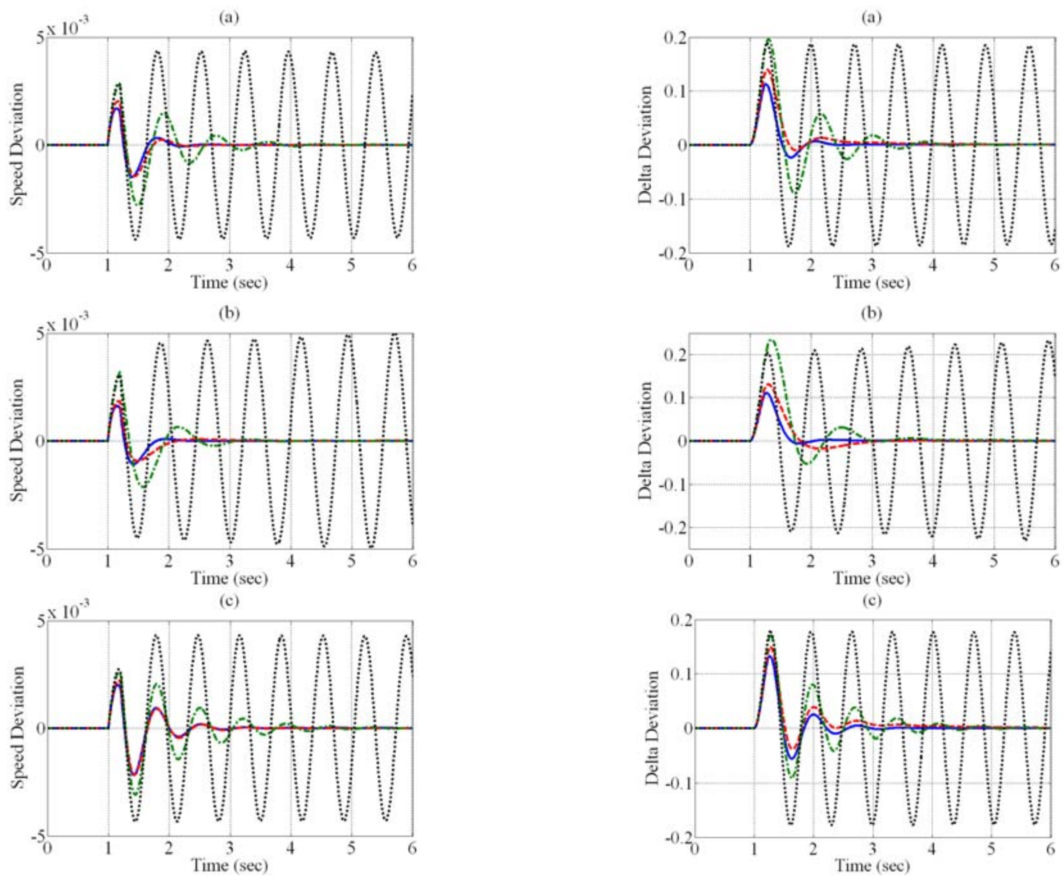

Figure 7. Dynamic responses of both speed and delta deviation with (a) normal, (b) heavy and (c) Light loads: Solid (*m* & *φ* based controller), Dashed (PSS & *m* based controller), Dot-Dashed (PSS & *φ* based controller), and Dotted (Without controller)

Table 4. Eigenvalues of system in different operating conditions

Load condition	Controller					
	φ based	PSS based	m based	PSS & φ based	PSS & m based	φ and m based
Normal(pu) $P = 0.8$ $Q = 0.114$	-18.772 -0.618 ± 8.503j -1.604 -0.0008	-17.720 -0.935 ± 7.615j -1.635 -0.0017	-19.390 -3.245 ± 7.469j -1.425 -0.001	-18.736 -2.391 ± 16.217j -1.625 -0.0019	-18.7403 -5.335 ± 15.379j -1.6247 -0.002	-18.774 -8.469 ± 13.318j -1.626 -0.0009
Light(pu) $P = 0.2$ $Q = 0.007$	-18.705 -0.486 ± 9.047j -1.673 -0.0006	-18.527 -0.517 ± 8.943j -1.672 -0.0013	-18.906 -1.783 ± 8.410j -1.485 -0.001	-18.679 -0.954 ± 11.287j -1.681 -0.0013	-18.683 -2.195 ± 11.432j -1.649 -0.003	-18.718 -3.289 ± 10.669j -1.675 -0.001
Heavy(pu) $P = 1.2$ $Q = 0.264$	-18.817 -0.760 ± 8.012j -1.607 -0.0011	-17.199 -0.796 ± 6.135j -1.592 -0.0027	-19.611 -4.120 ± 6.119j -1.343 -0.0077	-18.808 -3.163 ± 18.169j -1.554 -0.0014	-18.814 -8.662 ± 16.312j -1.550 -0.0098	-18.849 -11.548 ± 13.810j -1.553 -0.0065

Table 5. Values of performance indices *ITAE* and *FD*

	Controller											
Load condition	φ based		PSS based		m based		PSS & φ based		PSS & m based		φ and m based	
	ITAE	*FD*	*ITAE*	*FD*	*ITAE*	*FD*	*ITAE*	*FD*	*ITAE*	*FD*	*ITAE*	*FD*
Normal	12.12	4.559	8.587	3.607	1.438	0.598	3.833	1.753	1.217	0.5357	1.054	0.4463
Light	12.97	4.627	9.024	3.624	3.128	1.299	5.792	2.030	2.864	1.1442	2.125	0.8018
Heavy	9.401	3.656	5.708	2.287	1.367	0.5571	2.823	1.129	1.163	0.4852	0.855	0.3472

APPENDIX

Generator	M = 8 MJ/MVA, T'_{do}= 5.044 s X_d = 1pu, X_q = 0.6pu , X'_d = 0.3pu
Excitation system	K_A = 10, T_A = 0.05 s
Transformers	$X_t = X_E = X_B$ = 0.1pu
Transmission line	X_L = 0.5 pu
Operating condition	P = 0.8 pu , V_b=1 pu
DC link parameter	V_{DC} =2 pu, C_{DC} =1 pu
SSSC parameter	$\varphi = -78.21^{\circ}$, T_s = 0.05, m = 0.08 , K_s = 1

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