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REGULAR PAPER

Optimal reactive power dispatch considering multi-type FACTS devices using harmony search algorithms

Optimalno otpremanje jalove snage uzimajući u obzir raznovrsne FACTS uređaje uz korištenje algoritma harmonijske pretrage

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ABSTRACT

Optimal Reactive Power Dispatch (ORPD) plays an important role for the secure and reliable operation of power systems. The main purpose of ORPD is to find the settings of control variables such as voltage rating of generators, reactive power injection of VAr compensators and tap ratios of the tap setting transformers in order to minimize the total active power losses of the network while satisfying a given set of constraints. In this paper, Flexible AC Transmission System (FACTS) controllers such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Shifting Transformer (TCPST) are considered in addition with the conventional ORPD control variables for additional active power loss minimization. The whole ORPD problem is considered as a non-linear multi-modal optimization problem. Harmony search algorithm is a recent meta-heuristic algorithm which mimics the musician's improvization process. In this paper, two versions of harmony search algorithm, namely Basic Harmony Search Algorithm (HSA) and Improved Harmony Search Algorithm (IHSA) are applied to solve conventional ORPD, as well as ORPD considering FACTS devices. Studies on the proposed algorithm are carried out on IEEE 14 and 57 bus systems. Comparison of simulation results reveals the effectiveness of proposed algorithms over other well-established population-based optimization techniques.

Optimalno otpremanje jalove snage (ORPD) ima veliku ulogu u sigurnom i pouzdanom radu elektroenergetskog sustava. Glavna je svrha ORPD-a pronaći postavke upravljačkih varijabli, kao što su napon generatora, injektirana jalova snaga VAr kompenzatora ili omjer transformatora preklapanjem izvoda, s ciljem minimizacije ukupnih gubitaka radne snage mreže uz poštivanje danog skupa ograničenja. U ovom radu, razmatrani su regulatori za fleksibilni AC prijenosni sustav (FACTS), kao što su statički VAr kompenzator (SVC), tiristorski regulirana banka kondenzatora (TCSC) ili tiristorski regulirani transformator za pomak faze (TCPST), uz dodane klasične ORPD upravljačke varijable za dodatno smanjenje gubitaka radne snage. Cijeli ORPD problem razmatra se kao nelinearni više-modalni optimizacijski problem. Algoritam harmonijske pretrage novi je metaheuristički algoritam koji oponaša improvizacijski proces glazbenika. U radu su korištene dvije verzije algoritma harmonijske pretrage, osnovni algoritam harmonijske pretrage (HSA) i unaprijeđeni algoritam harmonijske pretrage, za proračun klasičnog ORPD-a te ORPD-a s FACTS uređajima. Istraivanje predloženog algoritma izvedeno je na IEEE 14 i 57 sabirnicama. Usporedba simulacijskih rezultata otkriva učinkovitost predloženih algoritama u odnosu na druge etablirane populacijske optimizacijske tehnike.

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1. Introduction

The optimal power flow (OPF) problem is a major and powerful tool for operating and planning of power systems first formulated by Carpentier in 1960s [1]. One of the main sub problems of OPF is optimal reactive power dispatch (ORPD) problem which includes the optimal setting of generator output voltages, compensators, tap ratios of transformers, and outputs of shunt reactive sources. This sub problem is used to minimize interested objective functions such as transmission losses while satisfying a given set of operating and physical limitations. The whole ORPD problem is considered as a non-linear multi-modal optimization problem with a combination of discrete and continuous variables. Deterministic algorithms such as Lagrange multipliers, Dynamic Programming (DP), Non-Linear Programming (NLP), Linear Programming (LP), Quadratic Programming (QP), and Sequential Quadratic Programming (SQP) have been proposed to solve ORPD problems [2,3]. However,

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computational intelligence based techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Evolutionary Programming (EP), Differential Evolution (DE), etc. seem to have shared the same dominance as deterministic algorithms [4–8]. This is because heuristic algorithms, unlike deterministic ones, are derivative-free, and capable of solving optimization problems without requiring convexity. On the other hand, heuristic algorithms have drawbacks such as being problem dependent, requiring parameter tuning, and unable to guarantee global solution attainment. Therefore, a variety of research efforts were directed at combining more than one technique into a single (hybrid) algorithms.

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The idea behind the hybridization is to improve the solution quality by overcoming the limitations of each individual technique.

Harmony search algorithm is a new meta-heuristic algorithm developed by Geem et al (2001) which is inspired by the natural musical performance process that occurs when a musician searches for a better state of harmony [9]. In the harmony search algorithm, the solution vector is analogous to the harmony in music, and the local and global search schemes are analogous to musician's improvizations. In comparison to other meta-heuristics in the literature, the Harmony algorithm imposes fewer mathematical requirements and can be easily adapted for solving various kinds of engineering optimization problems. Furthermore, numerical comparisons demonstrated that the evolution in the harmony algorithm was faster than genetic algorithms [12]. Therefore, the harmony search algorithm has attracted much attention and has been successfully applied to solve a wide range of practical optimization problems.

In this work, Flexible AC Transmission System (FACTS) controllers such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Shifting Transformer (TCPST) are considered in addition with the conventional ORPD for additional active power loss minimization. The SVC can generate or absorb reactive power according to the demand of reactive power in the network to improve voltage and reduce system losses. TCSC can provide continuous control of power on the AC line with variable series capacitive reactance. The TCPST acts by adding a quadrature component to the prevailing bus voltage in order to increase or decrease its angle. Along with the conventional control variables in ORPD the optimal location and the settings of SVC, TCSC and TCPST are included in the optimization problem for additional active power loss reduction.

The conventional ORPD problem was solved by the harmony search algorithm for IEEE 30 and 57 bus systems [17]. In this paper, two versions of harmony search algorithm, namely Basic Harmony Search Algorithm (HSA) and Improved Harmony Search Algorithm (IHSA) are applied to solve conventional ORPD, as well as ORPD considering SVC,TCSC and TCPST. Studies on the proposed algorithm are carried out on IEEE 14 and 57 bus systems. Comparison of simulation results reveals the effectiveness of the proposed algorithm over other well-established population-based optimization techniques.

2. Power flow model of facts devices

The location and setting of flexible AC transmission system (FACTS) devices such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Shifting Transformer (TCPST) are considered as additional control parameters in the ORPD problem for further system loss minimization. Representing FACTS devices in the load flow analysis is a basic requirement in ORPD problem [10,11]. Figure 1 shows the power flow model of the proposed FACTS devices.

2.1. Static Var Compensator

The Static Var Compensator (SVC) may have two characters: inductive or capacitive. In the first case, it absorbs reactive power while in the second one the reactive power is injected. The SVC is modelled with two ideal switched elements in parallel: a capacitance and an inductance.

2.2. Thyristor Controlled Series Capacitor

The Thyristor Controlled Series Capacitor (TCSC) may have one of the two possible characteristics: capacitive or inductive, respectively to decrease or increase the reactance of the line. It is modelled with three ideal switched elements in parallel: a capacitance, an inductance and a simple wire, which permits the TCSC to have the value zero. The capacitance and the inductance are variable and their values are function of the reactance of the line in which the device is located.

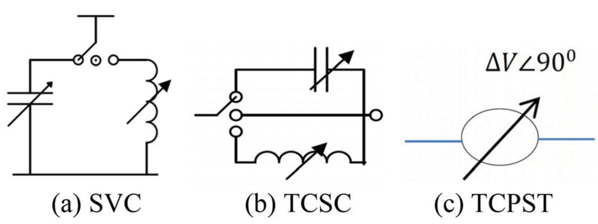

Figure 1. Power flow model of FACTS devices.

2.3. Thyristor Controlled Phase shifting Transformer

The Thyristor Controlled Phase shifting Transformer (TCPST) acts by adding a quadrature component to the bus voltage in order to increase or decrease its angle. The model used for this device is an ideal phase shifter with a series impedance equal to zero. It is inserted in series and may take values of angles comprised in the range of −5 deg to 5 deg. Zero is also a possible value for the TCPST.

3. Problem formulation

The solution of the optimal reactive power dispatch problem involves the optimization of the non-linear objective function with non-linear system constraints. The objective of the optimal reactive power dispatch is to minimize the active power loss in the transmission network, which can be defined as follows:

$$P_{\text{loss}} = \min\left[\sum_{k=1}^{NL} G_k(V_i^2 + V_j^2 - 2V_iV_j\cos\beta_{ij})\right], \quad (1)$$

where P_{loss} is the total active power loss, G_k is the conductance of the kth branch connected between ith and jth bus, β_{ij} is the admittance angle of transmission branch connected between ith and jth bus. NL is the number of transmission lines. V_i and V_j are the voltage magnitude of the ith and jth bus, respectively.

3.1. Equality Constraints

The below terms are the equality constraints, illustrating typical load flow equations.

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{NB} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}), \quad (2)$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{NB} V_j(G_{ij}sin\theta_{ij} + B_{ij}cos\theta_{ij}), \quad (3)$$

where $i = 1{,}2, \ldots .NB\text{-}1$ and NB is the number of buses, P_{Gi} is the active power generation,Q_{Gi} is the reactive power generation, P_{Di} is the active load demand, Q_{Di} is the reactive load demand, G_{ij} and B_{ij} are the conductance and susceptance, respectively.

3.2. Inequality constraints

Reactive power source installation restrictions, reactive generation restriction, transformer tap setting restriction, bus voltage restriction and power flow through the transmission lines restriction are used as inequality constraints. In ORPD problem, the generator bus voltages, tap position of transformers, and the amount of the reactive power source installations are the independent variables and these inequality constraints are mathematically expressed as

3.2.1. Generator constraints

Generator real power, reactive power and voltage outputs are restricted by their lower and upper limits as follows:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, i \in N_{PV}, \quad (4)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, i \in N_{PV}, \quad (5)$$

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}, i \in N_{PV}, \quad (6)$$

where P_{Gi} is the real power generation of bus i. P_{Gi}^{min} and P_{Gi}^{max} are the minimum and maximum limits of real power generation of bus i Where Q_{Gi} is the reactive power generation of bus i. Q_{Gi}^{min} and Q_{Gi}^{max} are the minimum and maximum limits of reactive power generation of bus i and V_{Gi} is the voltage of bus i, V_{Gi}^{min} and V_{Gi}^{max} are the minimum and maximum limits of voltage of bus i and N_{PV} is the total number of PV buses.

3.2.2. Transformer constraints

Transformer tap setting are bounded as follows:

$$Tj^{min} \leq T_j \leq T_j^{max}, j \in \text{NT}, \quad (7)$$

where T_j is the tap setting of jth transformer and T_j^{min} and Tj^{max} are the minimum and maximum tap settings of the transformer. NT is the number of transformers in the system.

3.2.3. Security constraints

These include the constraints of voltages at load buses and transmission line loading as follows:

$$V_k^{min} \leq V_k \leq V_k^{max}, k \in N_{PQ}, \quad (8)$$

$$S_{li} \leq S_{li}^{max}, \ i \in NL, \quad (9)$$

where V_k is the voltage of kth load bus. V_k^{min} and V_k^{max} are the minimum and maximum limits of the voltage of load buses. N_{PQ} is the total number of PQ buses. S_{li} is the apparent power flow in the transmission line i, S_{li}^{max} is the maximum limits of apparent flow in the transmission line. NL is the number of transmission line in the system.

3.2.4. SVC var constraints

To incorporate FACTS devices such as SVC, TCSC and TCPST with ORPD the following constraints are added as follows:

$$Q_{SVCw,min} \leq Q_{SVCw} \leq Q_{SVCw,max}, w \in NSVC, \quad (10)$$

where Q_{SVCw} is the VAR rating of SVC and $Q_{SVCw,min}$ and $Q_{SVCw,max}$ are the minimum and maximum VAr limits of SVC. NSVC is the number of nodes having SVC. w represents the current SVC bus number under consideration.

3.2.5. TCSC reactance constraints

TCSC reactance values are restricted within the limits as follows:

$$- 0.7X_{line} \leq X_{TCSCv} \leq 0.2X_{line} v \in NTCSC, \quad (11)$$

where X_{line} is the reactance of line where TCSC is connected. X_{TCSCv} is the reactance of vth TCSC. NTCSC is the number of lines having TCSC. v represents the current TCSC line number under consideration.

3.2.6. TCPST angle constraints

TCPST phase angle value are restricted within the following limits:

$$- 5deg \leq \theta_m \leq +5\deg m \in NTCPST, \quad (12)$$

where θ_m is the phase angle of mth TCPST, NTCPST is the number of lines having TCPST, m represents the current TCPST line number under consideration. Control variables are self-constrained, and dependent variables are constrained using penalty terms (λ_V, λ_Q) to the objective function. So the objective function is generalized as follows:

$$f = P_{loss} + \lambda_v \sum_{N_V^{lim}} (V_i - V_i^{lim})^2 + \lambda_Q \sum_{N_Q^{lim}} (Q_{Gi} - Q_{Gi}^{lim})^2, \quad (13)$$

$$V_i^{lim} = \begin{cases} V_{i,} & if\ V_i^{min} \leq V_i \leq V_i^{max} \\ V_i^{min} & if\ V_i < V_i^{min} \\ V_i^{max} & if\ V_i > V_i^{max} \end{cases}, \quad (14)$$

$$Q_{Gi}^{lim} = \begin{cases} Q_{Gi,} & if\ Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \\ Q_{Gi}^{min} & if\ Q_{Gi} < Q_{Gi}^{min} \\ Q_{Gi}^{max} & if\ Q_{Gi} > Q_{Gi}^{max} \end{cases} \quad (15)$$

4. Harmony search algorithms

4.1. Basic Harmony Search algorithm

The basic Harmony Search algorithm (HSA) is a meta-heuristic optimization algorithm inspired by the playing of music. It uses rules and randomness to imitate natural phenomena. Inspired by the cooperation within an orchestra, the HSA achieves an optimal solution by finding the best "harmony" among the system components involved in a process. Just as discrete musical notes can be played based on a player's experience or on random processes in improvization. The optimal design variables in a system can be obtained with certain discrete values based on computational intelligence and random processes. Musicians improve their experience based on aesthetic standards, whereas design variables can be improved based on an objective function.

The parameters of the HS algorithm are harmony memory size (HMS), i.e. the number of solution vectors in harmony memory, harmony memory consideration rate (HMCR), pitch adjusting rate (PAR), distance bandwidth (*bw*), number of improvizations (NI), upper bounds of decision variable UB and lower bound of decision variable LB. The computational procedure of the HSA algorithm for a minimization problem can be summarized as follows:

Step 1: Set the parameters HMS, HMCR, PAR, *bw* and NI.

Step 2: Initialize the HM and calculate the objective function values for each harmony vector.

Step 3: Improvise a new harmony x_{new} as follows:

$for\ each\ i \in [1, N] do$
$if\ (r_1 < HMCR) then$
$x_{new}(i) = x_a(i)\ where\ a \in (1, 2, \ldots .HMS)$
$if\ (r_2 < PAR) then$
$x_{new}(i) = x_{new}(i) \pm r \times bw\ where\ r \in (0, 1)$
$endif$
$else$
$x_{new}(i) = LB_j \pm r_3 \times (UB_j - LB_j)$
$where\ r_1, r_2, r_3, \in (0, 1)$
$endif$
$endfor$

4.2. Improved Harmony Search Algorithm

The Improved Harmony Search Algorithm (IHSA) was developed by Mahdavi et al (2007) and has been successfully applied to various benchmarking tests and standard engineering optimization problems [12]. Numerical results have proven that the improved algorithm can find better solutions than the basic HSA and other heuristic or deterministic methods. The key difference between the IHSA and traditional HSA is in the manner by which PAR and *bw* are adjusted. The IHSA uses variable PAR and *bw* values in the improvization step to improve the performance of the HSA and eliminate the drawbacks associated with using fixed PAR and *bw* values. The PAR values change dynamically with the generation number and expressed as follows:

$$PAR(gn) = PAR_{min} + \frac{(PAR_{max} - PAR_{min})}{NI} \times gn \quad (16)$$

where PAR is the pitch adjustment rate for each generation, PAR_{min} is the minimum pitch adjustment rate, PAR_{max} is the maximum pitch adjustment rate, NI is the number of solution vector generations, and gn is the generation number. bw changes dynamically with the generation number and is defined as follows:

$$bw(gn) = bw_{max} \exp(c.gn), \quad (17)$$

$$c = \frac{ln\left(\frac{bw_{max}}{bw_{min}}\right)}{NI}, \quad (18)$$

where $bw(gn)$ is the bandwidth at each generation, and bw_{min} and bw_{max} are the minimum and maximum bandwidths, respectively.

5. Application of harmony search algorithms to ORPD considering facts devices

The implementation of the harmony search algorithms for the ORPD considering FACTS devices includes finding the optimal value of control variables such as generator voltages, tap ratio of tap changing transformers, amount of VAR injection by shunt reactive sources. SVC bus location, SVC MVAr setting, TCSC line location, TCSC reactance setting, TCPST line location and TCPST angle setting to minimize the objective function while satisfying the constraints. The implementation process of harmony search algorithms to the optimal reactive power dispatch problem is described in the following steps:

Step 1: Read power system parameters such as bus, branch, and generator data. Read the parameters of harmony search algorithms such as harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), number of improvizations (NI), bandwidth (bw). minimum pitch adjustment rate PAR_{min}, maximum pitch adjustment rate PAR_{max}, minimum bandwidth bw_{min}, and maximum bandwidth bw_{max}.

Step 2: Initialize harmony memory (HM) with the number of rows equal to HMS and number of columns equal to the number of the control variable. For example, the harmony memory (HM) for ORPD problem of IEEE 14 bus system with one SVC, one TCSC and one TCPST installed is given below:

$$\begin{bmatrix} V_1^1 & V_2^1 & .. & V_8^1 & V_8^1 & T_{4-7}^1 & T_{5-6}^1 & Qc_9^1 \\ V_1^2 & V_2^2 & .. & V_8^2 & V_8^2 & T_{4-7}^2 & T_{5-6}^2 & Qc_9^2 \\ . & . & .. & . & . & . & . & . \\ . & . & .. & . & . & . & . & . \\ V_1^49 & V_2^49 & .. & V_8^49 & V_8^49 & T_{4-7}^49 & T_{5-6}^49 & Qc_9^{49} \\ V_1^50 & V_2^50 & .. & V_8^50 & V_8^50 & T_{4-7}^50 & T_{5-6}^50 & Qc_9^{50} \end{matrix}$$
$$\begin{matrix} Qc_14^1 & A_1^1 & B_1^1 & C_1^1 & Q_{SVCA_1^1}^1 & X_{TCSCB_1^1}^1 & \theta_{TCPSTC_1^1}^1 \\ Qc_14^2 & A_1^2 & B_1^2 & C_1^2 & Q_{SVCA_1^2}^2 & X_{TCSCB_1^2}^2 & \theta_{TCPSTC_1^2}^2 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ Qc_14^49 & A_1^49 & B_1^49 & C_1^49 & Q_{SVCA_1^49}^49 & X_{TCSCB_1^49}^49 & \theta_{TCPSTC_1^49}^{49} \\ Qc_14^50 & A_1^50 & B_1^50 & C_1^50 & Q_{SVCA_1^50}^50 & X_{TCSCB_1^50}^50 & \theta_{TCPSTC_1^50}^{50} \end{bmatrix} \quad (19)$$

where V_1,V_2,V_3,V_6,V_8 are the voltages of generators and T_{4-7},T_{4-9} and T_{5-6} are the tap ratios of transformers. Q_{c9} and Q_{c14} are the VAr injection from shunt reactive sources. A_1 is the bus location of SVC, B_1 is the line location of TCSC and C_1 is the line location of TCPST. Q_{SVCA_1} is the MVAr rating of SVC located at bus number A_1, X_{TCSCB_1} is the reactance of TCSC located at line number B_1 and $\theta_{TCPSTC_1}$is the angle of TCPST located at line number C_1.

Step 3: The power flow programme is run to calculate the objective function of each solution vector of HM [13]. The HM is sorted in ascending order.

Step 4: A new harmony is improvised through position, memory consideration random selection and pitch adjustment. For improved harmony search algorithm use pitch adjustment rate and bandwidth using Equations (16)–(18) to calculate new harmony.

Step 5: The worst harmony in HM is replaced with the new harmony.

Step 6: Check for the equality and inequality constraints of the ORPD considering FACTS devices

Step 7: Whether the stopping criterion (Number of Improvizations $> = 50000$) is satisfied go to the next step otherwise repeat step 3 to step 6.

Step 8: Print optimal setting of control variables and active power loss.

6. Case study

In this paper, harmony search algorithms are applied to IEEE 14 and IEEE 57 standard test power systems for the solution of the conventional ORPD problem as well as ORPD problem considering FACTS devices. Description of these studied test systems is depicted in Table 1. The software is written in MATLAB 2009b and applied on a 2.40 GHz Intel (R) core (TM) i3 CPU personal computer with 3GB RAM.

Table 1. Description of test systems.

Description	IEEE 14	IEEE 57
Buses, NB	14	57
Generators, NG	5	7
Transformers, NT	3	15
Shunts, NQ	2	3
Branches, NL	20	80
Control variables, CV	10	25
Base case P_{Loss}, MW	13.49	28.462

Table 2. Limits of control variables for IEEE 14 bus system considering FACTS devices.

V_G^{max}	V_G^{min}	T_k^{max}	T_k^{min}	Q_c^{max}	Q_c^{min}	Q_{SVC}^{min}	
1.1	0.95	1.1	0.9	0.3	0.0	−0.3	0.3
		X_{TCSC}^{min}	X_{TCSC}^{max}	θ_{TCPST}^{min}	θ_{TCPST}^{max}		
		$-0.8X_{ij}$	$0.2X_{ij}$	−5°	5°		

Table 3. Parameter settings of harmony search algorithms for IEEE 14 bus system considering FACTS devices ($n = 16$).

Algorithm	HMS	HMCR	PAR	bw	NI
HSA	10	0.9	0.3	0.01	50000
IHSA	10	0.9	$PAR_{min} = 0.01$ $PAR_{mzx} = 0.99$	$bw_{max} = 0.0005$ $bw_{min} = 0.0001$	50000

Table 4. Active power loss comparison for IEEE 14 bus system considering FACTS devices.

	P_{loss} in MW (HSA)	P_{loss} in MW (IHSA)
Case 1	12.792	12.687
Case 2	12.471	12.417
Case 3	**12.198**	**12.065**

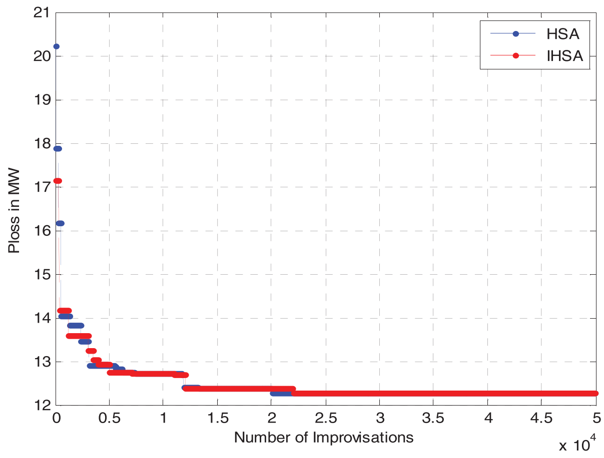

Figure 2. Convergence of power loss for IEEE 14 bus system considering FACTS devices with ORPD.

6.1. IEEE 14 bus test systems

6.1.1. Experimental settings

The system consists of 20 branches, 17 of which are transmission lines and 3 are tap- changing transformers. The total system load is 259MW and 73.5 MVAr. The initial system active power loss is 13.493 MW. The busdata and linedata are taken from Refs[14]. In this test network, three cases are studied as follows:

- Case 1: Installation of single type FACTS device (one SVC)
- Case 2: Installation of two type FACTS devices (one SVC, one TCSC)
- Case 3: Installation of three type FACTS devices (one SVC, one TCSC and one TCPST).

For example, for case 3 there are 16 control variables, which consists of 5 generator voltages, 3 tap ratio of transformers,2 shunt reactive sources MVAr rating, SVC bus location, TCSC line location, TCPST line location, SVC MVAr Rating, TCSC reactance setting and TCPST angle setting. Table 2 illustrates the limits of the control variable of IEEE 14 bus system considering FACTS devices. Table 3 gives the parameter setting of harmony search algorithm for IEEE 14 bus system considering FACTS devices.

where "n" denotes the dimension of the problem.

In Table 2. X_{ij} represents the reactance of the line where TCSC is connected.

6.2. Simulation results

Table 4 gives the active power loss computation by HSA and IHSA for the three cases. Table 5. presents the control variable setting for the IEEE 14 bus system for case 3. The optimal bus location and line location of FACTS devices are given within the braces. According to results presented in Table 4, the installation of single type FACTS device brings the active power loss to 12.792 MW for HSA and 12.687 MW for IHSA. Similarly, according to Table 4, the installation of two type FACTS devices fetches total active power loss to 12.471 MW for HSA and 12.417 MW for IHSA. If three type FACTS devices SVC, TCSC and TCPST are simultaneously installed the total active power loss will be equal to

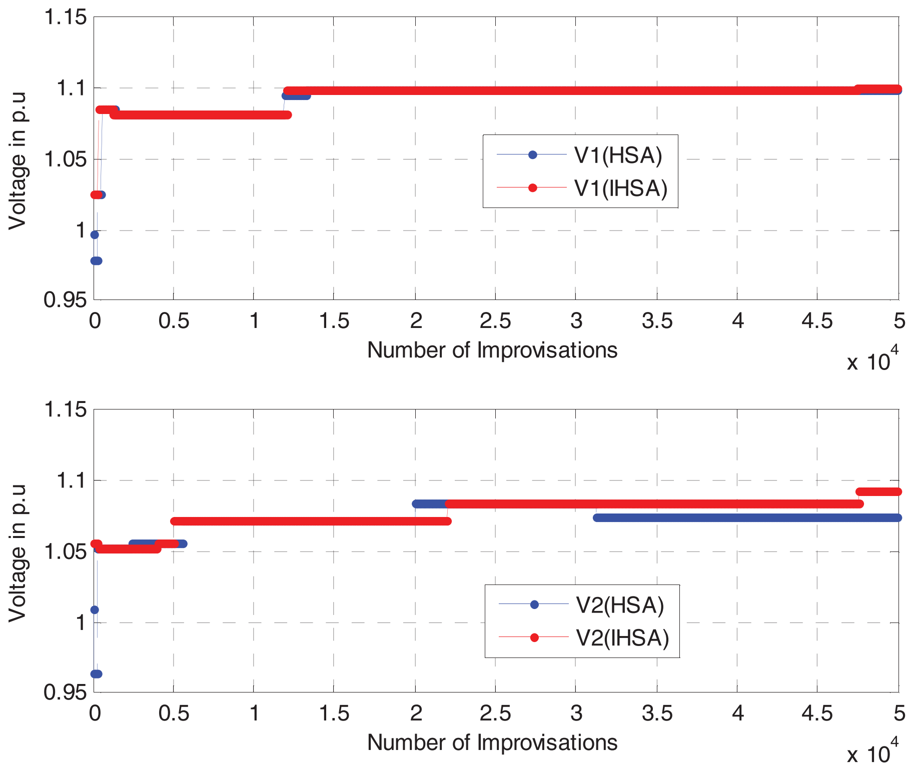

Figure 3. Convergence of generator voltages V1 and V2 for IEEE 14 bus system considering FACTS devices.

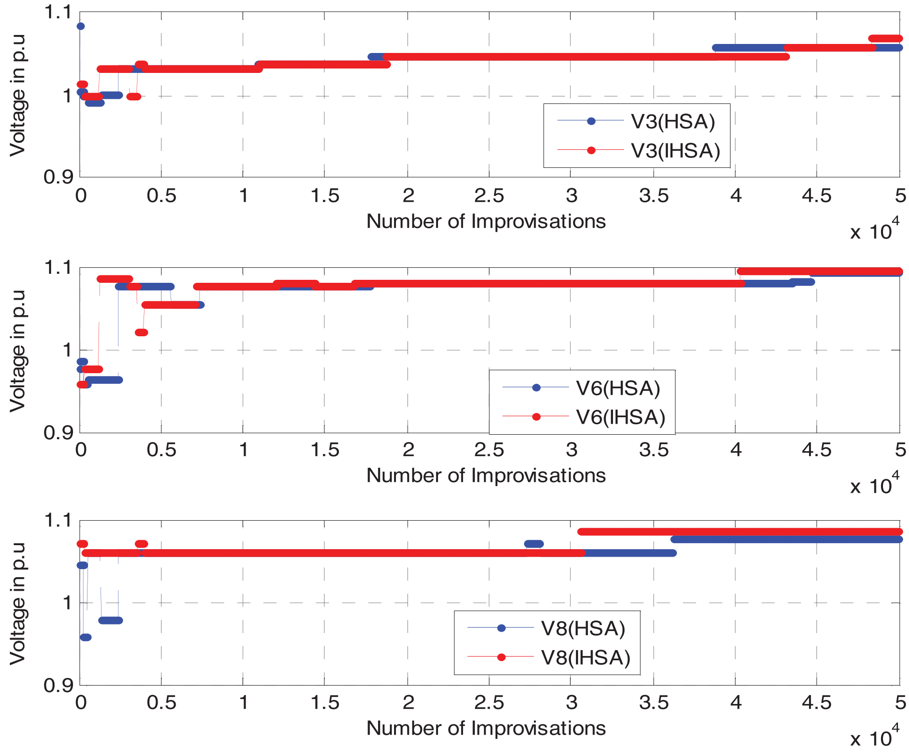

Figure 4. Convergence of generator voltages V3, V6 and V8 for IEEE 14 bus system considering FACTS devices.

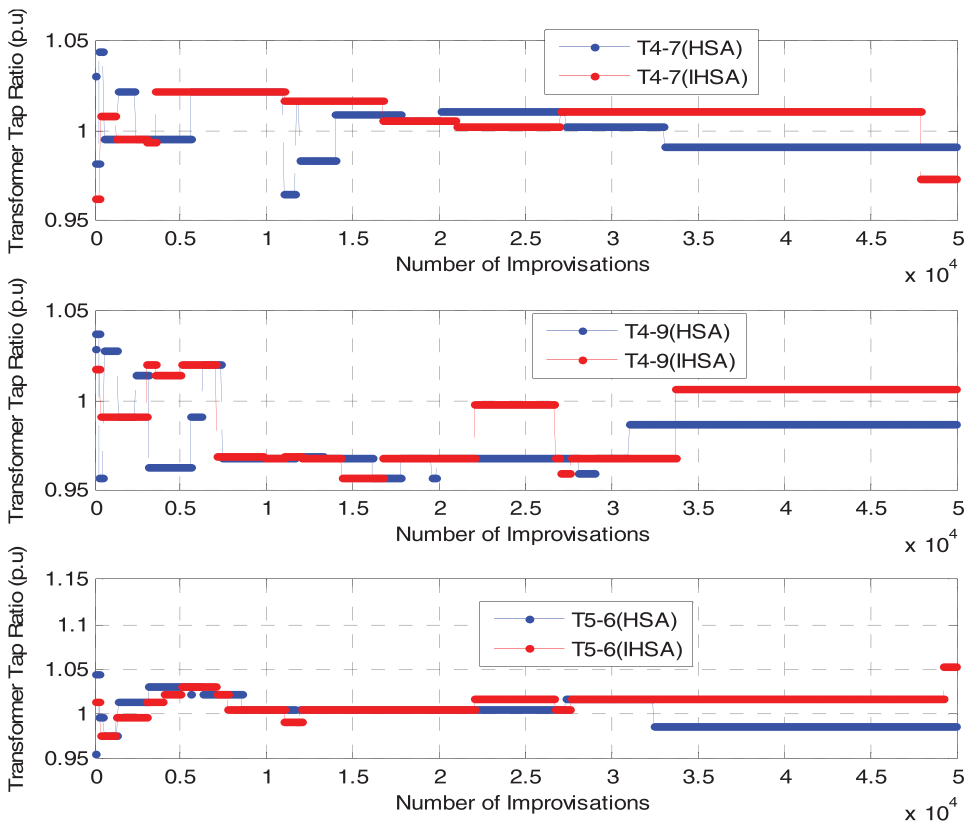

Figure 5. Convergence of transformer tap-ratio for IEEE 14 bus system considering FACTS devices.

12.198 MW for HSA and 12.065 MW for IHSA. Active power loss convergence by harmony search algorithms implemented in IEEE 14 bus system for case 3 is shown in Figure 2. As it is obvious, IHSA has a better convergence property. The convergence graph of control variables is shown in Figures 3–8.

6.2.1. Solution quality

The best active power losses (Best), the worst active power losses (Worst), the mean active power losses (Mean), the standard deviation (Std) and percentage power saved (%Psave) for the all the optimization techniques are summarized in Table 6 over total 50 runs. Table 5 data indicates ORPD considering FACTS devices significantly decrease the active power loss. The simultaneous application of three type FACTS devices reduces the system active power loss to 12.065MW for IHSA and 12.198MW for HSA which is the biggest reduction of active power loss in comparison to that of results obtained by solving conventional ORPD problem. Table 6 confirms that the maximum percentage of power saved is 10.56% for ORPD considering FACTS devices.

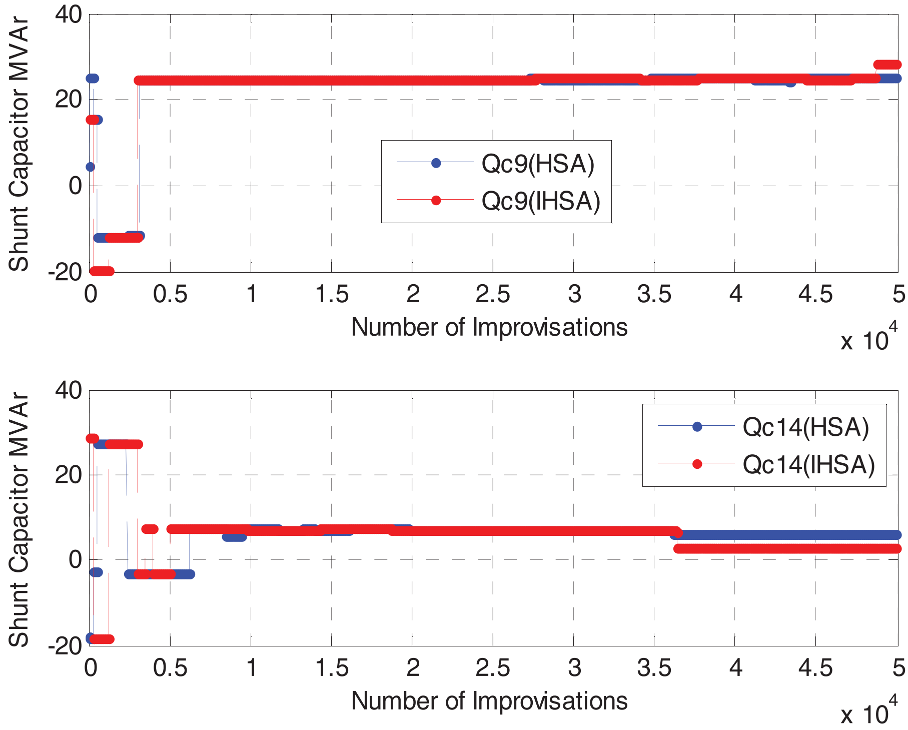

Figure 6. Convergence of shunt capacitor MVAr for IEEE 14 bus system considering FACTS devices.

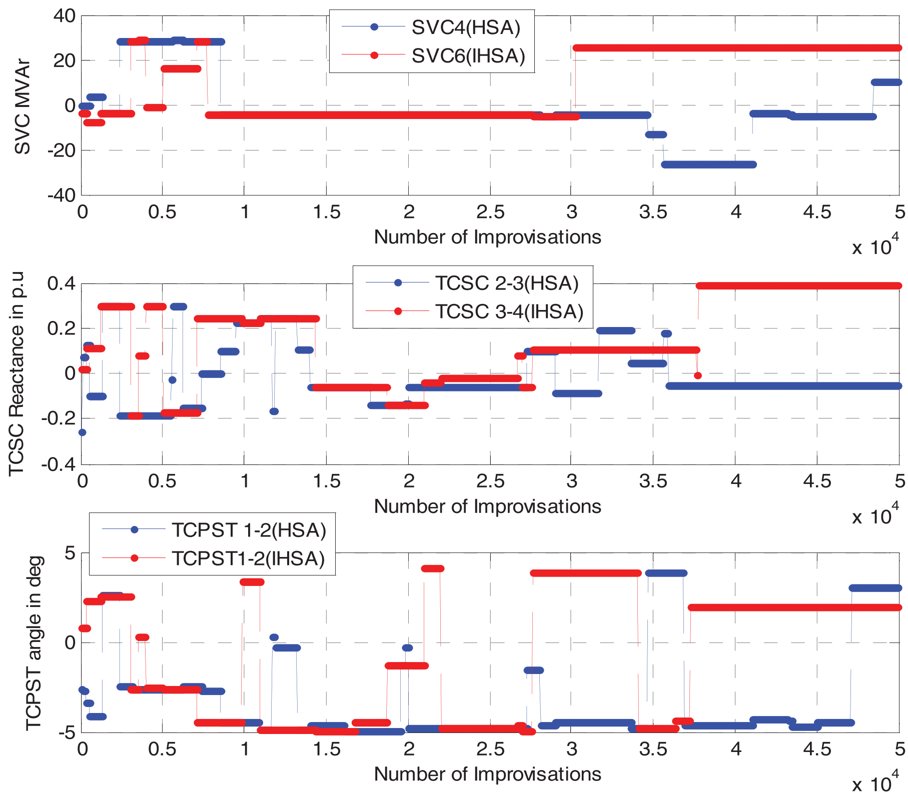

Figure 7. Convergence of SVC MVAR, TCSC reactance and TCPST angle for IEEE 14 bus system.

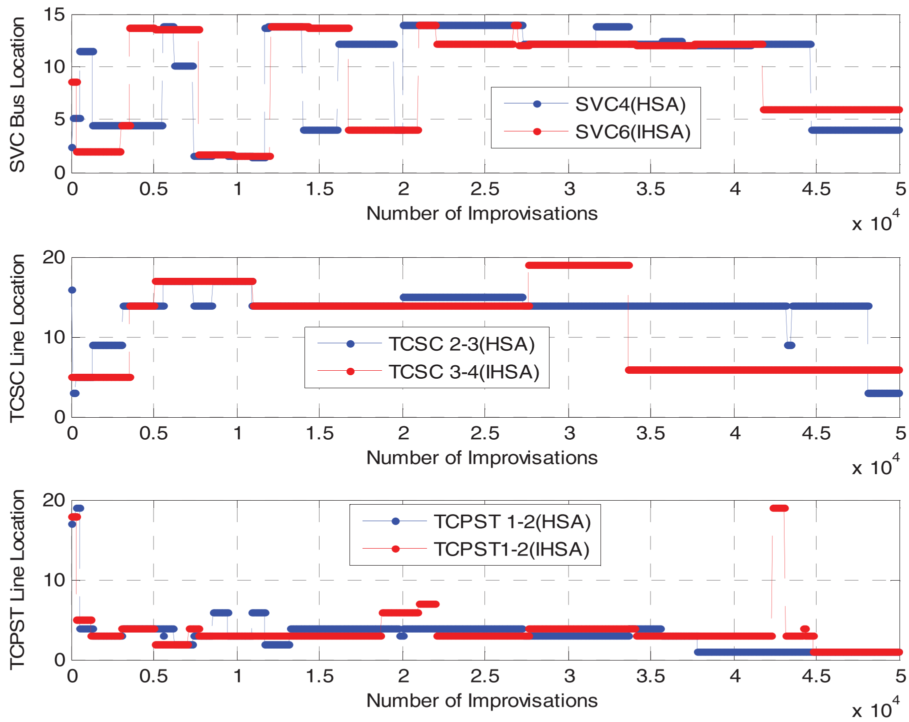

Figure 8. Convergence of SVC, TCSC, TCPST location for IEEE 14 bus system.

Table 5. Best control variables settings and active power loss for IEEE 14 bus system considering FACTS devices for case 3.

Control variables	ORPD		ORPD with FACTS devices	
Generator voltage	**HSA**	**IHSA**	**HSA**	**IHSA**
V_1,p.u.	1.0899	1.0932	1.099	1.1
V_2,p.u.	1.0659	1.065	1.074	1.0931
V_3,p.u.	1.0448	1.0461	1.0587	1.0687
V_6,p.u.	0.9887	1.0703	1.0938	1.0954
V_8,p.u.	1.0092	1.0362	1.0767	1.0865
Transformer tap ratio				
T_{4-7}	1.0458	1.0159	0.9916	0.97347
T_{4-9}	0.9544	1.02	0.9872	1.007
T_{5-6}	1.0866	0.9926	0.9864	1.0526
Capacitor banks MVAr				
Q_{c-9}	12.7368	16.0675	25.105	28.315
Q_{c-14}	10.4165	18.3021	6.1897	2.9778
SVC MVAr Rating				
SVC	–	–	10.561(4)	25.883(6)
TCSC Reactance (p.u)				
X_{tcsc}	–	–	0.05148 (2–3)	0.39109 (3–4)
TCPST Angle in degrees				
θ_{TCPST}	–	–	3.0291 (1–2)	1.9611 (1–2)
P_{Loss}, MW	12.806	12.789	12.198	12.065

Table 6. Best solutions of all algorithms for IEEE 14 bus system.

Algorithms	Best (p.u.)	Worst (p.u.)	Mean (p.u.)	Std.	% Psave	Average times (s)
DE [14]	0.13239	0.13275	0.1325	1.61×10^{-4}	1.86	8.172
PSO [14]	0.1325	0.13402	0.13352	0.64×10^{-3}	1.75	9.283
ACOR[16]	0.131226	0.135682	0.133912	7.1854×10^{-2}	2.72	9.74
DE/best/2/bin[15]	0.129914	0.13009	0.130864	6.5036×10^{-4}	3.7	10.81
ABC[15]	0.129333	0.131172	0.129625	9.422×10^{-4}	4.13	9.15
LCA[15]	0.129891	0.131638	0.130474	5.5283×10^{-3}	3.71	10.86
CSS[15]	0.129748	0.132995	0.13116	4.206×10^{-2}	3.82	10.04
BRCFF[15]	0.129264	0.129778	0.129341	8.8191×10^{-5}	4.18	8.13
BB–BC[15]	0.130039	0.132251	0.13108	4.7604×10^{-3}	3.6	9.36
PBIL[15]	0.130008	0.131947	0.130854	9.7075×10^{-4}	3.63	9.75
TLA[15]	0.129229	0.129525	0.129307	9.0283×10^{-5}	4.2	10.25
MTLA [15]	0.129106	0.1292	0.129165	7.6832×10^{-5}	4.3	9.64
DDE [15]	0.129286	0.129297	0.129293	5.0065×10^{-5}	4.16	10.48
MTLA-DDE[15]	0.128978	0.128986	0.128982	6.486×10^{-6}	4.39	8.35
HSA	0.12806	0.128271	0.12814	5.346×10^{-6}	**5.07**	**9.51**
IHSA	0.12789	0.12875	0.12813	6.974×10^{-6}	**5.20**	**8.84**
HSA (Case3)	0.12198	0.12243	0.12222	6.73×10^{-6}	**9.58**	**9.68**
IHSA (Case3)	0.12065	0.12111	0.12091	6.81×10^{-6}	**10.56**	**9.54**

Table 7. Limits of control variables for IEEE 57 bus system considering FACTS devices.

Reactive power limits for generators							
Bus	1	2	3	6	8	9	12
Q_G^{max}	2.0	0.5	0.6	0.25	2.0	0.09	1.55
Q_G^{min}	−1.4	−0.17	−0.1	−0.08	−1.4	−0.03	−1.5

Limits of voltage and tap setting				
	V_G^{max}	V_G^{min}	T_k^{max}	T_k^{min}
	1.1	0.95	1.1	0.9

Q_{SVC}^{min} Parameter limits for FACTS devices					
Q_{SVC}^{min}	Q_{SVC}^{max}	X_{TCSC}^{min}	X_{TCSC}^{max}	θ_{TCPST}^{min}	θ_{TCPST}^{max}
−0.3	0.3	$-0.8X_{ij}$	$0.2X_{ij}$	−5°	5°

Table 8. Best control variables settings and active power loss for IEEE 57 bus system considering FACTS devices- IHSA.

Control variables	ORPD		ORPD with FACTS devices	
Generator voltage	**HSA**	**IHSA**	**HSA**	**IHSA**
V_1,**p.u.**	1.0938	1.0954	1.0959	1.0951
V_2,**p.u.**	1.078	1.0814	1.0823	1.0876
V_3,**p.u.**	1.0628	1.0688	1.0615	1.0730
V_6,**p.u.**	1.0724	1.0743	1.0791	1.0768
V_8,**p.u.**	1.098	1.0951	1.0956	1.0978
V_9,**p.u.**	1.0699	1.0704	1.0615	1.0687
V_{12},**p.u**	1.0649	1.0699	1.0543	1.0524
Transformer tap ratio				
T_{4-18}	1.0737	1.0699	1.0868	1.0914
T_{4-18}	1.0509	1.0564	1.0431	1.0533
T_{21-20}	1.0487	1.044	1.0516	1.0374
T_{24-26}	1.0683	1.0642	1.0448	1.0383
T_{7-29}	1.019	1.0225	1.0312	0.9993
T_{34-32}	1.0605	1.0596	1.0654	1.0485
T_{11-41}	0.96488	0.96946	0.972	0.96148
T_{15-45}	0.95725	0.96296	0.97004	0.96166
T_{14-46}	0.94474	0.93991	0.95267	0.94767
T_{10-51}	0.97827	0.97683	0.98042	0.98225
T_{13-49}	0.94639	0.94005	0.9645	0.93838
T_{11-43}	1.0896	1.0986	1.0854	1.0779
T_{40-56}	0.95238	0.95172	0.95482	0.9646
T_{39-57}	1.0557	1.057	1.0534	1.0720
T_{9-55}	1.0024	1.0001	1.0224	1.0016
Capacitor banks MVAr				
Q_{c-18}	15.503	13.396	15.027	17.2000
Q_{c-25}	6.8815	8.5066	2.2793	5.0562
Q_{c-53}	20.243	18.951	15.376	16.1050
SVC MVAr Rating				
SVC	–	–	13.715 (41)	25.5950 (37)
SVC	–	–	10.717 (33)	12.1650 (13)
SVC	–	–	14.337 (45)	20.7940 (7)
TCSC Reactance(p.u)				
X_{tcsc}	–	–	0.26322 (54–55)	−0.0332 (9–11)
X_{tcsc}	–	–	0.13096 (50–51)	0.1166 (9–12)
TCPST Angle in degrees				
θ	–	–	2.8925 (1–2)	3.5477 (2–3)
θ	–	–	−2.7476 (13–49)	−3.4959 (13–49)
P_{Loss},**MW**	23.710	23.448	22.504	22.057

6.3. IEEE 57 bus test systems

6.3.1. Experimental settings

The system consists of 80 branches, seven generator-buses and 15 branches under load tap setting transformer branches. The possible reactive power compensation buses are 18, 25 and 53. The busdata and linedata are taken from Refs[18]. Seven buses are selected as PV buses and slack bus as follows: PV buses: bus 2, 3, 6, 8, 9, 12; slack bus: bus 1. The others are PQ buses. The total system load is 1250.8MW and 336.4 MVAr. The initial system active power loss is 28.462 MW. In this test network, three cases are studied as follows:

- Case 1: Installation of single type FACTS device(3 SVC)
- Case 2: Installation of two type FACTS devices (3 SVC, 2 TCSC)
- Case 3: Installation of three type FACTS devices (3 SVC,2 TCSC and 2 TCPST).

Totally for case 3, there are 39 control variables, which consists of 7 generator voltages, 15 tap changing transformers,3 shunt compensation capacitor banks MVAr rating, 3 SVC bus location, 2 TCSC line location, 2 TCPST line location, 3 SVC MVAr Rating, 2 TCSC reactance setting and 2 TCPST angle setting. Table 7

Table 9. Active power loss comparison for IEEE 57 bus system considering FACTS devices.

	P_{loss} in MW (HSA)	P_{loss} in MW (IHSA)
Case 1	23.341	23.112
Case 2	23.047	22.321
Case 3	**22.504**	**22.057**

illustrates the limits of the control variable of IEEE 57 bus system considering FACTS devices.

The parameter setting of harmony search algorithm for IEEE 57 bus system considering FACTS devices is same as that of IEEE 4 bus system.

6.3.2. Simulation results

Table 9. gives the active power loss computation by HSA and IHSA for the three cases. Table 8 presents the control variable setting for IEEE 57 bus system for case 3 using HSA and IHSA respectively. The optimal bus location and line location of FACTS are given within braces. According to results presented in Table 9, the installation of single type FACTS device brings the active power loss to 23.341 MW for HSA and 23.112 MW for IHSA. Similarly, according to Table 9, the installation of two type FACTS devices makes the total active power loss to 23.047 MW for HSA and 23.321 for IHSA. Simultaneous installation of SVCs, TCSCs and TCPSTs will yield a total active power loss equal to 22.504 MW for HSA and 22.057 MW for IHSA.

Active power loss convergence by harmony search algorithms implemented on IEEE 57 bus system for case 3 is shown in Figure 9. As it is obvious, IHSA has a better convergence property.

6.3.3. Solution quality

The best active power losses (Best), the worst active power losses (Worst), the mean active power losses (Mean), the standard deviation (Std) and percentage power saved (%Psave) for all the optimization algorithms are summarized in Table 10 over total 50 runs. Table 8. data indicates ORPD considering FACTS devices significantly decrease the active power loss. The simultaneous application of three type FACTS device reduces the system active power loss to 22.504 MW for IHSA and 22.057 MW for IHSA which is the biggest reduction of active power loss in comparison to that of results obtained by solving conventional ORPD problem. Table 10 confirms that the maximum percentage of power saved is 22.5% for ORPD considering FACTS devices.

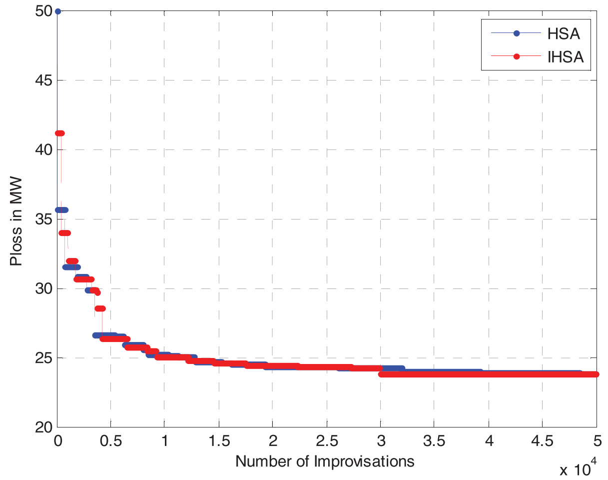

Figure 9. Convergence of power loss for IEEE 57 bus system considering FACTS devices with ORPD.

7. Conclusions

Harmony search algorithms are used to find the optimal settings of control variables such as generator voltages, tap ratio of tap changing transformers and amount of reactive compensation for IEEE 14, 57 and 118-bus test power systems. The simulation results show that HSA and IHSA have better performance in balancing global search ability with better convergence speed than other algorithms.

The location and setting of flexible AC transmission system (FACTS) devices such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Shifting Transformer (TCPST) are considered as additional control

Table 10. Best solutions of all algorithms for IEEE 57 bus system.

Algorithms	Best	Worst	Mean	Std	% PSave	Average times (s)
NLP [16]	0.2590231	0.3085436	0.278584	1.167×10^{-2}	8.9934	NR
CGA [16]	0.2524411	0.2750772	0.262935	6.295×10^{-3}	11.3059	411.38
AGA [16]	0.2456484	0.2676169	0.251278	6.006×10^{-3}	13.6925	449.28
PSO-w [16]	0.2427052	0.2615279	0.247259	7.014×10^{-3}	14.7266	408.48
PSO-cf [16]	0.2428022	0.2603275	0.246980	6.629×10^{-3}	14.6925	408.19
CLPSO [16]	0.2451520	0.2478083	0.246730	9.341×10^{-4}	13.8669	426.85
SPSO-07[16]	0.2443043	0.2545745	0.247522	2.833×10^{-3}	14.6925	137.35
L-DE [16]	0.2781264	0.4190941	0.331778	4.707×10^{-2}	13.8669	431.41
L-SACP-DE [16]	0.2791553	0.3697873	0.310326	3.223×10^{-2}	14.1647	428.98
L-SaDE [16]	0.2426739	0.2439142	0.243112	4.815×10^{-4}	2.28150	410.14
SOA [16]	0.2426548	0.2428046	0.242707	4.208×10^{-5}	14.7443	391.32
HSA [17]	**0.249059**	0.269653	0.259240	–	–	–
HSA	**0.2371**	0.242719	0.238975	4.469×10^{-5}	**16.6959**	**409.12**
IHSA	**0.23448**	0.2401145	0.237548	4.177×10^{-5}	**17.6165**	**395.21**
HSA (Case3)	**0.22504**	0.22534	0.22113	5.1773×10^{-5}	**20.93**	**455.87**
IHSA (Case3)	**0.22057**	0.22098	0.22062	5.0078×10^{-5}	**22.50**	**441.57**

parameters in the ORPD problem for further system loss minimization. Power flow models of SVC, TCSC and TCPST have been presented.

Harmony search algorithms are applied to IEEE 14, IEEE 57 and IEEE 118 standard test power systems for the solution of ORPD problems considering FACTS devices. For each test system, three cases are studied. Simulation results show that by including the FACTS devices in the complete ORPD problem, additional reduction in the total active power loss in the system has been achieved as compared to the conventional ORPD in all test cases.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Momoh JA, El-Hawary ME, Adapa R. A review of selected optimal power flow literature to 1993 part I & II. IEEE Trans Power Syst. Feb. 1999;14(1):96–111.
[2] Lee KY, Park YM, Ortiz JL. A united approach to optimal real and reactive power dispatch. IEEE Trans Power Appar Syst PAS. 1985;104(5):1147–1153.
[3] Granville S. Optimal reactive power dispatch through interior point methods. IEEE Trans Power Syst. 1994; 9(1):98–105.
[4] Bakare GA, Venayagamoorthy GK, Aliyu UO. Reactive power and voltage control of the Nigerian grid system using microgenetic algorithm. Proc. IEEE power Eng. Soc. general meeting; San Francisco, CA. 2005, vol. 2, p. 1916–1922.
[5] Wu QH, Cao YJ, Wen JY. Optimal reactive power dispatch using an adaptive genetic algorithm. Int J Elect Power Energy Syst. Aug. 1998;20:563–569.
[6] Zhao B, Guo CX, Cao YJ. A multi-agent based particle swarm optimization approach for reactive power dispatch. IEEE Trans Power Syst. 2005;20(2):1070–1078.
[7] Yoshida H, Fukuyama Y, Kawata K, et al. Aparticle swarm optimization for reactive power and voltage controlconsidering voltage security assessment. IEEE Trans Power Syst. 2001;15(4):1232–1239.
[8] Miranda V, Srinivasan D, Proenca L. Evolutionary computation in power systems. Elect Power Energy Syst. 1998;20(2):89–98.
[9] Geem ZW, Kim JH, Loganathan GV. A new heuristic optimization algorithm:harmony search. Simulation. 2001;76(2):60–68.
[10] Galiana FD, Almeida K, Toussaint M, et al. Assessment and control of the impact of FACTS devices on power system performance. IEEE Trans Power Systems. Nov.1996;11(4).
[11] Gerbex S, Cherkoui R, Germond AJ. Optimal location of multi type FACTS devices in a power system by means of genetic algorithms. IEEE Trans Power Syst. 2001;16(1):537–544.
[12] Mahdavi M, Fesanghary M, Damangir E. An improved harmony search algorithm for solving optimization problems. Appl Math Comput. 2007;188(2):1567–1579.
[13] Zimmerman RD, Murillo-Sanchez CE, Gan D. MATPOWER: A MATLAB power system simulation package. Power Systems Engineering Research Center [Online]. Available: http://www.pserc.cornell.edu/matpower; 2011.
[14] Varadarajan M, Swarup K. Differential evolutionary algorithm for optimal reactive power dispatch. Int J Electr Power Energy Syst. 2008;30:435–441.
[15] Mojtaba G, Mohammad Mehdi G, Sahand G. Modified teaching learning algorithm and double differential evolution algorithm for optimal reactive power dispatch problem: A comparative study. Information Science. 2014;278:231–249.
[16] Dai C, Chen W, Zhu Y, et al. Seeker optimization algorithm for optimal reactive power dispatch. IEEE Trans Power Syst. 2009;24(3):1218–1231.
[17] Khazali AH, Kalantar M. Optimal reactive power dispatch based on harmony search algorithm. Int J Elect Power Energy Syst. 2011;33(3):684–692.
[18] The IEEE 57-Bus Test System [online] Available at http://www.ee.washington.edu/research/pstca/pf57/pg_tca57bus.htm