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OPTIMAL CHOICE AND ALLOCATION OF SHUNT FACTS DEVICES USING DIFFERENTIAL SEARCH ALGORITHM[1]

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Abstract

In this paper, new and efficient heuristic algorithm, Differential Search Algorithm (DSA), is used for optimal choice and allocation of shunt Flexible AC transmission systems (FACTS) devices, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM). In the proposed optimal location method, SVC and STATCOM devices are located randomly and dynamically with objective of minimizing the real power loss, improving the voltage profile and enhancing the voltage stability. The best solution sets for objectives aforementioned are achieved by minimizing each objective functions by the proposed approach. In order to evaluate the proposed methodology, it has been tested on IEEE 30 bus system and compared to another widely used optimization algorithm, Artificial Bee Colony (ABC) algorithm. The validity of the proposed optimization algorithm is proven by the results and comparative analysis with other method.

Keywords: Optimization, optimal location, differential search algorithm , artificial bee colony, static VAR compensator, static synchronous compensator

1. Introduction

Optimal choice and location of Facts devices is an important task in operation and control of power system. Providing sufficient reactive power to the necessary load buses not only reduces the active power loss but also improves the voltage profile, and overcomes the instability issues on the system voltage. Hence, in recent studies it is achieved optimal utilization of power system capabilities by including FACTS devices is a popular topic in power engineering.

[1] Project code number: BAP-2018-1-TP3-2868.

SVC is a well known FACTS device that is generally used in transmission networks due to low cost and good performance with the purpose of improving the voltage stability. There is another compensator device, STATCOM, which is also connected to load buses in shunt. This device, like SVC, is also an important member of the FACTS family which are preferred to be used especially in long range transmission lines. The sole shunt capacitor, SVC, and STATCOM improves the security and quality of power by increasing the margin of system voltage stability and capacity of both active and reactive power transfer. The advantage of reactive power compensation mainly depends on the optimal size and placement of the compensator devices. Locating these controllers in shunt in all necessary load buses is nearly impossible and also unnecessary due to heavy economical issues. Thus, achieving the optimal number, capacity and the location of shunt var compensator can maximize the voltage profile improvement while maintaining requested high-quality operating conditions.

In recent years a variety of techniques with many population-based optimization algorithms have been used to solve shunt FACTS devices location problem. Lagrange multiplier techniques and simulated annealing algorithm used for optimal SVC planning and voltage stability enhancement. Nonlinear interior point [2] and fuzzy based optimization approach [3] for determining the optimal location TCSC and SVC devices has been done by using Sensitivity of total real power transmission loss techniques In [4] Harmony search algorithm (HSA) and Genetic Algorithm (GA) have applied to determine optimal location of FACTS devices such as UPFC, TCPAR and SVC, in a power system to improve power system stability. Genetic algorithm was used to improve the loadability of the system by using four different devices (TSCS, TCVR, TCPST, SVC) in [5]. In [6], the fuel cost along the loadability of the system is improved significantly by using SVC devices for the appropriate load buses. There are also some studies regarding the voltage profile improvement and reducing power loss which use particle swarm optimization (PSO) and genetic algorithm (GA) [7]. In [8] it is presented that SVC and TCSC devices are used with aim to optimize a multi objective voltage stability problem. There is also an algorithm based on the SA [9] is used to fix the location and type of shunt Var sources and their settings for various conditions with aim to improve security by using SA. It is presented the locating the FACTS devices optimally in order to improve security of the power systems by using HSA [10]. Optimal allocation and sizing of SVC devices are applied to a transmission system in by using Improved Harmony Search Algorithm (IHSA) [11].

The most suitable location of FACTS devices has been achieved by sensitivity based approach such that loss sensitvity index [12-13], determined of weakest voltage buses[14-15], modal analysis [16-17] tangent vector [18] and in random methods [11-19]. Furthermore, achievning the best device types is also possible by using heuristic methods.

In this work, an optimal allocation method is processed randomly and dynamically by he meta–heuristic algorithm DSA. The proposed technique simultaneously choses the best type and location of the compensator continually in during optimization process. Further, the proposed methodology is compared with voltage sensitivitiy analysis which is used to determine the critical load buses in a power system numerically. The obtained results using the DSA algorithm are then compared with the ABC optimization method for validation.

2. Modelling of the shunt FACTS devices

As aforementioned, this work focuses on the optimal settings and location of two types of shunt FACTS devices, the SVC and the STATCOM. The modeling of these devices used in this paper is given in detail below.

2.1 SVC susceptance model

In this paper , for study OPF the reactive power injection at the load buses is shown in Figure 1.
As can be seen from the figure, SVC can be modeled as an adjustable susceptance. SVC, which output is designed to switch capacitive or inductive current in terms of maintaining the stability of power system by controlling parameters such as load bus voltages.

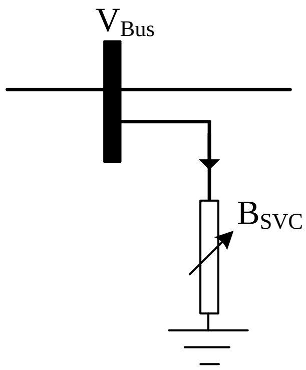

Figure 1. Susceptance model of SVC

The reactive power amount which is injected or absorbed by the SVC (Q_{svc}) for the bus k (Q_k) can be written as,

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} \tag{1}$$

where V_k and B_{SVC} are voltage of bus k and the equivalent susceptance value of SVC device, respectively.

2.2 STATCOM model

STATCOM is a similar device to SVC which can regulate the voltage profile of the load buses better compared to SVC. It consists of a DC capacitor and an inverter that can be connected to the line in parallel. The circuit modeling of the device is shown in Figure 2.

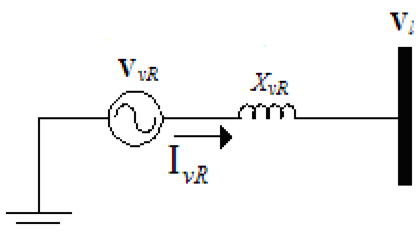

Figure 2. STATCOM equivalent circuit

The main load flow equation regarding to device can be presented as (2) and (3), thus the expression for the shunt system shown in Figure 2 is given by:

$$E_{vR} = V_{vR}(cos\delta_{vR} + j\ sin\delta_{vR}) \tag{2}$$

$$S_{vR} = P_{vR} + jQ_{vR} = V_{vR}Y_{vR}(V_{vR}^{*} - V_{l}^{*}) \tag{3}$$

where V_{vR} and Y_{vR} represents voltage source and the admittance of the STATCOM, respectively.

3. Formulation of optimal power flow problem

In this paper, the main goal is optimizing one or more objective functions while fulfilling a number of constraints that power flow, voltage magnitude of generators and load buses, shunt VAR compensator value, reactive power generation, transformer taps setting etc.

The general formulated is as follows:

Optimize: *f(x, u)* with the subject of: *g(x,u) = 0* and *h(x,u) ≤ 0* in accordance with,

$$x = [P_{Slack}\ V_L\ Q_G\ \ S_l] \tag{4}$$

where *x* denotes the state variables including the active power value of the slack bus P_G, voltage of all PQ buses V_L, generation of reactive power Q_G and transmission line loading S_l

$$u = [P_G\ \ V_G\ \ Q_C\ T] \tag{5}$$

u represents the variable vector for the elements including the active power P_G, generator voltage V_G, the reactive power of shunt VAR compensators Q_C and tap values of the tap change transformers *T*, *f* and *g* represents the objective function and the load flow equations respectively, *h* indicates the parameter limits of the system.

3.1. System constraints

Let *g*(*x*, *u*) =0 , be set of all equations related to load flow, the formulation could be easily written follows as,

$$P_{G_i} - P_{D_i} - \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) + P_{injFACTS_i} \tag{6}$$

$$Q_{G_i} - Q_{D_i} - \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) + Q_{injFACTS_i} \tag{7}$$

where P_{Gi} and Q_{Gi} are the the active and reactive power of all PV buses, P_{Di} and Q_{Di} are the active load and reactive load demand of bus *i*. The elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij} as magnitude and angle respectively. $P_{injFACTSi}$ and $Q_{injFACTSi}$ are the active power and reactive power injected to bus *i* respectively.

The generators voltages, active power and reactive power values can be limited by the user as given below,

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \qquad i = 1, \dots\dots, N_G \tag{8}$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \qquad i = 1, \ldots \ldots, N_G \tag{9}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad i = 1, \ldots \ldots, N_G \tag{10}$$

where N_G defines the number of generators including the slack bus.

The maximum and minimum limits of tap settings regarding the transformer is given by,

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad i = 1, \ldots \ldots, N_T \tag{11}$$

where N_T defines the number of tap changer transformers

The maximum and minimum reactive power that can be injected or absorbed by compensators are defined by the user as,

$$Q_{Ci}^{min} \leq Q_{Ci} \leq Q_{Ci}^{max} \qquad i = 1, \ldots \ldots, N_{QG} \tag{12}$$

where N_{QC} defines the number of shunt compensators

3.2.Security constraints

The load bus voltage constraints and the maximum value of loadability capacity of the transmission line is,

$$_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max} \qquad i = 1, \ldots \ldots, N_{VL} \tag{13}$$

$$S_{Li} \leq S_{Li}^{max} \qquad i = 1, \ldots \ldots, N_{SL} \tag{14}$$

where N_{PQ} *and* N_L represents the number load bus voltage and the number transmission line loading respectively.

4. Sensitivity analysis

The sensitivity analysis is applied to the power system with the purpose of determining bus number in which the most sensitive to the change in reactive power in terms of establishing SVC devices in the best locations. Shunt compensation is effective in improving voltage stability and V-Q sensitivity analysis is required to specify the location SVC devices in order to achieve the best efficiency.

The Jacobian matrix of the power system is used quite often in sensitivity analysis [21]. The diagonal elements of the matrix correspons to the steady state stability indices while the diagonal elements of the inverse reduced Jacobian matrix correspons to the sensitivities of the bus voltages. Sensitivity analysis is applied to load buses and positive sensitivity index indicates reduced stability limit as negative sensitivity indicates instability. The differentiation of voltage value is described as an equation of the J matrix and the variation of reactive power.

$$\Delta V = J_R^{-1} \Delta Q \tag{15}$$

where $J_R = [J_4 - J_3 \; J_1^{-1} \; J_2]$ is the reduced jacobian matrix of the system.

5. Application of DS algorithm for optimal location of SVC and STATCOM devices

5.1. DS Algorithm

DS, a newly developed optimisation algorithm that generates the Brownian-like random-walking movement used for migration by a living organism, states that the quality and productivity of the nutrient sources found in the nature like prairies and lakes may vary depending on the climate changes in a year, decade or century. Creatures migrate seasonally to find quality food sources and to survive famine. This conduct ensures that organism is transported to a new environment where the nutrition source is of a high quality and variety.

The migrating organisms form a super-organism made up of many individuals, and the super-organism begins to relocate, moving to areas containing high-quality nutritional sources. The motion of a super organism can be defined by a Brownian-like random-walk model. The action of superorganisms has been modeled using a set of computational sense algorithms such as PSO, cuckoo search, ant colony, and artificial bee colony. A few predatory species that have previously moved or migrated to an area control its fertility. In another saying , if a superorganism wants to move to a new site that can get together its needs, this superorganism locates in this new site for a while, at least. But, if a more fruitful area is found, the superorganism lasts its migration Pseudo-code showing the function of DS algorithm is given in Figure 3[22].

N: *The size of the population, where i*={1,2,3,…,N}
D: *The dimension of the problem*
G: *Number of the maximum generation*

Superorganism=initialize ( ), ***where*** *Superorganism*=[*ArtificialOrganism$_i$*]
y_i = *evaluate*(*ArtificialOrganism$_i$*)
for *cycle* =1:G ***do***
    donor= $SuperOrganism_{Random_{Shuffling(i)}}$
    scale= *randg* [2 * *rand*$_1$]x (*rand*$_2$- *rand*$_3$)
    StopoverSite= *Superorganism*+ *Scale* *(*donor* – *superorganism*)
    $p_1 = 0.3 * rand_4$, $p_2 = 0.3 * rand_5$
    if $rand_6 < rand_7$ ***then***
        if $rand_8 < p_1$ ***then***
        r=*rand (N,D)*
            for *counter*1= 1: *N* ***do***
                $r(Counter1,:) = r(Counter1,:) < rand_9$
            end for
        else
        r =*ones* (*N*,*D*)
            for *counter*2= 1: *N* ***do***
                $r(Counter2, randi(D)) = r(Counter2, randi(D)) < rand_{10}$
            end for
        endif
    else
        r =*ones* (*N*,*D*)
        for *Counter*3= 1: *N* ***do***
            d=*randi*(*D*,1,[$p_2 * rand * D$])

for *Counter*4= 1: *size*(*d*) **do**
$r(Counter3, d(Counter4)) = 0$
endfor
endfor
endif
$individuals_{I,J} \leftarrow r_{I,J} > 0 \mid I \epsilon\, i, J\, \epsilon\, [1, D]$
$StopoverSite(individuals_{I,}) := Superorganism(individuals_{I,})$
if $StopoverSite_{i,j} < low_{i,j}$ *or* $StopoverSite_{i,j} > up_{i,j}$ **then**
$StopoverSite_{i,j} := rand * (up_j - low_j) + low_j$
endif
$y_{SuperoverSite;i} = evaluate\ (StopoverSite_i)$
$$y_{Superorganism;i} = \begin{cases} y_{Stopoversite;i} & \textbf{if} \quad y_{Stopoversite;i} < y_{Superorganism;,i} \\ y_{Stopoversite;i} & \textbf{else} \end{cases}$$
$$Artificialorganism_i = \begin{cases} StopoverSite_i & \textbf{if} \ y_{Stopoversite;i} < y_{Superorganism;,i} \\ Artificialorganism_i & \textbf{else} \end{cases}$$
endfor

Figure 3. Pseudo-code of the proposed DS Algorithm.

5.2. Implementation of DSA in OPF

In DS Algorithm, N number of artificial organisms composed of D components determined initially forms a super organism. The super organism represents the candidate solution sets consist of OPF variables such as generator bus voltage, generation active power, load tap changer and shunt capacitance values. The fitness values of each solution set that consists the super organism are calculated and determined by applying the load flow equations. In [23], more knowledge on solving the optimal power flow problem with the algorithm can be found.

6. Results and discussion

The proposed method is applied to IEEE 30 bus [24] power system. The objective function of the system is considered to have only one objective by achieving the optimal placement of SVC and STATCOM devices at first. The objective functions; power loss, voltage deviation and voltage stability index are minimized by the ABC and DSA algorithm. SVC and STATCOM devices are randomly located dynamically during the optimization process. Thus, the best location and the best suitable device types are determined by the proposed method. The placement of these devices are decided randomly by the proposed algorithms and results are given by Table 1. There are two shunt capacitors which generate total reactive injected power 23.3 MVAR in the base condition of the test system. In during the optimization process, the total reactive power of the randomly located devices has been limited 20 MVAR.

The minimum power loss is obtained by placing 2 SVC on buses 15 and 20 with ABC. The DSA has specified the best location and the best suitable devices type a Statcom and a SVC device on buses 15 and 20 respectively. The minimum voltage deviation is obtained by placing SVC and STATCOM on buses 19 and 24 respectively with ABC. Furthermore, the DSA has specified the best location and the best suitable devices types, STATCOM devices on buses 19 and 24 respectively. In order to improve voltage stability, SVC and STATCOM devices are located on the buses 19 and 21 respectively with ABC; two SVC located devices are located on the buses 19 and 21 respectively with DSA.

6.1. Power Loss Minimization - Case 1

The proposed algorithm also considers the transmission loss minimization by selecting optimal location of FACTS devices. The real power losses can be calculated using,

$$f_1 = \sum_{i=1}^{N_L} g_l [V_k^2 + V_m^2 - 2V_k V_m \cos(\delta_k - \delta_m)] \quad (16)$$

where g_i is the conductance of the ith line; V_k and $V_m$are the voltage magnitude at the end buses k and m of the ith line, respectively, and δ_k and δ_m are the voltage phase angle at the end buses k and m [13].

In order to optimize the system, variable shunt devices are installed instead of using fixed shunt capacitors. At the end of the process, the active power loss is optimized as shown in Table 1. It appears that the minimum active power loss has been reduced from 5.600 MW to 3.045 MW and 3.041 MW by ABC and DSA, respectively. The reduction achieved by proposed algorithm method is equivalent to 45.69%.

It is shown in Table 1 that the proposed algorithm converges to better results when compared to the method ABC algorithm in Table 1. The convergence chart is given by Figure 4

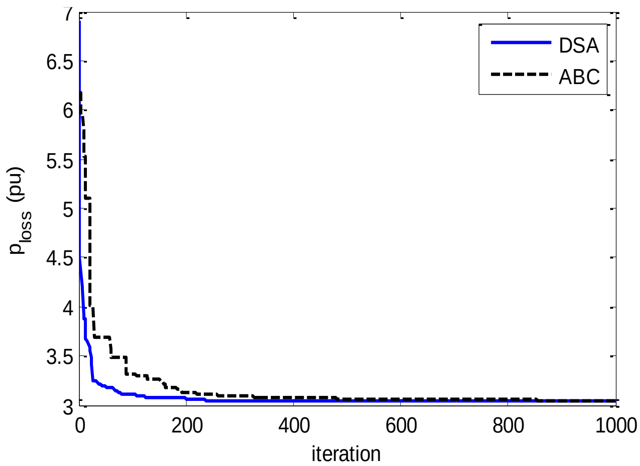

Figure 4. Convergence curves of two optimization algorithm for minimizing active power loss

6.2. Voltage profile improvement - Case 2

In this paper, the optimal location and size of FACTS devices is set by observing minimum value of voltage deviation(VD). Voltage deviation is calculated as follows,

$$f_2 = \sum_{i=1}^{N_{PQ}} |V_i - 1| \quad (17)$$

N_{PQ} denotes number load bus.

In order to optimize the voltage profile, given by (17), variable shunt devices are installed in different load buses. The shunt devices are placed randomly by the proposed algorithm and results are compared in Table 1. By using ABC algorithm, the minimum voltage deviation is obtained by placing SVC and STATCOM on buses 19 and 24 respectively. The optimal result for voltage deviation 0.0824 p.u is obtained by injecting 10.15 MVAR total reactive power.

By using proposed DSA methodology, the minimum voltage deviation is obtained by placing STATCOM devices on buses 19 and 24 respectively. The optimal result for voltage deviation is obtained 0.081 p.u by injecting 12.72 MVAR total reactive power. The objective function is reduced from 0.584 p.u down to 0.081 p.u. The obtained solution set converges to a better result than ABC method by 0.001 p.u which is better than initial value. This reduction is equivalent to 86.13%.It is shown that the proposed algorithm converges better results when compared to the ABC algorithm in Table 1. Convergence characteristics of the algorithms are given by Figure 5.

6.3. Voltage stability enhancement - Case 3

The voltage stability index is defined by the voltage values of a system without load and voltage collapse conditions [26].

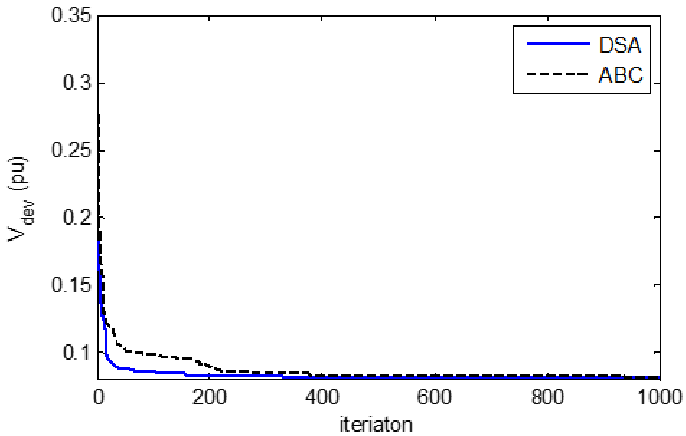

Figure 5. Convergence curves of two optimization algorithm for voltage deviation minimization

6.3.1. L_{index} calculation

The bus types in power systems can be divided in two parts as generator (PV and Slack) and load (PQ) buses. The power system expressed in the form through Kirchoff Law:

$$I_{system} = \begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \quad (18)$$

Subscript L means load bus, and G means generator bus.Here, $\mathrm{Z_{LL}} = \mathrm{Y_{LL}^{-1}}, \mathrm{A} = -\mathrm{Z_{LL}}\mathrm{Y_{LG}}$. For any load bus though the equation (21), the voltage of the bus is known as:

$$V_{oj}^* = -\sum_{k\epsilon G} A_{jk} V_k \tag{19}$$

The indicator of the voltage stability of the load bus j can be easily obtained.

$$L_j = \left| 1 + \frac{V_{oj}^*}{V_j^*} \right| \tag{20}$$

The objective function used for this case is given below,

$$f_3 = max(L_j) \tag{21}$$

In order to optimize the Voltage Stability Index variable shunt devices are installed by the minimum number and size of Var instead of using fixed shunt capacitors likewise. Voltage stability analysis results are given by Table 2.

In the proposed methodology by using ABC algorithm, the voltage stability index is obtained by placing SVC and STATCOM on buses 19 and 21 respectively. The optimal result for the voltage stability index 0.1095 is obtained by injecting 15.55 MVAR total reactive power. Lindex optimization achieved by DS algorithm is obtained by placing two SVC on buses 19 and 21 respectively. The optimal result for L_{index} 0.0107 is obtained by injecting 16.56 MVAR total reactive power which is 50% better than the initial condition.

The proposed algorithm converges better results when compared to the ABC given by Figure 6.

Table 1. Optimal settings of control variables for different cases of ABC and DSA

Variables	**Initial**	**Case I**		**Case II**		**Case III**	
		ABC	**DSA**	**ABC**	**DSA**	**ABC**	**DSA**
V1	1.05	1.100	1.100	0.995	0.995	0.950	0.950
V2	1.04	1.097	1.097	0.981	0.980	0.977	0.975
V5	1.01	1.079	1.079	1.018	1.019	1.100	1.100
V8	1.01	1.086	1.086	1.020	1.022	1.100	1.100
V11	1.05	1.056	1.075	0.969	0.957	0.950	0.950
V13	1.05	1.020	1.033	1.050	1.058	0.950	0.950
T11	1.078	1.100	1.100	0.979	0.967	1.100	1.100
T12	1.069	1.041	1.008	0.900	0.900	1.100	1.100
T15	1.032	0.952	1.073	1.055	1.060	1.067	1.080
T36	1.068	1.036	1.040	0.952	0.970	0.900	0.900
Q10	19.0	-		-	-	-	-
Q12	-	-		-	-	-	-

Q15	-	11.21 SVC	10.04 STATCOM	-	-	-	-
Q19	-	-	-	6.73 SVC	8.60 STATCOM	2.15 STATCOM	4.21 SVC
Q20	-	2.53 SVC	-	-	-	-	-
Q21	-	-	-	-	-	13.42 SVC	11.35 SVC
Q24	4.3	-	9.68 SVC	3.42 STATCOM	4.12 STATCOM	-	-
P_{loss}	5.842	3.045	3.041	0.068	0.063	0.674	0.682
VD	1.160	0.599	0.612	0.082	0.081	0.278	0.291
L_{max}	0.214	1.321	1.341	0.892	0.923	0.109	0.107
$\sum Q_C$	23.3	13.74	19.72	10.15	12.72	15.57	16.56

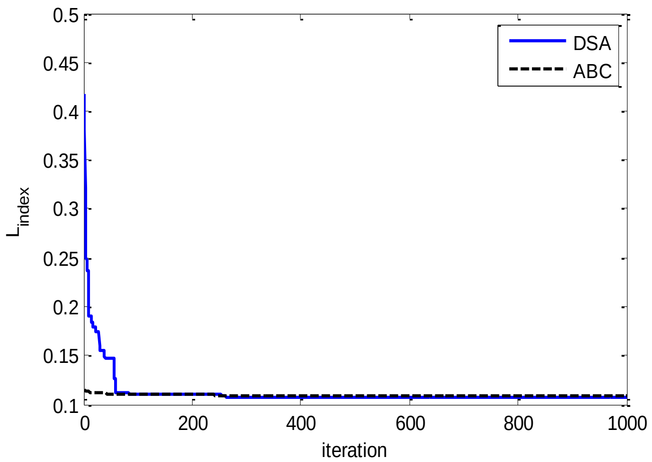

Figure 6. Convergence curves of two optimization algorithm for voltage stability index minimization

Table 2. Results of sensitivity analysis for 30 bus system

	Reactive loading (%125)	**Reactive loading (%150)**	**Reactive loading (%200)**
ΔV_3	0.0553	0.0568	0.0576
ΔV_4	0.0357	0.0368	0.0376
ΔV_6	0.0202	0.0210	0.0215
ΔV_7	0.0559	0.0585	0.0599
ΔV_9	0.0861	0.0900	0.0932
ΔV_{10}	0.1175	0.1276	0.1371
ΔV_{12}	0.0806	0.0865	0.0900
ΔV_{14}	0.2222	0.2392	0.2499
ΔV_{15}	0.1510	0.1641	0.1738
ΔV_{16}	0.1891	0.2036	0.2140
ΔV_{17}	0.1704	0.1852	0.1982
ΔV_{18}	0.2631	0.2867	0.3054

ΔV_{19}	0.2704	0.2958	0.3174
ΔV_{20}	0.2510	0.2734	0.2926
ΔV_{21}	0.1660	0.1829	0.1993
ΔV_{22}	0.1666	0.1832	0.1993
ΔV_{23}	0.2599	0.2845	0.3049
ΔV_{24}	0.2360	0.2628	0.2893
ΔV_{25}	0.3758	0.4148	0.4538
ΔV_{26}	**0.8703**	**0.9799**	**1.0970**
ΔV_{27}	0.3524	0.3846	0.4160
ΔV_{28}	0.0564	0.0586	0.0602
ΔV_{29}	0.7283	0.8033	0.8789
ΔV_{30}	**0.8227**	**0.9168**	**1.0145**

6.3.2. Validation of proposed method

In this section, the performance of proposed methodology is investigated in heavy loading conditions of the power system where the total reactive load is increased by 25%, 50% and 100%. The results have been compared with the method of voltage sensitivity analysis. Buses 26 and 30 that are critical buses determined by sensitivity analysis whose sensitivity index are the highest as shown in Table 2. By using proposed DS algorithm and ABC method, the best location and suitable device types on each loading conditions for voltage deviation objective function are achieved. The results can be found in Table 3.

Table 3. Optimal settings and controls for heavy loading conditions for ABC and DSA

Variables	Case 1		Case II		Case III	
	ABC	DSA	ABC	DSA	ABC	DSA
V1	1.100	1.100	1.100	1.100	1.100	1.100
V2	1.072	1.091	1.082	1.100	1.100	1.100
V5	1.065	1.062	1.100	1.098	1.100	1.100
V8	1.050	1.058	1.100	1.100	1.100	1.100
V11	1.018	1.036	1.068	1.100	1.100	1.100
V13	1.055	1.084	1.100	1.098	1.100	1.082
T11	1.060	1.073	1.045	1.089	1.100	1.100
T12	0.900	0.900	0.900	0.900	0.900	0.900
T15	1.100	1.100	1.100	1.100	1.100	1.100
T36	1.050	1.100	1.100	1.100	1.100	1.100
Q10	-	-	-	-	-	-
Q12	-	-	10.21	-	10.21	-
Q15	-	-	-	-	-	-
Q19	11.45	13.10	6.14	-	-	-
Q20	-	-	-	-	-	-
Q21	-	-	-	9.65	-	11.38
Q24	8.20	7.90	-	8.22	9.79	8.62

VD	0.109	0.107	0.162	0.158	0.221	0.203
Lmax	1.013	1.022	1.041	1.039	1.142	1.148
ΣQ_C	19.65	20	16.35	17.87	20	20

As shown in Table 4, the numerical sensitivity analysis method nominates buses 26 and 30 as critical buses in static power system. However, Table 4 also shows that the proposed methodology can converge to different suitable solution sets in different operation conditions by deciding the critical load buses for voltage sensitivity optimization dynamically.

Table 4. Device locations and types for heavy loading

	Reactive loading (%125)	**Reactive loading (%150)**	**Reactive loading (%200)**
Sensitivity analysis result	26 30	26 30	26 30
ABC	19 (SVC) 24 (STATCOM)	12 (SVC), 19 (STATCOM)	12(STATCOM) 24(STATCOM)
DSA	19 (STATCOM) 24 (STATCOM)	21 (STATCOM), 24 (SVC)	21(STATCOM) 24(STATCOM)

7. Conclusions

In this paper, a successful implementation of DS algorithm is provided with novel methodologies applied for the optimal locations of SVC and STATCOM devices. Voltage stability enhancement, minimization of the real power loss and voltage deviation are considered as objective functions for the proposed methodology. The most suitable device locations and types are decided by the proposed algorithm itself, where their optimal values are achieved for each objective functions. Thus, the performance of the proposed method is validated on heavy loading conditions where the location of devices are chosen with the objective of optimizing system voltage deviation dynamically when compared to numerical sensitivity analysis technique. The proposed DS algorithm was compared with another heuristic algorithm which that is name the Artificial Bee Colony Algorithm(ABC). And so it is concluded that DS Algorithm provides better solution performance, robustness and superiority and can effectively be used in large scaled, non-linear and non-convex problems of power system optimization owing to its high solution quality and rapid convergence speed.

References

[1] Chang , C. S., Huang, J. S., "Optimal SVC placement for voltage stability reinforcement", Electric Power Systems Research, 42 (1997) : 165-172.

[2] Biansoongnern, S., Chusanapiputt, S., Phoomvuthisarn, S., "Optimal SVC and TCSC placement for minimization of transmission losses", International Conference on Power System Technology 2006.

[3] Bhattacharyya, B., Gupta, V. K., "Fuzzy genetic algorithm approach for the optimal placement of flexible AC transmission systems devices in a power system", Electric Power Components and Systems, 42(8) (2014) : 779-787.
[4] Parizad, A., Khazali, A., Kalantar, M., "Application of HSA and GA in optimal placement of FACTS devices considering voltage stability and losses", Electric Power and Energy Conversion Systems, 2009 : 1-7.
[5] Gerbex, S., Cherkaoui, R., Germond, A. J., "Optimal location of multi-type FACTS devices in power system by means of genetic algorithm", IEEE Transactions on Power Systems : A Publication of the Power Engineering Society, 16(3) (2001) : 537-544.
[6] Abacı, K., Yamaçlı, V., Akdağlı, A., "Optimal power flow with SVC devices by using artificial bee colony algorithm", Turkish Journal Of Electrical Engineering & Computer Sciences, 2016, DOI: 10.3906/elk-1305-55.
[7] Farsangi, M. M., Nezamabadi-Pour, H., Lee, K. Y., "Multi-objective VAR planning with SVC for a large power system using PSO and GA", Proceeding of Power System Conference & Exposition, (2006) : 274-279.
[8] Benabid, R., Boudour, M., Abido, M. A., "Optimal location and setting of SVC and TCSC devices using non-dominated sorting particle swarm optimization", Electric Power Systems Research, 79 (2009) : 1668-1677.
[9] Hsiao, Y. T., Liu, C. C., Chiang, H. D., "A new approach for optimal VAR sources planning in large scale electric power systems", IEEE Transactions on Power Systems : A Publication of the Power Engineering Society, 8(3) (1993) : 988–996.
[10] Kazemi, A., Parizad, A., Baghaee, H., "On the use of harmony search algorithm in optimal placement of FACTS devices to improve power system security", Proceedings of the IEEE Eurocon, Tehran, Iran, (2009) : 570-576.
[11] Sirjani, R., Mohamed, A., Shareef, H., "Optimal placement and sizing of static VAR compensators in power systems using improved harmony search algorithm", Przegląd Elektrotechniczny, 87(7) (2011) : 214-218.
[12] Samimi, A., Gölkar, M. A., "A novel method of optimal placement of FACTS based on sensitivity analysis for enhancing power sysyem static security", Asian Journal of Applied Sciences , 5(1) (2012) : 1-19.
[13] Bhasaputra, P., Ongsakul, W., "optimal power flow with multi-type of FACTS devices by hybrid TS/SA approach," 2002 IEEE International Conference on Industrial Technology, (1) (2002) : 285-290.
[14] Musirin, I., Abdul Rahman, T. K., "Novel Fast Voltage Stability Index (FVSI) for voltage stability analysis in power transmission systems", Student Conference on Research and development (SCORED), (2002) : 265-268.
[15] Sode-Yome, A., Mithulananthan, N., "Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement", International Journal of Electrical Engineering Education, 41. 10.7227/IJEEE.41.2.7.
[16] Mansour, Y., Xu, W., Alvarado, F., Rinzin, C., "SVC placement using critical modes of voltage instability", IEEE Transactions on Power Systems, 9(2) (1994) : 757–763.
[17] Mohamed, A., Shareef, H., Sirjani, R., "Optimal allocation of shunt VAR compensators in power systems using a novel global harmony search algorithm", International Journal of Electrical Power & Energy Systems, 43(1) (2012) : 562-572.

[18] Zambroni de Souza, A. C., "Tangent vector applied to voltage collapse and loss sensitivity studies", Electric Power Systems Research, 47(1), (1998) : 65-70.

[19] Cai, L. J., Erlich, I., "Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms", Power Systems Conference and Exposition, IEEE PES (1) (2004) : 201-207.

[20] Acha, E,. Claudio, R., Ambriz-Perez, H., Angeles-Camacho, C., "Facts modelling and simulation in power networks", New York: John Wiley and Sons, 2004.

[21] Mahdad, B., Bouktir, T., Srairi, K., "Strategy of location and control of FACTS devices for enhancing power quality". Mediterranean Electrotechnical Conference; 16-19 May 2006, Malaga, Spain: IEEE. (2006) : 1068-1072.

[22] Çivicioğlu, P., "Transforming geocentric cartesian coordinates to geodetic coordinates by using differential search algorithm", Computers & Geosciences, 46 (2012) : 229-247.

[23] Abaci, K., Yamaçlı, V., "Differential search algorithm for solving multi-objective optimal power flow problem", 2015, IJEPES, DOI: 10.1016/j.ijepes.2015.12.021

[24] Alsac, O., Sttot, B., "Optimal load flow with steady state security", IEEE Trans. on Power Apparatus and Systems PAS-93 (1974). : 745–751.

[25] Udgir, S., Varshney, S., Srivastava, L., "Optimal placement and sizing of SVC for voltage security enhancement", International Journal of Computer Applications, 32(6) (2011) : 44-51.

[26] Kumaraswamy, I., Ramanareddy, P., "Analysis of voltage stability using L-Index method", International Journal of Electrical Engineering, 4(4) (2011) : 483-498.