Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 57(4), 881–892(2016)

D. Karthikaikannan, G. Ravi

Optimal Location and Setting of FACTS Devices for Reactive Power Compensation Using Harmony Search Algorithm

DOI 10.7305/automatika.2017.12.747
UDK 681.5.015.23-55:621.31.051.025.016.2

Original scientific paper

Reactive Power Compensation (RPC) is an important issue in the operation and control of power system. In this paper, two FACTS controller like Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) are considered for RPC. RPC is a multi-objective nonlinear optimization problem that minimizes the bus voltage deviation and real power loss. In this work, Harmony Search Algorithm (HSA) is used to determine the optimal location and setting of SVC and TCSC respectively. The efficacy of HSA is demonstrated on modified IEEE 30 bus power system for two operating conditions. A comparison of simulation results reveals the effectiveness of proposed algorithm over other well established population based optimization technique like Simple Genetic Algorithm (SGA),Particle Swarm Optimization (PSO) and Differential Evolution (DE).

Key words: Voltage Profile, Loss Reduction, Harmony Search Optimization

Optimalna lokacija i parametri za FACT uređaj za kompenzaciju reaktivne snage koristeći algoritam harmonijskog pretraživanja. Kompenzacija reaktivne snage (RPC) važan je zadatak pri radu i upravljanju energetskim sustavima. U ovome radu razmatra se FACT regulator kao što su statički kompenzator (SVC) i tiristorski serijski kondenzator (TCSC). RPC je više kriterijski nelinearni optimizacijski problem gdje se minimizira odstupanje napona sabirnice i gubitci snage. Korišten je HSA algoritam (engl. *Harmony Search Algorithm*) za određivanje položaja i parametara SVC i TCSC. Efikasnost sustava demonstrirana je na modificiranom energetskom sustavu IEEE 30 za dva različita uvjeta. Usporedbna simulacijskih rezultata prikazuje efikasnost predloženog algoritma u odnosu na ostale metode kao što su genetski algoritmi (SGA), čestična optimizacija roja (PSO) i diferencijalna evolucija (DE).

Ključne riječi: profil napona, smanjenje gubitaka, harmonijska optimizacija

1 INTRODUCTION

Reactive Power Compensation (RPC) plays an important role for secure operation of power systems[1,2]. Installing adequate reactive power support at the appropriate location not only reduces real power loss bus also improves voltage profile. Compared with conventional reactive power compensation devices such as shunt capacitor, shunt reactor etc., FACTS devices have advantages like ability to regulate strongly, low loss and without operational problems such as resonance. The FACTS is a concept based on power electronic controllers, which improve the value of transmission by increasing the use of their capacity [3].

In this paper, among various FACTS devices, Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) are considered for RPC. 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. Similarly TCSC can provide continuous control of power on the AC line with variable series capacitive reactance. The main objective of RPC is to improve the voltage profile and minimize real power losses. In addition, the voltage stability can be enhanced by reallocating reactive power generations. There are several methods proposed in literature for allocation of FACTS devices. The techniques used for optimal placement of FACTS devices can be broadly classified in to index based methods and heuristic optimization techniques. The index based methods such as modal analysis near point collapse[4], participation factors form modal analysis[5], extended voltage phasors approach[6], L index, tangent vector, combined hybrid participation factor based on static and dynamic loading margin are proposed for optimal allocation of the FACTS devices[7,8].

Due to the non-differential, non-linearity and nonconvex nature of RPC problem, majority of the conventional techniques converge to a local optimum. In recent years, heuristic optimization techniques such as genetic algorithm (GA)[9,10], particle swarm optimization (PSO)[11,12] benders decomposition are used to determine the optimal location and size of the FACTS controller. These methods present extremely superiority in obtaining the global optimum and in handling discontinuous and non convex objectives.

This paper uses harmony search algorithm (HSA) to optimize bus location, MVAr rating of SVC and line location, capacitive reactance value of TCSC. The HSA is a meta heuristic optimization method that is inspired by musicians adjusting the pitches of their instruments to find better harmony[13]. The main advantage of HSA over other methods is that it does not require initial setting for the decision variables and it can handle both discrete and continuous variables. HSA is applied to a wide range of optimization problems. HSA is presented for annual reconfiguration in electric distribution networks considering annual load level and switching cost [14]. HSA is presented to the optimal reactive power dispatch problem for determination of the global solution[15]. HSA has been implemented for centralized and distributed spectrum channel assignment in cognitive wireless networks.

This paper proposes HSA for optimizing the setting and location of SVC and TCSC respectively. The proposed algorithm is implemented on modified IEEE 30 bus system. The simulation results of the proposed method are compared with well-established population based optimization techniques such as simple genetic algorithm (SGA),particle swarm optimization (PSO) and differential algorithm (DE).The simulation results show that HSA has better performancethan the other algorithms. Rest of the paper is organized as follows: section 2 gives an overview of FACTS controller and its load flow model. In section 3, problem formulation for optimal placement and setting of FACTS controller is described. Overview of GA,PSO,DE and HSAarepresented in section 4. In section 5, implementation of HSA for reactive power compensation is presented.Then, in Section 6, HSA is compared with other approaches on modified IEEE 30 bus system for two operating cases. Finally, theconclusion is drawn in Section 7.

2 FACTS DEVICES AND ITS LOAD FLOW MODEL

In this paper, two FACTS devices have been considered. They are TCSC (Thyristor Controlled Series Capacitor) and SVC (Static Var Compensator). TCSC change the reactance of the line and SVC can be used to control the reactive power compensation. Power flow through the transmission line i-j namely P_{ij} depends on line reactanceX_{ij}, bus voltage magnitudes V_i,$V_j$and phase angle between sending and receiving buses $\delta_i$and δ_j

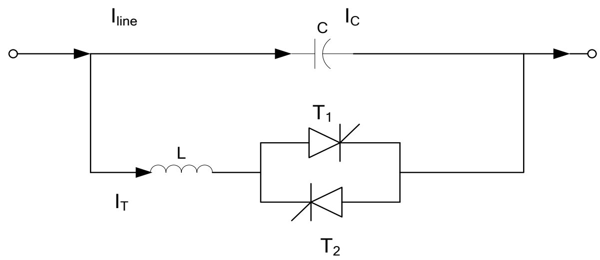

Fig. 1. Thyristor Controlled Series Capacitor

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \quad (1)$$

The above mentioned FACTS devices can be applied to control the power flow by changing the parameters of power system.

2.1 Thyristor Controlled Series Capacitor (TCSC)

A Thyristor Controlled Series Capacitor (TCSC) consists of a series capacitor shunted by a Thyristor controlled reactor. TCSC will provide a continuously variable capacitor by partially canceling the effective compensating capacitance by the TCR. A typical TCSC is shown in Fig.1.From the Fig.1. It is clear that the steady state impedance of TCSC is the parallel combination ofX_C and the variable inductive reactance $X_L(\alpha)$

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_L}, \quad (2)$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}. \quad (3)$$

The overall line reactance $X_{ij}$is given by

$$X_{ij} = X_{line} + X_{TCSC}, \quad (4)$$

where

α=delay angle of thyristor

X_{line} = Reactance of transmission line

X_{TCSC}=Reactance of TCSC

To avoid over compensation, the working range of TCSC is between -0.7 X_{line} and 0.2 X_{line}.

2.2 Static Var Compensator

Static var compensator (SVC) is a shunt controller which injects current into the bus where it is connected. The output of the SVC is adjusted to exchange capacitive or inductive current so as to maintain the bus voltage within prescribed limits. The SVC can be used for voltage control, VAR compensation, and damping oscillations and to

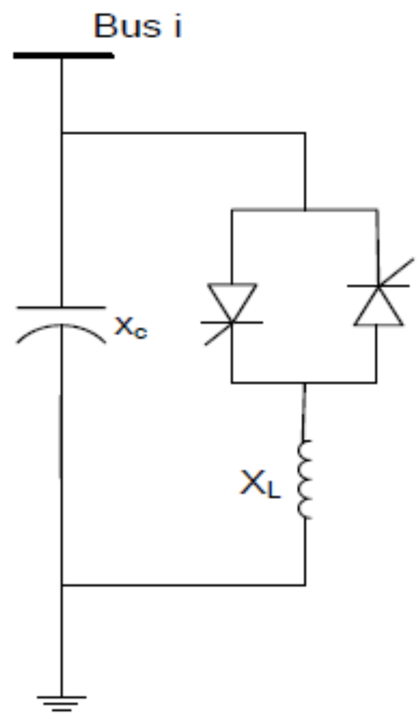

Fig. 2. Static Var Compensator

improve transient and dynamic stability. A SVC consisting of a fixed capacitor and a Thyristor Controlled Reactor (TCR) is shown in Fig.2. In this paper SVC is represented as a fast acting VAr sources (MVAr) to counteract unexpected load changes. The one of the objective of this paper is to optimize the MVAr rating of SVC..The reactive power injected by SVC into the bus i is given by

$$\triangle Q_C = \pm Q_{SVC}\text{MVAr} \quad (5)$$

2.3 Representation of TCSC and SVC in Load Flow Analysis

Power flow calculations is considered as the fundamental step for voltage profile improvement and loss reduction. In the past various power flow methods such as impedance matrix method, newton raphson method, decoupled newton power flow methods etc have been proposed . Among the power flow methods proposed, in this paper newton raphson method has been considered. The Newton-Raphson method has a unique quadratic convergence characteristic. It usually has a very fast convergence speed compared to other load flow calculation methods. It also has the advantage that the convergence criteria are

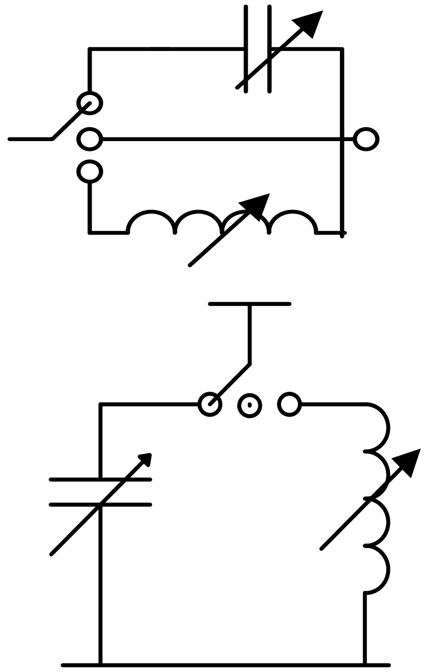

Fig. 3. Load Flow Model of TCSC (top) and SVC (bottom)

specified to ensure convergence for bus real power and reactive power mismatches. A detailed review of power flow methods can be found [16].

The model of TCSC and SVC are taken from [9] for load flow studies. The TCSC may be capacitive or inductive to decrease or increase the reactance of the transmission lineX_{line}. TCSC is modeled with a capacitance, an inductance and a simple wire connected in parallel. Figure 3 shows the load flow model of TCSC. To avoid resonance, only one of the three elements can be switched at a line.

The SVC may absorb or inject reactive power at bus. The SVC is modeled with two ideal switched elements in parallel a capacitance and an inductance. The MVAr rating of SVC lies between -100 MVAr and +100 MVAr. The load flow model of SVC is shown in Fig 3.

3 PROBLEM FORMULATION

FACTS controllers SVC and TCSC connected at appropriate location results in real power loss reduction and better voltage profile. The problem for placing FACTS devices can be formulated as a multi objective problem with the following objectives and constraints.

3.1 Active Power loss Minimization

The first objective function to minimize total active power loss in an electric power system is given by

$$\min f_1 = P_{loss} = \sum_{l=1}^{m} R_l I_l^2$$

$$= \sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] Y_{ii} \cos \emptyset_{ij} \tag{6}$$

where m is the number of lines, n is the number of buses, R_l is the resistance of line l. $I_l$is the current through line l. V_i and $\theta_i$are the voltage magnitude and angle at bus i. Y_{ii} and $\emptyset_{ij}$ are the magnitude and angle of the line admittance respectively.

3.2 Minimum voltage deviation

FACTS devices connected at the appropriate location play a leading role in improving voltage profile and avoiding voltage collapse in the power system. Therefore, the second objective is to minimize bus voltage deviation. This objective function can be expressed as

$$\min f_2 = \sum_{i=1}^{n} |V_{iref} - V_i|, \tag{7}$$

where V_i is the voltage magnitude at bus i, V_{iref} is the nominal voltage of bus i.

3.3 System constraints

3.3.1 Equality constraints

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{n} V_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}), \tag{8}$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{n} V_j (G_{ij} sin\theta_{ij} + B_{ij} cos\theta_{ij}), \tag{9}$$

where i=1,2,...,n-1

3.3.2 Inequality constraints

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

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \quad i \in mb \tag{10}$$

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max} \quad i \in mb \tag{11}$$

$$V_{Gi,min} \leq V_{Gi} \leq V_{Gi,max} \quad i \in mb \tag{12}$$

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, mb is the number of machine bus (PV bus), 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.

Transformer constraints Transformer tap setting are bounded as follows

$$T_{j,min} \leq T_j \leq T_{j,max} \quad j \in nt \tag{13}$$

T_j is the tap setting of j-th transformer and $T_{j,min}$ and $T_{j,max}$ are the minimum and maximum tap settings of transformer. nt is the number of transformers in the system.

SVC VAR constraints SVC VAR compensations are restricted by their limits as follows

$$Q_{SVCw,min} \leq Q_{SVCw} \leq Q_{SVCw,max} \quad \text{w} \in \text{nsvc} \tag{14}$$

Q_{svcw} is the VAR rating of SVC and $Q_{svcw,max}$ are the minimum and maximum VAr limits of SVC. nsvc is the number of SVC connected in the system.

TCSC reactance constraints TCSC reactance values are restricted within the limits as follows

$$-0.7X_{line} \leq X_{TCSCv} \leq 0.2X_{line} \quad v \in ntcsc \tag{15}$$

$X_{line}$is the reactance of line where TCSC is connected. X_{TCSCv} is the reactance of *vth* TCSC. *v* is the number of TCSC connected in the system.

Security constraints These includes the constraints of voltages at load buses and transmission line loading as follows

$$V_{k,min} \leq V_k \leq V_{k,max} \;\; k \in nd, \tag{16}$$

$$S_{li} \leq S_{li}^{max} \quad i \in nl. \tag{17}$$

V_k is the voltage of kth load bus. $V_{k,min}$and $V_{k,max}$ are the minimum and maximum limits of voltage of load buses. nd is the number of load 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.

3.4 Problem statement

A general multi objective optimization problem consists of a number of objectives to be optimized simultaneously. In this paper, the multi objective problem is converted to a single objective optimization problem by linear combination of active power loss and minimum voltage deviation

$$f_3 = \alpha f_1 + (1-\alpha) f_2. \tag{18}$$

Subject to

$$g\,(x,u) = 0,$$

$$h(x,u) \leq 0,$$

where α is the weight.$g(x,u)$ and $h(x,u)$ are the set of equality and inequality constraints respectively.

4 META-HEURISTIC ALGORITHMS

4.1 Simple Genetic Algorithm

The Simple Genetic Algorithm (SGA) was invented by Prof.John Holland in 1975 and then it has been made widely popular by Prof. David Goldberg at the University of Illinios. The main objective of the GA is to find an optimal solution to a problem. GAs use two basic processes from evolution first one is inheritance that is passing of features from one generation to the next and the next one is competition or survival of fittest which results in removing the bad features from individuals in the population. GAs work on a population or a collection of several alternative solutions to the given problem. Every individual in the population is called a string or chromosome. The population size determines the amount of information stored by the GA. The evaluation function also known as fitness function is used to determine the fitness of each candidate solution. Individuals are selected from the population for reproduction. Selection is one of the key operators on GAs that guarantee the survival of the fittest. The individuals selected from the population form pairs called parents. Reproduction between parents is done by the operator called crossover. Crossover operator combines portions of two parents to create new individuals called offspring which inherit a combination of features of the parents. Crossover is performed on each pair of parents with a probability PC which is called crossover probability. Mutation is an incremental change made to each member of the population with a very small probability PM called mutation probability. Mutation enables new features to be introduced into the population.Initially populations are generated randomly. Care should be taken while generating initial population because the population size determines the amount of information stored by the GA . Each individual (chromosomes) in the population is a solution to the problem at hand. Selection is biased towards more highly fit individuals. Various selection schemes like roulette wheel selection; stochastic universal selection and binary tournament selection with and without replacement may be used. The evolutionary operators' selection, crossover and mutation are repeated until all entries in new generations are filled. New generations are evolved until some stopping criterion is met. Number of generations may be fixed or it may be terminated when all the individuals in the population converge to the same string.

4.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a new evolutionary computation technique first introduced by Kennedy and Eberhart. The development of its idea was based on simulation of social behavior of animals such as a flock of birds, a school of fish or a group of people who pursue a common goal in their lives. PSO is initialized with generating a population of random solutions, which is called a swarm. Each individual is referred to as a particle and presents a candidate solution to the optimization problem. The position of each particle is represented by XY axis position and also velocity is expressed by Vx (the velocity of X axis) and Vy(the velocity of Y axis). Accordingly, in PSO algorithm, the best experiences of the groups are always shared with all particles and hence, it is expected that the particles move toward better solution areas. Each particle knows its best value so far (Pbest) and its XY position. Moreover, each particle knows the best value in the group (Gbest) among Pbests. Each particle tries to modify its position using the current velocity and the distance from Pbest and Gbest.The modification can be represented by the concept of velocity. Velocity and current position of each particle can be modified by the following equations

$$\begin{aligned} V_i^{k+1} =& wV_i^k + c_1 \times rand1 \times \left(P_{besti} - S_i^k\right) \\ & + c_2 \times rand2 \times \left(G_{besti} - S_i^k\right) \end{aligned} \tag{19}$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \tag{20}$$

where

V_i^{k+1} is the velocity of particle at $(k+1)^{th}$ iteration

V_i^k is the velocity of particle at k^{th} iteration

w is the inertia weight

c_1, c_2 is the weighting factors

S_i^{k+1} is the current position of particle at $(k+1)^{th}$ iteration

$S_i^k$is the current position of particle at k^{th} iteration

$rand1$, $rand2$ are the uniformly distributed random numbers between 0 and 1.

P_{besti} is the P_{best} of particle i

G_{besti} is the G_{best} of the group

4.3 Differential Evolution

Differential Evolution (DE) algorithm is a stochastic, population based optimization algorithm like Genetic Algorithm (GA), using similar operators: crossover, mutation and selection. The DEA differs from GA by using mutation operation as the primary search mechanism. In this method a population of solution vectors is successively updated by addition, subtraction and component swapping. The brief steps of the DE algorithm are given below.

Initialization

Evaluation

Repeat

Mutation

Recombination

Evaluation

Selection

Until (stopping criteria is met)

4.4 Harmony Search Algorithm

Harmonic Search Algorithm (HSA) is a music based meta heuristic optimization algorithm inspired by playing of music [13]. It uses rules and randomness to imitate natural phenomena. It is based on the analogy between music improvisations which seeks the best harmony determined by aesthetic estimation and the searching in optimization process for the optimal solution determined by objective function evaluation. The HSA looks for the vector or the path of X that reduces the computational cost or shortness the path. The computational procedure for the HS algorithm is as follows.

Step 1: Parameter initialization

Consider an optimization problem that is described by

$$Minimize\; F\left(x\right) x_i \in X_i, \quad i = 1, 2, \ldots . N \tag{21}$$

Where F(x) is the objective function, x is the set of design variables ,Xi is the range set of the possible values for each design variable. The following HS algorithm parameters are also specified. The harmony memory size(HMS) or number of solution vectors in the harmony memory; the harmony memory considering rate (HMCR); the pitch adjusting rate (PAR); the number of decision variables (N); the number of improvisations (NI) and the stopping criterion.

Step 2 Harmony memory initialization

The harmony memory (HM) matrix is filled with randomly generated solution vectors for HMS and sorted by the values of objective function f(x)

Step 3 New Harmony improvisations

A new harmony vector $x^1 = (x^1_{1,} x^1_{2,} \ldots .., x^1_n)$is generated based on three criteria: memory consideration,pitch adjustment and random selection. Generating a new harmony is called improvisation. The HMCR, which varies between 0 and 1is the rate of choosing one value from the historical values stored in the HM, while (1-HMCR) is the rate of randomly selecting one value from the possible range of values.

$$\begin{aligned}
&if(rand() < HMCR)\\
&x'_i \leftarrow x'_i \in \{x^1_i, x^2_i, \ldots ..x^{HMS}_i\}\\
&else\\
&x'_i \leftarrow x'_i \in X_i,\\
&end
\end{aligned} \tag{23}$$

where $rand()$is a uniformly distributed random number between 0 and 1 and is the set of the possible range of values for each decision variable. Every component obtained with memory considerationis examined to determine if pitch is to be adjusted. This operationuses the rate of pitch adjustment as a parameter as shown

in the following:

$$\begin{aligned}
&if\ (rand\,() < PAR)\\
&x'_i = x'_i + rand\,() * bw\\
&\text{else}\\
&x'_i = x'_i\\
&\text{end,}
\end{aligned} \tag{24}$$

where bw is an arbitrary distance bandwidth for the continuous design variable and $rand(\;)$ is uniform distribution between -1 and 1.

Step 4: update harmony memory

If the new harmony vector $x' = (x'_1, x'_2, \ldots . x'_N)$ has better fitness function than the worst harmony in the HM, the new harmony is included in the HM and the existing worst harmony is excluded from the HM

Step 5: Checking the stopping criterion

If the stopping criterion, which is based on the maximum numberof improvisations, is satisfied, the computation is terminated.Otherwise, Steps 3 and 4 are repeated.

5 IMPLEMENTATION OF HSA TO RPC

The implementation of the HSA for the RPCproblem includes finding the optimal location and size of SVC and TCSC to minimize the objective function while satisfying

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \begin{matrix} \to f(x^{(1)}) \\ \to f(x^{(2)}) \\ \vdots \\ \to f(x^{(HMS-1)}) \\ \to f(x^{(HMS)}) \end{matrix} \tag{22}$$

	SVC Bus Location			SVC MVAr Rating			TCSC Line Location		TCSC X_{TCSC}	
	9	18	3	0.224	0.112	0.361	8	17	0.0211	0.0315
	7	16	11	0.124	0.514	0.702	4	34	0.064	0.0512
HM =	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.
	4	13	21	0.875	0.453	0.625	15	31	0.0142	0.074

Fig. 4. Structure of Harmony Matrix

the constraints. The implementation process of HSA to the RPC problem is described in the following steps:

HSA Algorithm for RPC Problem	
Step 1	Read the parameter of power system and those of HSA and specify minimum and maximum limits of each variable
Step 2	Initialize harmony memory (HM) with the size *HMS*×*N*
Step 3	Evaluate objective function (18) of each solution vector of HM based on the results of Newton Raphson load flow analysis and sort it in ascending order
Step 4	Generate new harmony vector using random selection, memory consideration and pitch adjustment based on equations (23),(24)
Step 5	Update the harmony memory
Step 6	Check for the equality and inequality constraints of the problem
Step 7	If the maximum number of generations reached go to step 8 otherwise repeat step 3 to step 6
Step 8	Print optimal location and values of FACTS devices

6 NUMERICAL RESULTS AND DISCUSSIONS

The HSA has been tested on modified IEEE 30 bus system for reactive power compensation. Modified IEEE 30 bus system was obtained from IEEE 30 bus system after relocating the generators from bus 1 and bus 6. The modified IEEE 30 bus system has 6 PV buses, 24 PQ buses and 41 transmission lines of which three branches (9-11) (9-12) and (8-13) are with tap setting transformers. The data of IEEE 30 bus system is given in [17]. It is planned to install three SVC and two TCSC to the modified IEEE 30 bus system because this system is not such a large network

Fig.4 shows the structure of the solution vectors which is set for modified IEEE 30 bus system. The first three columns are the SVC bus location; 4th to 6th parameters are the rating of SVC; 7th and 8th represents the TCSC line location and finally 9th and 10th denotes the reactance of TCSC. The goal is to find the optimal location and value of SVC and TCSC which will minimize the total system loss and at the same time regulate the bus voltage within prescribed limits($0.95 \leq V_i \leq 1.05$). Two cases are discussed to show the effectiveness of the HSA. In the case 1 a lightly loaded (Base load 1) condition is created by reducing randomly the loads at all buses in the standard bus data of IEEE 30 bus system. Similarly for the case 2 a heavily loaded (Base load 2) state is created by increasing randomly the loads at all buses in the standard bus data of IEEE 30 bus system. The simulation studies were carriedout in Matlab R2009b software and executed on a Core(TM) i3 CPU 2.39GHz with 3-GB randomaccessmemory (RAM). To validate the efficacy of HSA, meta heuristic algorithms like GA,PSO and DE has also been implemented to solve the same problem. The parameters of meta heuristic algorithms are given in Table 1 to Table 4.

Table 1. Parameter Setting of HSA

HMS	50
HMCR	0.85
PAR	0.3
Number of improvisations	100

6.1 Case 1

A lightly loaded condition was created by reducing the loads randomly at all the buses. The total system load is 212.55 MW and 94.65 MVAr. Power flow calculations are performed in per unit, with base apparent power Sbase =100 MVA. Parameters values of meta-heuristic algorithms are adjusted according to Table 1 to Table 4.. The

Table 2. Parameter Setting of GA

Population size	50
Crossover rate	0.9
Mutation rate	0.05
Number of generations	100

Table 3. Parameter Setting of PSO

Population size	50
$w_{min}\&w_{max}$	0.4 & 0.9
$C_1 = C_2$	1.4
Velocity bounds	(-3,7)
Max Iteration	100

Table 4. Parameter Setting of DE

Population size N	50
Max iteration	100
Mutation factor F	0.5
Crossing factor CR	0.9

total system loss and the rest of the results in 10 independent runs for all the four algorithms are reported in Table 5.The convergence of power loss for this case for four algorithms is shown in Fig.5. It is obvious that HSA has better convergence property than other three algorithms. The optimal system loss using HSA was found to be **3.870 MW** which is comparatively less than power loss obtained by GA,PSO and DE. It may be noted that the total system loss without compensation is 4.945 MW. The average bus voltage for this case as per Table 5 is 1.1148. The system requires inductive VAr to mitigate this situation. Table 7 gives the SVC optimal location and ratings. Table 7 shows that HSA correctly tunes the SVC units to produce inductive MVAr (negative) to manage the lightly loaded conditions. It is found from Table 7 the total MVAr requirement yield byHSA is less than other three algorithms which validates the effectiveness of HSA.

Table 9 gives the TCSC optimal line location and reactance values. The convergence of SVC bus locations and TCSC line locations for this case using HSA have been shown in Fig 7 and Fig 9 respectively. It is found that the HSA yields best performance with respect to VAr sources requirement, loss reduction, CPU time and better voltage profile.

6.2 Case 2

A heavily loaded condition was introduced by increasing randomly the loads at all buses. The total system load

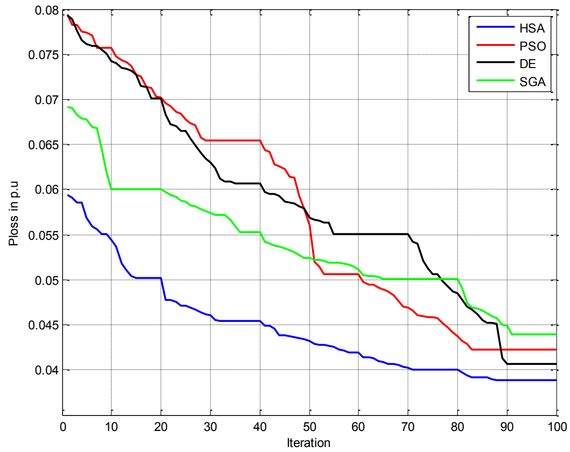

Fig. 5. Objective function evolution (case 1)

is 533.59 MW and 226.03 MVAr. Power flow calculations are performed in per unit, with base apparent power Sbase =100 MVA. Parameters values of meta-heuristic algorithms are adjusted according to Table 1 to Table 4. The optimal system loss in 10 independent runs has been calculated as 55.31 **MW** for HSA,57.74 MW for SGA, 57.10 MW for PSO and 56.97 MW for DE which confirms the effectiveness of HSA. It may be noted that the power loss without compensation is 58.14 MW. Table 6. Summarizes the comparative performance of HSA in 10 independent simulations with GA,PSO and DE. The optimal bus location, MVAr rating of SVC units is given in Table 8. The average bus voltage for this case as per Table 6 is 0.9914 p.u. The system needs capacitive VAr to manage this situation. Table 8 shows that HSA correctly tunes the SVC units to produce capacitive MVAr (positive) to overcome the heavily loaded conditions. It is found from Table 8MVAr requirement to manage the heavily loaded conditionsfor HSAis less than other three algorithms.Table 10 gives the optimal line location and reactance values of TCSC units. The convergence of power loss for case 2 is shown in Fig.6. It is clear that HSA has better convergence property than other three algorithms.The convergence of SVC bus locations and TCSC line locations using HSA for this case have been shown in Fig 8 and Fig 10 respectively It is found that in this case also the HSA yields best performance with respect to VAr sources requirement, loss reduction, CPU time and better voltage profile.

7 CONCLUSION

The application of HSA algorithm as a heuristic optimization method for determining the optimal location and setting of FACTS devices for reactive power compensation has been presented. The algorithm is easy to implement

Table 5. Comparison of Performance (case 1)

Techniques	**Base load 1**	**SGA**	**PSO**	**DE**	**HSA**
Best P_{loss}in p.u	0.04945	0.04350	0.04121	0.04019	**0.0387**
Worst P_{loss}in p.u	–	0.04771	0.04401	0.04297	0.04009
Mean P_{loss}in p.u	–	0.0442	0.04312	0.04192	0.03941
Standard Deviation	–	0.005404	0.00390	0.003004	0.00299
V_{min}inp.u	1.0458	1.0358	1.0281	1.0301	0.9877
V_{max}inp.u	1.1953	1.0500	1.0514	1.0498	1.0440
Average Voltage(p.u))	1.1148	1.0443	1.0358	1.0387	1.0327
Average time (in sec)	–	142.21	127.54	129.83	73.42

Table 6. Comparison of Performance (case 2)

Techniques	**Baseload 2**	**SGA**	**PSO**	**DE**	**HSA**
Best P_{loss}in p.u	0.58142	0.57741	0.57104	0.56978	**0.5531**
Worst P_{loss}in p.u	–	0.5792	0.57876	0.57012	0.56371
Mean P_{loss}in p.u	–	0.57851	0.57215	0.56991	0.55872
Standard Deviation	–	0.002602	0.002061	0.002345	0.001732
V_{min}inp.u	0.9129	0.9544	0.9541	0.9553	0.9579
V_{max}inp.u	1.0913	1.0589	1.049	1.0511	1.0504
Average Voltage(p.u))	0.9914	1.0371	1.0331	1.0257	1.0314
Average time (in sec)	–	195.27	152.31	148.72	105.38

Table 7. SVC optimal location and ratings (case 1)

SGA		PSO		DE		HSA	
Bus no	**MVAr Rating**	**Bus no**	**MVAr Rating**	**Bus no**	**MVAr Rating**	**Bus no**	**MVAr Rating**
9	-24	9	-29	9	-27	9	-27
15	-25	21	-23	12	-20	20	-19
24	-23	28	-24	20	-21	26	-18

Table 8. SVC Optimal location and ratings (case 2)

SGA		PSO		DE		HSA	
Bus no	**MVAr Rating**	**Bus no**	**MVAr Rating**	**Bus no**	**MVAr Rating**	**Bus no**	**MVAr Rating**
7	+29	7	20	6	21	6	+22
13	+62	15	72	14	49	14	+28
17	+31	20	35	24	40	17	+22

Table 9. TCSC Optimal line location and XTCSC value (case 1)

SGA		PSO		DE		HSA	
Bus no-Bus no	**XTCSC**	**Bus no-Bus no**	**XTCSC**	**Bus no-Bus no**	**XTCSC**	**Bus no-Bus no**	**XTCSC**
2-4	0.0341	2-4	0.0214	2-4	0.0514	2-4	0.0152
12-14	0.0503	29-30	0.0214	22-24	0.0261	25-26	0.0241

Table 10. TCSC Optimal line location and XTCSC value (case 2)

SGA		PSO		DE		HSA	
Bus no-Bus no	**XTCSC**	**Bus no-Bus no**	**XTCSC**	**Bus no-Bus no**	**XTCSC**	**Bus no-Bus no**	**XTCSC**
9-11	0.0562	4-12	0.0594	2-4	0.0441	2-4	0.0535
12-16	0.0043	14-15	0.0071	16-17	0.0321	12-16	0.0757

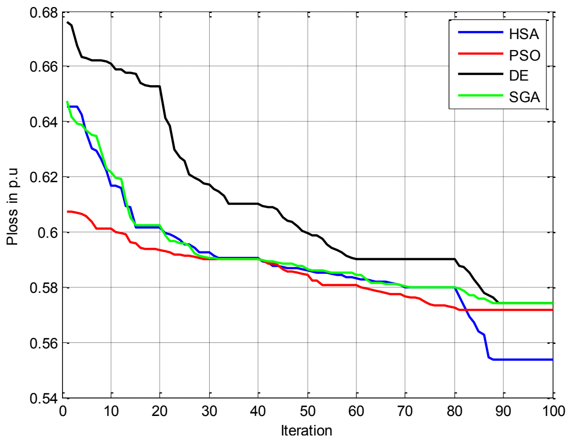

Fig. 6. Objective function evolution (case 2)

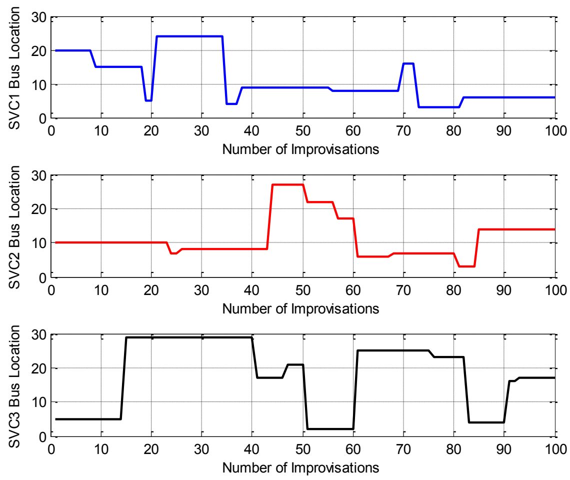

Fig. 8. Convergence of SVC bus location (case2)

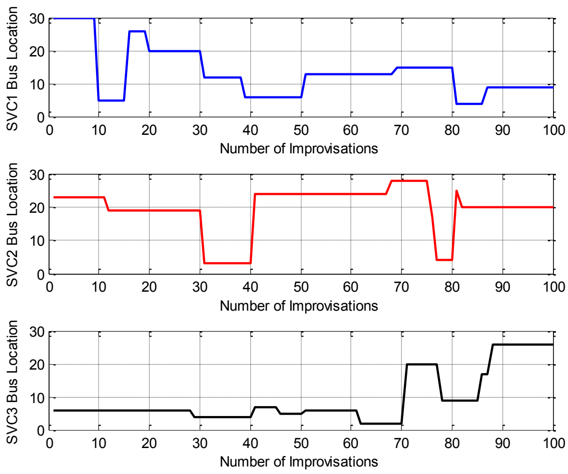

Fig. 7. Convergence of SVC bus location (case1)

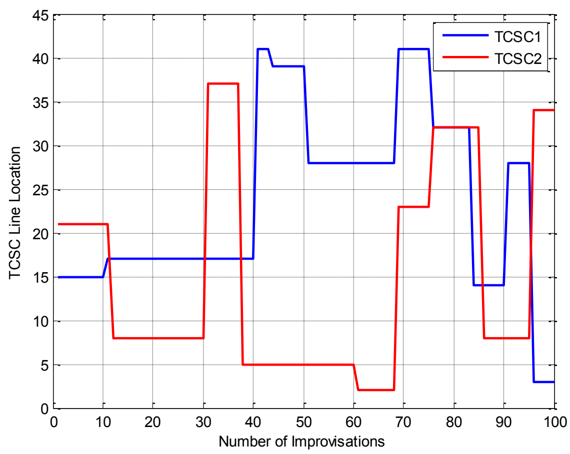

Fig. 9. Convergence of TCSC Line Location (case1)

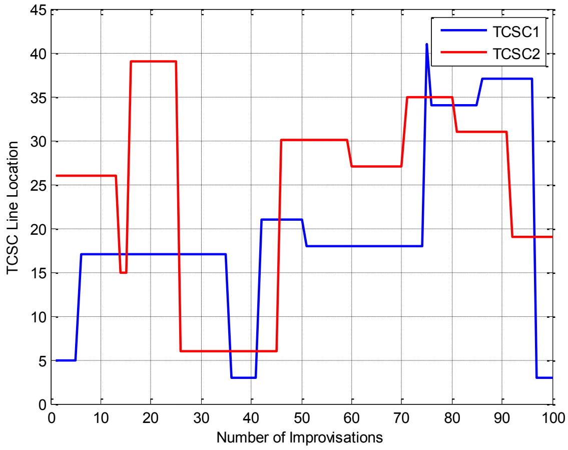

Fig. 10. Convergence of TCSC Line Location (case2)

and can find multiple optimal solutions to constrained optimization problem. The extents of reduction in the power system loss and improvement of bus voltage profile are used as measures of power system performance in the optimization algorithm. The HSA algorithm is validated on modified IEEE 30 bus system for two operating conditions. The result shows the HSA algorithm produces greater reduction in power loss and voltage deviation than SGA, PSO and DE algorithms. Moreover, the HSA not only performs better in finding better solutions but also converges faster compared with other reported meta heuristic algorithms.

REFERENCES

[1] J. Z. Zhu and M. R. Irving. Combined active and reactive dispatch with multiple objectives using an analytic hierarchical process. *Proc. Inst. Elect. Eng.*, vol. 143, no. 4, pp. 344–352, 1996.

[2] J. Z. Zhu and X. F. Xiong, VAr optimization and pricing in multi-areas power system presented at the IEEE General Meeting, Toronto, ON, Canada, Jul. 13–18, 2003.

[3] N.G. Hingurani, L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, New York, 2000.

[4] Mansour Y, Xu W, Alvarado F, Rinzin C. SVC placement using critical modes of voltage instability. IEEE Trans Power Syst. 1994;9:757–63.

[5] Farsangi MM, Nezamabadi-pour H, Yong-Hua Song, Lee KY. Placement of SVCs and Selection of Stabilizing Signals in Power Systems. IEEE Trans Power Syst 2007;22:1061–71.

[6] Messina AR, Pe'rez MA, Herna'ndez E. Coordinated application of FACTS devices to enhance steady state voltage stability. Int J Elect Power Energy Syst

[7] Sharma NK, Ghosh A, Varma RK. A novel placement strategy for FACTS controllers. IEEE Trans Power Syst 2003;18:982–7.

[8] Thukaram D, Lomi A. Selection of static VAR compensator location and size for system voltage stability improvement. Electr Power Syst Res 2000;54:139–50.

[9] Gerbex S, Cherkaoui R, Germond AJ. Optimal location of multi-type FACTS devices in power system by means of genetic algorithm. IEEE Trans Power Syst 2001;16:537–44.

[10] Cai LJ, Erlich I, Stamtsis G. Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms. IEEE PES Power Syst. Conf. and Expo, 2004.

[11] Mínguez Roberto, Milano Federico, Zárate-Miñano Rafael, Conejo Antonio J. Optimal network placement of SVC devices. IEEE Trans Power Syst 2007;22:1851–60.

[12] Saravanan M, Mary Raja Slochanal S, Venkatesh P, Prince Stephen Abraham J. Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability. Elect Power Syst Res 2007;77:276–83.

[13] Geem Z, Kim J, Loganathan A. A new heuristic optimization algorithm:harmony search. Simulation 2001;76(2):60–8.

[14] Shariatkhah MH, Haghifam MR, Salehi J, Moser A. Duration based reconfiguration of electric distribution networks using dynamic programming and harmony search algorithm. Int J Electr Power2012;41(1):1–10.

[15] Khazali AH, Kalantar M. Optimal reactive power dispatch based on harmony search algorithm. Int J Electr Power 2011;33(3):684–92.

[16] Stott.B, Review of load flow calculation methods. proc. of the IEEE,1974, vol 62, no 7, pp.916-929

[17] O. Alsac, B. Stott, Optimal load flow with steady state security, IEEE Transactionson Power Apparatus and Systems 93 (1974) 745–751

D. Karthikaikannan received B.E., degree in Electrical and Electronics Engineering from Madras University in 2002. M.E., from Annamalai university in 2005 and Ph.D from Anna University Chennai. At present he is working as Assistant Professor III in School of Electrical and Electronics Engineering, SASTRA University, Tanjore. His fields of interest are Automatic Generation Control, Voltage Stability and soft computing techniques.

G. Ravi received B.E., degree in Electrical & Electronics Engineering from Mysore University in 1992. M.E.,from Annamalai University in 1994 and Ph.D (Engg) from Jadavpur University in 2005. At present he is a professor in Electrical & Electronics Engineering department at Pondicherry Engineering College, Pondicherry,india. His research area includes electrical machines, power system operation, planning, optimization and soft computing techniques.

AUTHORS' ADDRESSES
Asst. Prof. D.Karthikaikannan, Ph.D.
Department of Electrical and Electronics Engineering,
School of Electrical and Electronics Engineering,
SASTRA University,
Tirumalaisamudram-613401,
Tamilnadu, India
email:gdkkannan@yahoo.co.in
Prof. G.Ravi Ph.D.
Department of Electrical and Electronics Engineering,
Pondicherry Engineering College,
Puducherry-605014, India
Email:ravigpec@yahoo.com

Received: 2014-01-24
Accepted: 2016-10-04