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Optimal placement and sizing of Static Var Compensators in power systems using Improved Harmony Search Algorithm

***Abstract**. This paper presents the application of the improved harmony search (IHS) algorithm for determining the optimal location and sizing of static Var compensator (SVC) to improve the voltage profile and reduce system power losses. A multi-criterion objective function comprising of both operational objectives and investment costs is considered. The results on the 57-bust test system showed that the IHS algorithm give lower power loss and better voltage improvement compared to the particle swarm optimization method in solving the SVC placement and sizing problem.*

***Streszczenie.** Artykuł przedstawia zastosowanie algorytmu IHS (Improved harmony search) do określania optymalnej lokalizacji kompensatora mocy biernej. Rezultaty testów wykazały że algorytm zapenia mniejsze straty mocy oraz zniekształcenia w porównaniu do innych metod optymalizacji. (**Optymalizacja lokalizacji kompensatora mocy biernej z wykorzystaniem algorytmu IHS**)*

Keywords: Static Var Compensator, Power Loss, Voltage Profile, Harmony Search Algorithm
Słowa kluczowe: komensacja mocy biernej, algorytm HIS.

Introduction

Flexible AC transmission system (FACTS) can provide benefits in increasing system transmission capacity and power flow control flexibility and rapidity [1]. FACTS devices are power electronic converters that have the capability of controlling various electrical parameters in transmission circuits, facilities, both in steady state power flow and dynamic stability control. These devices include thyristor controlled series compensator, static Var compensator (SVC), unified power flow controller, static compensator (STATCOM), etc [2]. The most widely used shunt FACTS devices within power networks is the SVC due to its low cost and good performance in system enhancement. It is a shunt-connected static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to provide voltage support and when installed in a proper location, it can also reduce power losses.

Many methods and approaches have been reported in the literature to determine the optimal location of SVC in the power system using different techniques such as genetic algorithm (GA), simulated annealing (SA), artificial immune system (AIS) and particle swarm optimization (PSO) [3, 4]. A solution algorithm based on SA is used to determine the location, types and sizes of Var sources and their settings at different loading conditions [5]. The purchase cost, the installation cost and the total cost of energy loss over the life of the Var sources, are minimized considering operational constraints [5]. In [6], GA is applied to determine the best location of only one SVC within a power system in which the objective function is defined for reducing power loss, voltage deviation and cost. An AIS technique is used to minimize the total loss and improve the voltage in a power system [7] by determining the correct placement of SVC. The well known PSO is explored in [8] to obtain optimal locations of SVCs in the IEEE 30 bus system.

This paper presents a relatively new optimization technique known as the improved harmony search (IHS) algorithm for finding optimal placement and sizing of SVC in power systems. The harmony search algorithm is a meta-heuristic optimization method that is inspired by musicians in improvising their instrument pitches to find better harmony [8]. It has several advantages in which it does not require initial value settings for the decision variables and it can handle both discrete and continuous variables. Harmony search algorithm has been successfully applied to solve optimal placement of FACTS devices to improve power system security [9]. In this paper, the IHS algorithm is applied to determine the optimal placement of five SVCs for voltage profile improvement and power loss reduction in a 57-bus test system. The obtained results using the IHS algorithm are then compared with the PSO optimization method for validation.

Problem Formulation

A. SVC ideal model

In its simplest form, the SVC consists of a thyristor-controlled reactor in parallel with a bank of capacitors. From the operational point of view, the SVC behaves like a shunt connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network. It is used extensively to provide fast reactive power and voltage regulation support. The thyristor's firing angle control enables the SVC to have almost instantaneous speed in response. As an important component for voltage control, it is usually installed at the receiving node of the transmission lines. In Fig. 1, the SVC has been considered as a shunt branch with a compensated reactive power Q_{SVC}, set by available inductive and capacitive susceptances [12].

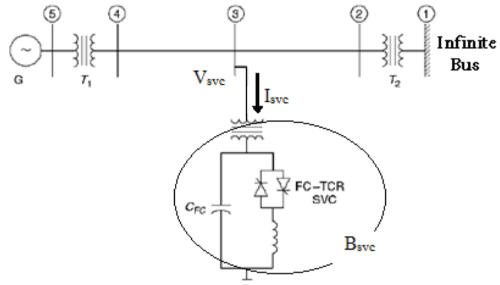

Fig.1. Circuit diagram of SVC connected to an infinite bus

From Fig.1, the current drawn and reactive power injected by the SVC can be expressed as:

$$I_{SVC} = jB_{SVC} \times V \quad (1)$$

$$Q_{SVC} = -jB_{SVC} \times V^2 \quad (2)$$

where B_{svc}, I_{svc} and Q_{svc} are the susceptance, injected current and injected reactive power of SVC, respectively.

The size of an SVC is expressed as an amount of reactive power supplied to a bus whose voltage is 1 p.u. The SVC either operates in a capacitive state by generating reactive power and injects it into the network or in an inductive state, where the SVC absorbs reactive power from the network [6].

B. The objective function

A multi-objective function is considered in searching for a solution consisting of both the SVC location and size that minimizes the voltage deviation, active power loss and installation cost as explained below [6]:

Minimize the active power loss:

The total active power loss in an electric power system is given by,

(3)

$$P_{loss} = \sum_{l=1}^{b} R_l I_l^2 = \sum_{i=1}^{b} \sum_{j=1, i\neq j}^{b} [V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)] Y_{ii} \cos\varphi_{ij}$$

where b is the number of lines, R_l is the resistance of line *l*, I_l is the current through line *l*, V_i and δ_i are the voltage magnitude and angle at node *i* and Y_{ij} and φ_{ij} are the magnitude and angle of the line admittance.

Minimize the voltage deviation:

The voltage improvement index for a power system is defined as the deviation of voltage magnitudes of each and every bus from unity. Thus, for a given system, the voltage improvement index is defined as,

(4) $$L_v = \sum_{i=1}^{b} \left(\frac{V_{iref} - V_i}{V_{iref}} \right)^2$$

where n is the number of buses, V_{iref} is the reference voltage at bus *i* and V_i is the actual voltage at bus i.

Minimize the investment cost:

The total SVC cost in US$/kVAr are given as [11]:

(5) $$C_{SVC} = \sum_{k=1}^{n} 0.0003 Q_k^2 - 0.3051 Q_k + 127.38$$

where Q_k is the reactive power capacity of k^{th} installed SVC, in MVar.

C. Operational constraints

Since the objective of applying SVC is to control system variables such as line real and reactive power flows and bus voltages, the following constraints are considered.

Power flow balance equations:

The balance of active and reactive powers must be satisfied in each node. Power balance with respect to a bus can be formulated as:

(6) $$P_{Gi} - P_{Li} = V_i \sum_{j=1}^{b} [V_j [G'_{ij} \cos(\delta_i - \delta_j) + B'_{ij} \sin(\delta_i - \delta_j)]]$$

(7) $$Q_{Gi} - Q_{Li} = V_i \sum_{j=1}^{b} [V_j [G'_{ij} \sin(\delta_i - \delta_j) - B'_{ij} \sin(\delta_i - \delta_j)]]$$

where, P_{Gi} and Q_{Gi} are the generated active and reactive powers, and P_{Li} and Q_{Li} are the load active and reactive powers at node *i*. The conductance, G'_{ik} and susceptance, B'_{ik} represent the real and imaginary components of element Y'_{ij} of the [Y'_{bb}] matrix, obtained by modifying the initial nodal admittances matrix when introducing the SVC .

Power flow limit:

The apparent power that is transmitted through a branch *l* must not exceed a limiting value, $S_{l\,max}$, which represents the thermal limit of the line or transformer in steady-state operation:

(8) $$S_l \leq S_{l\max}$$

Bus voltage limits:

For several reasons such as stability and power quality, the bus voltages must be maintained around the nominal value and it is given by:

(9) $$V_{i\min} \leq V_{inom} \leq V_{i\max}$$

In practice, the accepted deviations can reach up to 10% of the nominal values [7].

The objective function for solving the SVC optimal placement problem is computed using equations (3)-(5). The constraints of this particular problem do not explicitly contain the variables and therefore the effect of the constraints must be included in the value of the fitness function. The constraints are checked separately and the violations are handled using a penalty function approach. Due to the fact the three objectives are different, it would be impossible to incorporate all the constraints in the same mathematical function. An overall fitness function [7] is considered such that each objective function is normalized in a comparative manner with the base case system without SVC. This fitness function is given by,

(10) $$f(x) = \alpha \frac{P_{loss}}{\sum \Delta Loss_{base}} + \beta \frac{L_v}{\sum \Delta V_{base}} + \eta \frac{C_{SVC}}{C_{\max}} - \xi . \sum_{i=1}^{nr} bal_i - \zeta . \sum_{k=1}^{n} thermal_k - \nu . \sum_{k=1}^{n} voltage_k$$

where P_{loss}, L_v and C_{SVC} are total active power loss, voltage deviation index and total SVC cost, respectively. α, ß and η are the corresponding coefficients the corresponding objective functions; cost factor, $\sum \Delta Loss_{base}$ is the total base case active power loss in the network, $\sum V_{base}$ is the total base case voltage deviation and C_{max} is the maximum investment cost. The element, bal_i is a factor equal to 0 if the power balance constraint at bus *i* is not violated and 1 otherwise. The sum of these violations represents the total number of buses in the network that do not follow the constraints (6) and (7) and it is multiplied by a penalty factor meant to increase the fitness function up to an unacceptable value so as to discard the unfeasible solution. The second and third sums in the fitness function represent the total number of violations of constraints (8) and (9), respectively and are also multiplied by cost factors.

The last three sums in this fitness function are measures of unfeasibility for each candidate solution. The penalty factors used in this study are ξ, ζ and ν which are set to 100. Without the cost integrated in the fitness function; the algorithm tends to set the SVC size close to its superior limit, as this would improve the voltage profile. The cost function, on the other hand, tries to keep the SVC size closer to its inferior limit. As a result of these two contradictory objectives, the solution method finds an optimum that satisfies both the limits [6].

Taking into consideration the fact that the cost objective function is less important than the power loss reduction and voltage profile improvement, the corresponding coefficients for each objective are defined as α =40%, ß=40% and η=20%.

Improved Harmony Search Algorithm

Harmony search algorithm is a meta-heuristic optimization algorithm inspired by the operation of orchestra music to find the best harmony between components which are involved in the operation process, for optimal solution. It is based on rules and randomness to imitate natural phenomena. As musical instruments can be played with some discrete musical notes based on player experience or based on random processes in improvisation, optimal design variables can be obtained with certain discrete values based on computational intelligence and random processes [11]. Among the advantages of the HS algorithm are that it can consider discontinuous functions as well as continuous functions because it does not require differential gradients; it does not require initial value setting for the variables; it is free from divergence and may escape local optima [11].

In the HS algorithm, it looks for vector or the path of X which can reduce the computational function cost or shorten the path. The computational procedures of the HS algorithm are described as follows [8] :

Step 1: *Initialization of the Optimization Problem*

Consider an optimization problem which is described as,

(11) *Minimize F(x) subject to* $x_i \in X_i$ *, i=1,2,3,…..N.*

where *F(x)* is the objective function, *x* is the set of each design variable (x_i), X_i is the set of the possible range of values for each design variable ($Lx_i < X_i < Ux_i$) and *N* is the number of design variables.

Here, the HS algorithm parameters are also specified in which the parameters are the harmony memory size (HMS) or the number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); number of decision variables (N); number of improvisations (NI) and the stopping criterion.

Step 2: *Initialization of the Harmony Memory*

The harmony memory (HM) matrix shown in (12) is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function, *f* (*x*).

(12)
$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \ldots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \ldots & x_{N-1}^2 & x_N^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_1^{HMS-1} & x_2^{HMS-1} & \ldots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \ldots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \begin{matrix} \Rightarrow & f(x^{(1)}) \\ \Rightarrow & f(x^{(2)}) \\ . & . \\ . & . \\ . & . \\ \Rightarrow & f(x^{(HMS-1)}) \\ \Rightarrow & f(x^{HMS)}) \end{matrix}$$

Step 3: *Improvisation a New Harmony from the HM set*

A new harmony vector, *x′* = (*x*1′, *x*2′ ,...,*xn*′), is generated based on three rules, namely, random selection, memory consideration and pitch adjustment. These rules are described as follows:

<u>*Random Selection:*</u> When HS determines the value, x_i' for the new harmony, *x′* = (x_1', x_2' ,...x_n'), it randomly picks any value from the total value range with a probability of *(1-HMCR)*. Random selection is also used for previous memory initialization.

<u>Memory Consideration:</u> When HS determines the value x_i', it randomly picks any value x_i^j from the HM with a probability of HMCR since j= {1*, 2,…*, HMS*}*.

(13)
$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} & with\,probablity\,HMCR \\ x'_i \in X_i & with\,probablity\ \ (1-HMCR) \end{cases}$$

<u>*Pitch Adjustment:*</u> Every component of the new harmony vector *x′* = (x_1', x_2' ,...x_n'), is examined to determine whether it should be pitch-adjusted. After the value x_i' is randomly picked from HM in the above memory consideration process, it can be further adjusted into neighboring values by adding certain amount to the value, with probability of *PAR*. This operation uses the *PAR* parameter, which is the rate of pitch adjustment given as follows:

(14)
$$x'_i \leftarrow \begin{cases} Yes & with\,probablity\,PAR \\ No & with\,probablity\ \ (1-PAR) \end{cases}$$

The value of *(1-PAR)* sets the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' is replaced as follows:

(15)
$$x'_i \leftarrow x'_i \pm bw$$

where *bw* is the arbitrary distance bandwidth for a continuous design variable. In this step, pitch adjustment or random selection is applied to each variable of the new harmony vector.

Step 4: *Updating HM*

If the new harmony vector *x′* = (x_1', x_2' ,...x_n') is better than the worst harmony in the HM, from the viewpoint of the objective function value, the new harmony is entered in the HM and the existing worst harmony is omitted from the HM.

Step 5: *Checking stopping criterion*

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

The traditional HS algorithm uses fixed value for both *PAR* and *bw*. The *PAR* and *bw* values adjusted in the initialization step (Step 1) cannot be changed during new generations. The main drawback of this method appears in the greater number of iterations the algorithm needs to find an optimal solution. To overcome this drawback, an improved Harmony Search algorithm (IHS) [12] has been developed and applied to solving various engineering optimization problems. Numerical results proved that the improved algorithm can find better solutions when compared to the conventional HS and other heuristic or deterministic methods. The key difference between IHS and traditional HS method is in the way of adjusting *PAR* and *bw*. To improve the performance of the HS algorithm and eliminate the drawbacks lies with the fixed values of *PAR* and *bw*, the IHS algorithm uses variables *PAR* and *bw* in the improvisation step (Step 3). The *PAR* values change dynamically with generation number as shown in Fig. 3 and expressed as follows [12]:

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

where *PAR* is the pitch adjusting rate for each generation, PAR_{min} *is the* minimum pitch adjusting rate, PAR_{max} is the maximum pitch adjusting rate, *NI is the* number of solution vector generations and *gn is the* generation number.

bw changes dynamically with generation number as shown in Fig. 4 and defined as follows:

(17) $bw(gn) = bw_{max} \exp(c \cdot gn)$

(18)
$$c = \frac{Ln(\frac{bw_{\max}}{bw_{\min}})}{NI}$$

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

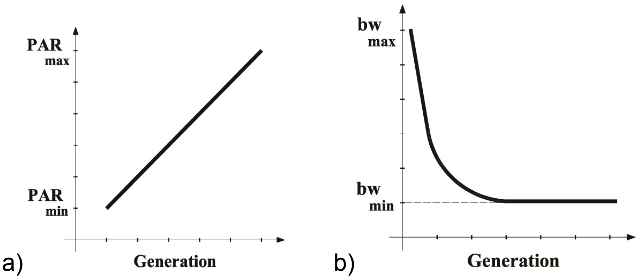

Fig.2. a) Variation of PAR versus generation number b)Variation of *bw* versus generation number

Application of IHS Algorithm for Optimal Placement of SVC

The optimal placement of SVC at the buses is found by using the IHS algorithm in which the optimal SVC set $\{Q^{svc}_{1,...}, Q^{svc}_{i,...}, Q^{svc}_{N}\}$ leads to a maximum power loss reduction, minimum voltage deviation and cost saving. Here, the Newton-Raphson power flow is applied for computing the power loss. The procedures for implementing the proposed method for optimal placement of SVC are described as follows:

i. Input system parameters such as buses, branches and generators data.
ii. Randomly add the SVC for reactive power compensation at allowed buses. Calculate the total power loss, voltage deviation and total cost, respectively. Each SVC set is considered as the harmony vectors. Initialize the arrays of HM randomly as in equation (12). The number of columns in the HM is equal to number of buses in the test system. In this case, the optimal parameters of the test system, Lx_i and Ux_i are assumed to have minimum and maximum MVAR values of *0* MVAR and *20* MVAR, respectively. Thus, the harmony memory size (HMS) is assumed 10.
iii. Improvise a new harmony using the three rules of random selection, memory consideration and pitch adjustment. In this step, the optimal parameters are assumed as: HMCR = 90% , PAR_{max}= 0.99, PAR_{min}= 0.4, bw_{max}=1 , bw_{min}=0.0001 and NI = 5000.
iv. Run the power flow to calculate the bus voltages.
v. Calculate power loss, Voltage deviation and total cost.
vi. Check if the SVC set (New Harmony) gives less total cost than the worst harmony in the HM. If yes, the worst harmony is replaced with the New Harmony in the HM. Otherwise, generate new *PAR* and new *bw* using equations (16) and (17), respectively and then go to step (iii).
vii. Determine the optimal SVC set (best harmony) which gives maximum power loss reduction, minimum voltage deviation and maximum cost saving.

Fig. 3 describes the procedures involved in solving the optimal SVC placement problem using the IHS algorithm.

Case Study and Results

The proposed method is tested on a 57-bus system shown in Fig.4. The network consists of 7 generators, of which one is the slack node, 50 load buses and 80 lines, and the system data can be found in [13]. The base case system load is 12.508 pu and the system power loss is 0.2845 pu. The power flow program is used to calculate the minimum power loss, P_{loss} , when reactive power injection is varied in steps of 0.01 per unit independently at all the load buses. The reduction of the P_{loss} due to Q injection at the load bus is recorded together with the bus number.

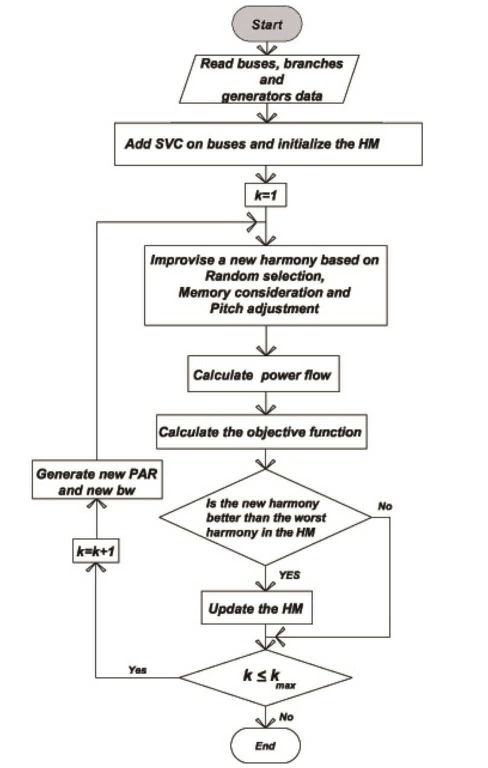

Fig.3. The IHS algorithm for solving the SVC placement problem

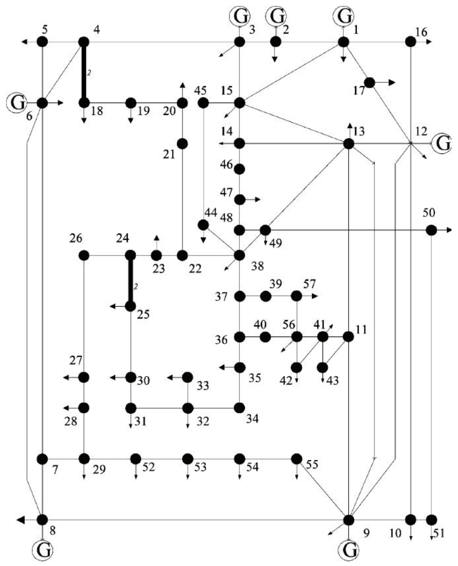

Fig .4 . Network configuration of IEEE 57-bus power system

The proposed IHS algorithm was implemented to determine the optimal location and size of SVC devices in the network. In the determination of optimal placement of SVC, only five SVCs are considered to be placed at the appropriate buses of the 57-bus system. The results obtained from the IHS algorithm are compared with the results using the PSO method as shown in Table 1. This study is performed with the restriction that the injected Q does not exceed 20 MVar. The results indicate that the SVC placement at the five buses determined by the IHS algorithm are not the same as that detrmined by PSO.

For a more detailed analysis of the results, consider Table 2 which shows the various objective functions after installation of the SVC devices. From Table 2, it is observable that the SVC placement by using the IHS algorithm lead to lower fitness function value, lower total power loss, lower SVC cost and slightly less voltage deviation in comparison with the PSO method.

Table 1. SVC placement results using PSO and IHS

SVC on Bus	PSO	IHSA
	(MVar)	
11	0	2.17
26	4.90	3.69
30	0	3.46
31	5.99	4.03
32	2.25	3.62
33	2.03	0
46	1.87	0

Table 2. Comparison of objective functions after installing SVC

Objective function	PSO	IHSA
Total Power Losses (MW)	27.66	27.48
Total Voltage deviation (p.u)	0.457	0.453
SVC cost ($)	17,205	13,367
Fitness function value	0.583	0.578

The voltage profiles and total voltage deviations for all cases are presented in Fig. 5 and Fig.6 , respectively. The results show that although the voltage deviation drops after SVC placement, the voltage improvement by using IHS algorithm are not significantly greater than using PSO.

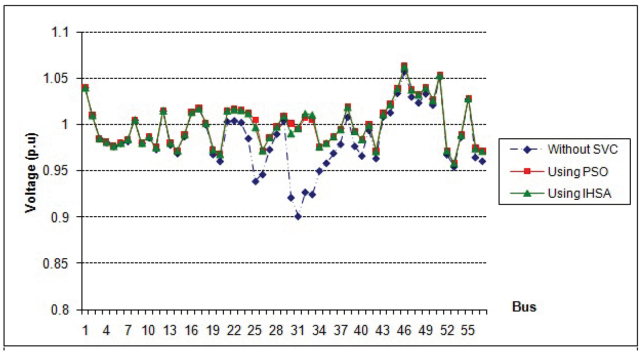

Fig.5. Voltage profiles for various cases

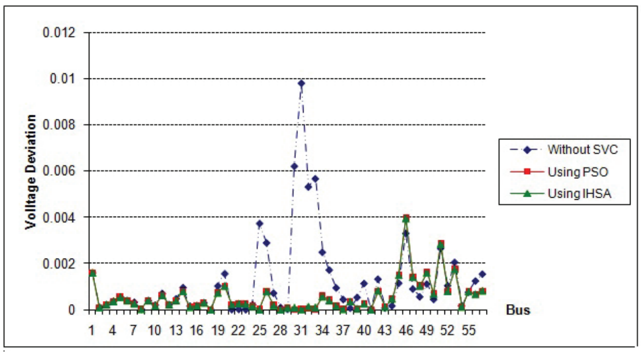

Fig.6. Total voltage deviations

Conclusion

The application of the IHS algorithm as a new meta heuristic optimization method for determining the optimal location and size of SVC devices in a transmission network has been presented. The proposed multi-objective IHS algorithm has been validated on the 57-bus transmission network and the obtained results showed that the IHS algorithm gives greater reduction in total power loss and total SVC costs compared to the PSO method. The simulation results clearly indicate the efficiency of the proposed IHS algorithm while it determines the optimal location and sizing of the SVC devices. This algorithm is practical and easy to implement in large-scale power systems.

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