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Optimal siting and sizing of SSSC Using Improved Harmony Search Algorithm Considering Non-smooth Cost Functions

Mohamed Ebeed
Department of Electrical Engineering,
Faculty of Engineering, Sohag
University, Sohag, Egypt
mohamedebeed11@gmail.com

Salah Kamel
Department of Electrical Engineering,
Faculty of Engineering, Aswan
University, 81542 Aswan, Egypt
skamel@aswu.edu.eg

Loai S. Nasrat
Department of Electrical Engineering,
Faculty of Engineering, Aswan
University, 81542 Aswan, Egypt
loaisaad@yahoo.com

Abstract— **Static Synchronous Series Compensator (SSSC) is an elegant member of Flexible Alternating Current Transmission Systems (FACTS) devices. SSSC can be used to control the active and reactive power flows of transmission lines. In this paper, improved harmony search algorithm (IHS) is applied to determine the optimal location and parameter settings of SSSC in power systems. The optimal power flow (OPF) problem is solved with and without incorporating of SSSC in power systems considering the valve point loading effect and the prohibited operating zones of generation units. A simple model of SSSC based on power injection approach is implemented into OPF algorithm. The main advantage of the simplified model is avoiding any modifications in the original structure of Jacobian matrix. Consequently, the complexities of OPF algorithm are reduced. In addition, the resistance of SSSC is considered in this model. The OPF solution with the simplified SSSC model using IHS optimization technique are validated based on the standard IEEE 30-bus test system. The comparative study with conventional harmony search (HS) and other techniques demonstrates the superiority of the developed OPF solution using IHS algorithm.**

Keywords—Optimal power flow, improved harmony search, valve effect, prohibited zones, static synchronous series compensator.

I. INTRODUCTION

The Flexible Alternating Current Transmission Systems (FACTS) devices have been widely used in electrical power systems. SSSC controller is an efficient FACTS device based on voltage source converter (VSC). It can inject a controllable voltage in series with transmission line to control the power flow through transmission line [1]. Many successful efforts have been done for modelling of FACTS devices to be incorporated on power system. Inclusion of FACTS devices that based on VSCs requires some modifications in load flow solutions especially in Jacobian matrix and the admittance matrix. Refs. [2-4], have presented simple models for FACTS devices. The main advantage of these models is avoiding modifications of Jacobian matrix.

OPF is an optimization tool that is applied for obtaining the best operating point (control variables) for a certain objective functions with satisfying the system equality and inequality constraints. The OPF problems are solved by several conventional methods such as; linear programming, non-linear program, quadratic programming, mixed integer, linear programming and New-ton method [5, 6]. The main drawbacks of the conventional methods are probability of trapping in local minima. Moreover, some of these methods can't be applicable for non-smooth or non-convex objective functions. Recently, many meta-heuristic optimization techniques have been employed for solving the OPF problem to overcome the shortages of the traditional method such as; particle swarm optimization (PSO) [7], differential evolution (DE) [8] and moth flame optimization algorithm [9] etc.

Harmony search algorithm is an effective optimization technique proposed by Geem and Kim. [10]. HS algorithm simulates improvisation process of musicians to get the best harmony. The improved harmony search (IHS) algorithm was proposed by Mahdavi. Procedures of the IHS algorithm are similar to HS algorithm except that some parameters of HS algorithm are changed dynamically during iterative process to enhance performance and global search ability of this algorithm [11].

The quadratic fuel cost is a smooth function but ripples may appear on the input-output characteristics of generation units due to opening the valves of the steam governors (valve point effect [12]. Practically the generation units (thermal or hydraulic units) have prohibit operating zones (POZ) where, operating of these units are avoided at these zones due physical limitations of generation units and their components such as shaft bearing vibration, pumps and boilers [13]. The aim of this paper is to identify the optimal location and size of SSSC controller in power systems using IHS algorithm considering the non-smooth cost functions. A simple SSSC modelling in optimal load flow algorithm is developed. However, the paper is organized as follows: Section II describes the developed SSSC model. Section III presents the optimal power flow formulation. Section IV presents the IHS algorithm. In Section V, the numerical results with discussion of the standard IEEE 30-bus test system are presented. Finally, the conclusions are drawn in Section VI.

II. MODEL OF SSSC

SSSC is a series FACTS device that consists of voltage source converter connected to a common DC link as shown in Fig. 1. The equivalent circuit of SSSC can be represented as

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voltage source (V_{se}) connected in series with the impedance of coupling transformer (Z_{se}) as shown in Fig. 2.

The simple model of SSSC can be obtained by converting the voltage source into a current source in parallel with Z_{se}. This current can calculated as:

$$I_{inj} = \frac{V_{se}}{Z_{se}} = \frac{V_{se}}{R_{se}+jX_{se}} \tag{1}$$

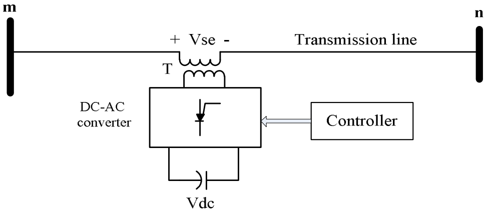


Fig. 1. SSSC schematic diagram**.**

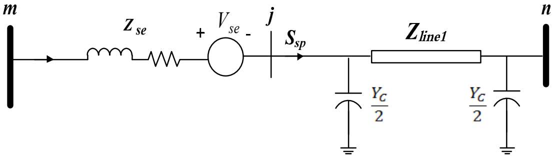


Fig. 2. Equivalent circuit of SSSC.

This current can be injected at buses (*m, j*) as shown. The new injected currents can calculated as a function of the specified active and reactive powers flow of transmission line. By applying Kirchhoff current law's at bus *j*

$$I_{inj} = I_{sp} - I_{mj} = \left(\frac{S_{sp}}{V_j}\right)^* - \left(\frac{V_m - V_j}{R_{se}+jX_{se}}\right) \tag{2}$$

where, $S_{sp} = P_{sp} + jQ_{sp}$

These currents also can be injected as complex loads at buses *m* and *j*, as shown in Fig. 3, as:

$$S_m = V_m\left(I_{inj}\right)^* \tag{3}$$

$$S_j = -V_j\left(I_{inj}\right)^* \tag{4}$$

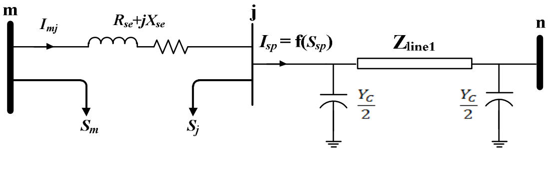


Fig. 3. The simplified SSSC model.

III. OPTIMAL POWER FLOW FORMULATION

Generally the OPF can be formulated as:

$$Min\ F(x) \tag{5}$$

Subjected to

$$g_j(x,u) = 0 \quad j = 1,2,\ldots,m \tag{6}$$

$$h_j(x,u) \le 0 \quad j = 1,2,\ldots,p \tag{7}$$

where F is the objective function, x is a vector represents the dependent variables, u is a vector represents the independent (the control) variables, g_j and h_j are the equality and inequality constraints, respectively. m and p are number of equality and inequality constraints, respectively.

The independent variables can be described as:

$$u = [P_{G2} \ldots P_{GNG}, V_{G1} \ldots V_{GNG}, Q_{C1} \ldots Q_{CNC}, T_1 \ldots T_{NT}, P_{sp}, Q_{sp}, L_c] \tag{8}$$

where,

P_G : Generator active power output
V_G : Voltage of generation bus
Q_C: Reactive power of shunt compensator
T: Transformer tap
NG : Number of generating units.
NC : Number of shunt compensator units
NT : Number of regulating transformers
P_{sp} : Specified active power
Q_{sp} : Specified reactive power
L_c : SSSC location

The dependent variables can be described as:

$$x = [P_{G1}, V_{L1} \ldots V_{LNPQ}, Q_{G1} \ldots Q_{GNG}, S_{TL1} \ldots S_{TLNTL}, |V_{se}|, \theta_{se}] \tag{9}$$

P_{G1}: Slack bus power
V_L : Voltage of load bus
Q_G: Generator reactive power output
S_{TL}: Apparent power flow in transmission line
NPQ : Load buses number
NG : Number of generating units
NTL : Transmission lines number
$|V_{se}|, \theta_{se}$: Voltage magnitude, phase angle of SSSC injected voltage.

3.1 Objective function

Generally the total fuel cost can be represented as:

$$F(x,u) = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NG}(a_i + b_i P_{Gi} + c_i P^2{}_{Gi}) \tag{10}$$

where, F_i is the fuel cost of i^{th} generator. a_i, b_i and c_i are the cost coefficients of i^{th} generator.

3.1.1 Valve point effect

Practically, the fuel cost of thermal unit isn't smooth function due to valve-point effects. The valve-point effect can be represented by adding a sine component to the quadratic cost function as:

$$F(x,u) = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NG}(a_i + b_i P_{Gi} + c_i P^2{}_{Gi}) + \left|d_i sin(e_i(P_{Gi}^{min} - P_{Gi}))\right| \tag{11}$$

where, d_i and e_i are the fuel cost coefficients of the i^{th} unit with valve-point effect.

3.1.2 Prohibited operating zones

The generation units has prohibited operating zones (POZs) due to the practical performance or the physical limitations of these units. However, the input–output characteristics of these units with POZs have discontinuous sub-regions.

3.1.3 Constraints

(a) Equality constrains:

These constraints represent the balanced load flow equations as:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{NB}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_{ij}) \tag{12}$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{NB}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_{ij}) \tag{13}$$

where, P_{Gi} and Q_{Gi} are the generated active and reactive powers at bus *i*, respectively. P_{Di} and Q_{Di} are the active and reactive load demand at bus i, respectively. $|Y_{ij}|$ and θ_{ij} are the admittance matrix magnitude and phase.

(b) Inequality constraints:

These constraints represent the operating limits of system components including:

1) $P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \qquad i = 1,2,\ldots,NG$ (14)
2) $V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \qquad i = 1,2,\ldots,NG$ (15)
3) $Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \qquad i = 1,2,\ldots,NG$ (16)
4) $T_{i}^{min} \le T_{i} \le T_{i}^{max} \qquad i = 1,2,\ldots,NT$ (17)
5) $Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \qquad i = 1,2,\ldots,NC$ (18)
6) $S_{Li} \le S_{Li}^{min} \qquad i = 1,2,\ldots,NTL$ (19)
7) $V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \qquad i = 1,2,\ldots,NPQ$ (20)
8) $V_{se}^{max} \le V_{se} \le V_{se}^{min}$ (21)
9) $\theta_{se}^{max} \le \theta_{se} \le \theta_{se}^{min}$ (22)

The constraints can be considered in solution by adding the penalty factor associated with the constraints to objective function. Thereby, the objective function can be formulated as:

$$F_g(x,u) = F_i(x,u) + e_G\left(P_{G1} - P_{G1}^{lim}\right)^2 + e_Q \sum_{\text{i}=1}^{NPV}\left(Q_{Gi} - Q_{Gi}^{lim}\right)^2 + e_V \sum_{\text{i}=1}^{NPQ}\left(V_{Li} - V_{Li}^{lim}\right)^2 + e_S \sum_{\text{i}=1}^{NTL}\left(S_{Li} - S_{Li}^{lim}\right)^2 + e_F(V_{se} - V_{se}^{lim})^2 + e_t(\theta_{se} - \theta_{se}^{lim})^2 \tag{23}$$

where e_G, e_V, e_Q, e_S , e_F and e_t are the penalty factors, x^{lim} acts the limit value of dependant variable.

IV. IMPROVED HARMONY SEARCH ALGORITHM

The Harmony search (HS) algorithm is an efficient optimization algorithm that mimics the improvisation process of musicians to seek the best harmony extraction [10]. In HS algorithm, a group of solution vectors (harmony vectors) are constructed randomly and stored in harmony memory (HM) which has a predefined size (HMS). The improvisation process depends up on finding a new solution vectors from the original vectors of HM based on harmony memory considering rate (HMCR), pitch adjusting rate (PAR) and random selection. The objective function is calculated in terms of New Harmony vector and compared with the original vectors in HM. The worst vector in HM is exchanged by the new better. This process is repeated until stopping criteria is achieved. In HS algorithm, pitch adjusting rate (PAR) and Distance bandwidth (BW) are constant values but in IHS, the values of PAR and BW are changed dynamically with iterative process for enhancing the algorithm performance [11]. The algorithm steps can be summarized as:

Step (1) Initialize the optimization problem and the IHS parameters as:

a) Upper and lower limits of control variables
b) Harmony memory considering rate(*HMCR*) where, 0.0≤ HMCR ≤ 1.0
c) Pitch adjusting rate (*PAR*)where, 0.0 ≤ *PAR* ≤ 1.0
d) Distance bandwidth (*BW*)
e) Maximum number of improvisations (*NI*)

Step (2) Initialization of the harmony memory by generating a group of solution vectors randomly to construct harmony memory as:

$$HM = \begin{bmatrix} u_1^1 & u_2^1 & \ldots & u_N^1 \\ u_1^2 & u_2^2 & \ldots & u_N^2 \\ \vdots & \vdots & \vdots & \vdots \\ u_1^{HMS-1} & u_2^{HMS-1} & \ldots & u_N^{HMS-1} \\ u_1^{HMS} & u_2^{HMS} & \ldots & u_N^{HMS} \end{bmatrix} \tag{24}$$

Step (3) Improvisation a new harmony, where new solution vectors are generated from harmony memory based on HMCR, PAR and random selection. HMCR represents the rating of choosing one value from harmony memory. The obtained values by HMCR are tested to be changed (pitch-adjusted) based on PAR which determines the probability of adjusting the obtained values or not as:

$$U_{i_{new}} = \begin{cases} U_i \pm rand \times BW & with\,probability\;\; PAR \\ U_i & with\,probability\;(1-PAR) \end{cases} \tag{25}$$

where, BW is a distance bandwidth and rand is a random number in the range [0, 1]. For enhancing the global search ability and convergence characteristic of the algorithm, values of PAR and BW are changed dynamically with algorithm iterations as:

$$PAR(t) = PAR_{min} + \left(\frac{PAR_{max}-PAR_{min}}{NI}\right) \times t \tag{26}$$

$$BW(t) = BW_{max}exp(\frac{Ln\frac{BW_{min}}{BW_{max}}}{NI} \times t) \tag{27}$$

where, PAR_{min} and PAR_{max} are the minimum and maximum values of PAR respectively. $BW_{min}$and BW_{max} are the minimum and maximum values of the distance bandwidth. t is the current iteration and NI is the maximum number of iterations or improvisations.

Step (4) Updating the harmony memory, where the New Harmony is included in harmony memory if the results obtained from the new vector in terms of objective function is better than results of the worst vector in HM.

Step (5) Check stopping criterion, if the current iterations is reached to the maximum number of improvisations, terminate the algorithm.

V. SIMULATION RESULTS

In this section, the *IHS* algorithm is employed to determine the optimal location and parameter settings of SSSC controller. The *IHS* algorithm and the simplified model of SSSC are tested using IEEE 30-bus to verify their performance and effectiveness. The system data can be obtained from [14]. The generator data are given in [15]. The upper and lower limits of control variables are reported in [16]. The permission voltage limit of PQ buses is [0.95, 1.05] p.u. The working range for the series injected voltage magnitudes and phase angles of SSSC are [0.001, 0.2] p.u. and [-π, π] degree respectively. For all studied cases, the impedance of SSSC is equal to 0.06 + j0.1 p.u. The system base MVA is 100. The program code was written in MATLAB 2009a and run on a PC with core i5 processor, 2.50 GHz and 4 GB RAM. The parameters of IHS are selected as follows: *HMS* = 25, *HMCR* = 0.95, PAR_{min} = 0.45, PAR_{max}= 0.99, BW_{min}= 0.00001, BW_{max}= 0.1 and *NI* = 500. The initial parameters of harmony search algorithm are similar to IHS algorithm except that PAR = 0.65 and BW =0.7.

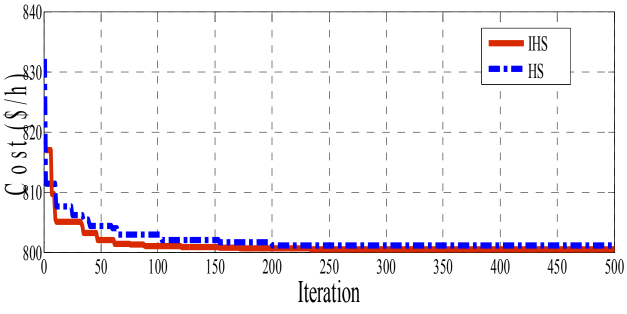
It should point out that, the penalty factors in (23) are set to 100. The lines that including the transformers are avoided for determining the optimal location of SSSC controllers.

4.1 Case1: OPF problem without valve-point effect and prohibited zones

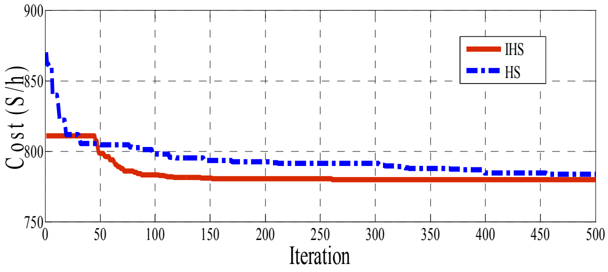
In this case, the considered objective function is the quadratic fuel cost. The optimal control variables without incorporating SSSC controller by IHS and HS algorithms are listed in 2*nd* and 3*rd* columns of Table I, respectively. The obtained fuel costs using *IHS* and *HS* algorithms are 800.477 \$/h and 801.124 \$/h. Referring to the comparison results of case1 in Table II, it obvious that, the obtained result using *IHS* algorithm is better than HS and those results reported in this table. The obtained fuel costs using IHS algorithm with incorporating SSSC in power system equals to 779.99 \$/h. Hence, the fuel cost in presence of SSSC is reduced by 2.56 % compared with case of no SSSC controller embedded in system. The optimal control variables in case of incorporating SSSC controller in the system using *IHS* and *HS* algorithms are listed in 2*nd* and 3*rd* columns of Table III. The optimal location of SSSC using *IHS* is determined at line number 7(4-6) and the optimal location using *HS* algorithm is determined at line number 14 (9-10). Fig. 4 shows the rapid convergence characteristics of *HS* and *IHS* algorithms with and without incorporating SSSC.

4.2 Case2: OPF problem with valve-point effect

In this case the OPF problem is solved with considering the valve-point effect as depicted in (11). Referring to Table I, the obtained fuel cost with valve point effect in case of using IHS and HS algorithms are 834.411 \$/h and 835.602\$/h, respectively. The obtained fuel costs with valve point effect are reduced to 800.692 \$/h and 810.487 \$/h with incorporating SSSC in case of using *IHS* and *HS* algorithms, respectively. Hence, with incorporating the SSSC in system, the fuel costs are decreased by 4.041 % and 3.006 % in case of using of *IHS* and *HS* algorithms, respectively. The convergence characteristics of *HS* and *IHS* algorithms are shown in Fig. 5. It is clear that the fuel cost decrease rapidly. Moreover, the *IHS* gives better results compared with *HS* algorithm.

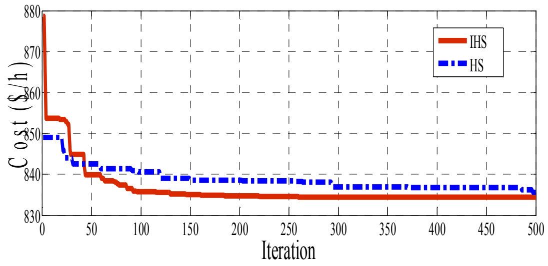


(a) Without SSSC

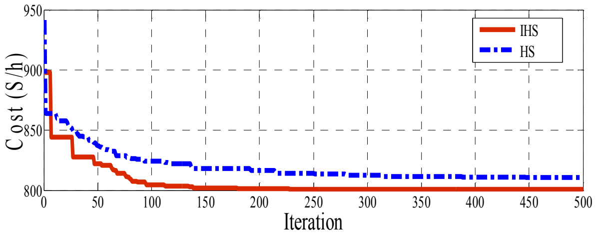


(b) With SSSC

Fig. 4. Convergence characteristic of HS and IHS for case1



(a) Without SSSC



(b) With SSSC

Fig. 5. Convergence characteristics of HS and IHS for case2

4.3 Case3: OPF problem considering the prohibited operating zones of generation units

In this case, the OPF is solved with considering the prohibited operating zones of generation units. Referring to Table I, the obtained fuel costs with considering prohibited zones using IHS and HS are 800.878 \$/h and 801.754 \$/h, respectively. Referring to the comparison results of case 3 in Table II, it is clear that the obtained result using IHS algorithm is better than HS and the others reported results.

With incorporating SSSC, the fuel costs are reduced to 780.297 \$/h and 785.443 \$/h in case of using *IHS* and *HS* algorithms, respectively. The control variables including the location and parameter settings of SSSC in case of using *IHS* and *HS* algorithms for fuel cost are listed in 6*th* and 7*th* columns of Table III. The convergence characteristics of HIS and HS algorithms are shown in Fig. 6.

TABLE I. OPTIMAL CONTROL VARIABLES FOR DIFFRENT STUDIED CASES WITHOUT INCORPORATING SSSC.

Variables (p.u)	**Case1**		**Case2**		**Case3**	
	IHS	**HS**	**IHS**	**HS**	**IHS**	**HS**
P1	1.7706	1.7895	1.9441	1.9389	1.7927	1.7848
P2	0.4857	0.4766	0.4855	0.4907	0.4495	0.4494
P5	0.2141	0.2292	0.1893	0.19.15	0.2155	0.23.10
P8	0.2146	0.2042	0.10.00	0.10.00	0.2230	0.2194
P11	0.1191	0.1066	0.100	0.100	0.1239	0.1217
P13	0.1200	0.1200	0.1200	0.1200	0.1200	0.1200
V1	1.0836	1.0844	1.0819	1.0801	1.0795	1.0831
V2	1.0843	1.1000	1.1000	1.1000	1.0999	1.1000
V5	1.0328	1.0907	1.0279	1.0264	1.0285	1.0816
V8	1.0366	1.0143	1.0346	1.0258	1.0231	1.0242
V11	1.0683	1.1000	1.0808	1.0079	1.0368	0.9888
V13	1.0337	1.0410	1.0544	1.0287	1.0709	0.9831
T11	1.0240	1.1000	1.0535	1.0045	0.9654	1.0490
T12	0.9260	0.9120	0.9117	0.9644	0.9840	0.9326
T15	0.9700	0.9457	0.9869	1.0581	1.0094	0.9999
T36	0.9721	0.9912	0.9782	0.9979	0.9716	1.0210
Q10	0.0042	0.0063	0.064	0.0372	0.0496	0.0364
Q12	0.0419	0.0000	0.0390	0.0458	0.0178	0.0500
Q15	0.0484	0.0000	0.0499	0.0331	0.0417	0.0500
Q17	0.0489	0.0194	0.0475	0.0500	0.0499	0.0000
Q20	0.0438	0.0500	0.0344	0.05000	0.0478	0.0000
Q21	0.0499	0.0500	0.0493	0.0142	0.0500	0.0500
Q23	0.0285	0.0340	0.0373	0.0249	0.0325	0.0500
Q24	0.0499	0.0500	0.0498	0.0000	0.0499	0.0500
Q29	0.0185	0.0000	0.0259	0.0000	0.0229	0.0171
Ploss(p.u)	0.0902	0.0921	0.0105	0.0072	0.0908	0.0917
VD (p.u)	0.8986	0.6902	0.8624	0.3814	0.8815	0.4022
Fuel cost ($/h)	800.477	801.124	834.411	835.602	800.878	801.754

TABLE II. COMPARISON RESULTS FOR DIFFERENT CASES WITHOUT INCORPORATING SSSC.

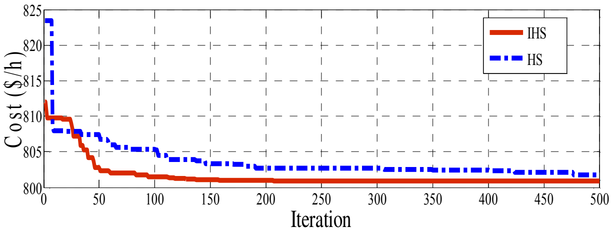
	Algorithm	Fuel Cost($/h)	Description	Ref.
Case 1	**IHS**	**800.477**	Improved Harmony Search	
	HS	801.1235	Harmony Search	
	IGA	800.805	Improved Genetic Algorithms	[17]
	TS	802.290	Tabu search	[18]
	MDE	802.376	Modified Differential Evolution Algorithm	[19]
	IEP	802.465	Improved Evolutionary Programming	[20]
	EP	802.62	Evolutionary Programming	[21]
	RGA	804.019	Refined Genetic Algorithm	[22]
	GM	804.853	Gradient Method	[16]
	GA	805.937	Genetic algorithm	[22]
Case 2	**IHS**	**834.411**	Improved Harmony Search	
	HS	835.6021	Harmony search	
Case 3	**IHS**	**800.878**	Improved Harmony Search	
	HS	801.0513	Harmony Search	
	SOS	801.839	Symbiotic organisms search algorithm	[23]
	BSA	801.85	Backtracking Search Algorithm	[23]
	Hybrid SFLA-SA	805.815	Hybrid Shuffle Frog Leaping Algorithm – Simulated Annealing	[24]
	PSO	806.433	Particle Swarm Optimization	[24]
	SA	808.717	Simulated Annealing	[24]
	GA	809.231	Genetic algorithm	[24]

VI. CONCLUSIONS

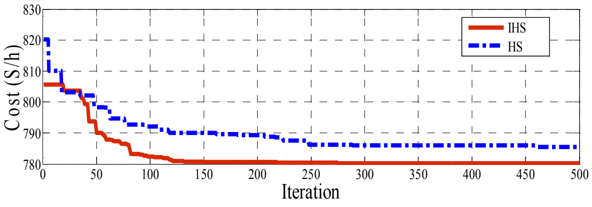
In this paper, the optimal location and parameters settings of SSSC have determined using the improved harmony algorithm for different objective functions. The OPF problems are solved with and without incorporating SSSC in power system including fuel cost minimization and fuel cost minimization considering the valve point loading effect and prohibited zones. In this paper, a simple model of SSSC has applied for the optimal power flow solution. The developed model is based on power injection approach to avoid any modifications in the original Jacobian matrix. The improved harmony search (IHS) algorithm and the developed model of SSSC were successfully implemented in standard IEEE 30-bus test system. The simulation results have validated the effectiveness and superiority of IHS algorithm for OPF problem compared with harmony search (HS) algorithm and others reported methods. Furthermore, well results are obtained with incorporating of SSSC in term of the objective functions.

TABLE III. Optimum control variables with for different studied cases with incorporating SSSC.

Variables (p.u)	Case1		Case2		Case 3	
	IHS	**HS**	**IHS**	**HS**	**IHS**	**HS**
P1	1.7500	1.7271	1.8892	1.9198	1.7738	1.69.35
P2	0.4865	0.4990	0.4471	0.4445	0.4477	0.5568
P5	0.2116	0.2493	0.1830	0.1843	0.2148	0.2226
P8	0.1919	0.2493	0.1000	0.1017	0.1961	0.1602
P11	0.1052	0.1000	0.1000	0.1000	0.1114	0.1223
P13	0.1202	0.1200	0.1200	0.1200	0.1221	0.1200
V1	1.0160	1.0349	0.9602	1.0779	1.0184	1.0249
V2	1.0024	1.0427	1.0171	1.0851	1.0067	1.0637
V5	1.0157	1.0040	0.9840	1.0227	1.0291	1.0385
V8	1.0539	0.9887	0.9915	1.0058	1.0381	1.0164
V11	1.0993	1.0327	1.0950	1.0484	1.0835	1.0185
V13	0.9506	1.0936	1.0794	0.9741	0.9770	1.0486
T11	1.0906	1.0124	1.0011	0.9661	1.0944	0.9259
T12	1.0149	1.1000	0.9004	1.1000	1.0244	1.0166
T15	0.9004	1.0886	0.9834	1.0758	0.9000	1.0936
T36	1.0168	0.9579	0.9416	1.0018	0.9924	0.9959
Q10	0.0408	0.0500	0.0148	0.0000	0.0473	0.0381
Q12	0.0005	0.0304	0.0479	0.0000	0.0000	0.0500
Q15	0.0077	0.0000	0.0474	0.0122	0.0046	0.0368
Q17	0.0225	0.0000	0.0499	0.0036	0.0102	0.0000
Q20	0.0343	0.0274	0.0437	0.0048	0.0407	0.0000
Q21	0.0399	0.0000	0.0489	0.0253	0.0457	0.0000
Q23	0.0343	0.0235	0.0385	0.0500	0.0348	0.0000
Q24	0.0442	0.0500	0.0499	0.0280	0.0459	0.0500
Q29	0.0204	0.0063	0.0270	0.0181	0.0186	0.0276
Ploss (p.u)	0.1644	0.2013	0.3102	0.2045	0.1662	0.1635
VD (p.u)	0.4892	0.4083	0.7609	0.7759	0.4003	0.7691
Fuel cost($/h)	779.99	783.77	800.692	810.487	780.297	785.443
Parameters of SSSC controller						
Location	7(4-6)	14(9-10)	1(1-2)	14(9-10)	7(4-6)	7(4-6)
P_{sp}(MW)	83.00	8.97	100.1	10.822	84.485	35.177
Q_{sp}(MVar)	1.083	39.51	21.990	49.995	5.847	30.235
V_s(p.u)	0.1933 $\angle 33^o$	0.1899 $\angle -68^o$	0.2000 $\angle -35^o$	0.1877 $\angle -72^o$	0.1995 $\angle 33^o$	0.1810 $\angle -32^o$



(a) Without SSSC



(b) With SSSC

Fig. 6. Convergence characteristics of HS and IHS for case3

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