Optimization of Size and Cost of Static VAR Compensator using Dragonfly Algorithm for Voltage Profile Improvement in Power Transmission Systems

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Abstract- Voltage stability is a major concern in power transmission systems due to mismatch between power generation and demand. Hence maintenance of voltage profile within the acceptable limit becomes a challenging task. In this paper the weak buses to implement the reactive power compensators are identified by applying eigenvalue decomposition technique on partitioned Y-admittance matrix. The Dragonfly algorithm is used to optimize the size and cost of the SVC with the overload factor, voltage deviation and VAR regulation as the design constraints. The dragonfly algorithm is implemented on IEEE 14 and 30 bus systems and the results obtained with and without the placement of Static VAR Compensators are compared with other algorithms to show its effectiveness. To emphasize the possibility to integrate the renewable energy and to demonstrate its effectiveness a 2 MW solar generation is installed at one of the weakest buses of IEEE 30 bus system and the improvement in voltage profile is shown. The further scope of this work is to implement the wind generators at the weakest buses so as to reduce the electrical distance between the generators and the farthest load buses and to secure the system from voltage collapse.

Keywords Voltage profile, Static VAR Compensator, Dragonfly algorithm, Eigenvalue decomposition, Y-admittance matrix, wind generators

1. Introduction

In general there is a major difference between the power generation and the power requirement. This power deficit leads to many power quality issues out of which voltage stability is important. If voltage violation is not addressed immediately it may lead progressively to a blackout. Hence maintenance of voltage profile within the nominal limits by proper reactive power compensation becomes essential. Many researchers have investigated to optimize the location to implement the FACTS devices for reactive power compensation. Various mathematical optimization techniques and meta-heuristic techniques are followed in the literature. In particular the meta-heuristic techniques have gained the interest of the researchers for its computational flexibility and solution accuracy.

FACTS devices can improve the transmission capacity and flexibility in power control [1]. FACTS are capable of both steady state and dynamic control of power flow by controlling the various parameters on the considered transmission network [2]. There are many types FACTS devices such as shunt controlled Static VAR Compensator (SVC) and static Compensator (STATCOM), series controlled Thyristor Controlled Series Compensator (TCSC) and Static Synchronous Series Compensator (SSSC) and shunt-series controlled Unified Power Flow Controller (UPFC). Shunt controlled SVC is considered for the implementation because of its remarkable features such as good stabilization of voltage particularly in weak zones, increased transmission capacity with minimized losses, reduced need for installation of new lines, better transient stability limits with increased damping capability for negligible disturbances. If SVC is installed in right location, it either absorbs or generates the reactive power so as to maintain the required voltage with reduction in losses.

Many techniques were presented in the literature to obtain the optimal location of SVC. Few such techniques are Genetic algorithm (GA), Artificial Immune System (AIS), Particle Swarm Optimization (PSO) and Simulated Annealing (SA) [3]. In [4] SVC is allocated on the basis of reactive power spot price under contingency condition. Simulated annealing is used to locate the SVC sources to support the load conditions that vary [5]. GA is considered to implement only a single SVC in the given network in which the objective is formulated to minimize the voltage variation, line losses and the installation cost [6]. GA is applied to identify the location and setting of the SVC so as to improve the system stability margin [7].

An exact location for SVCs are identified using AIS method in order to reduce the losses and to improve the overall voltage profile [8][9]. Particle swarm optimization is implemented to allocate the SVC optimally in the considered test system so as to minimize the real power losses and voltage variation [10][11][12]. Improved harmony search technique is used in order to obtain the optimal location and size of SVC for the given power system network so as to improve the voltage profile and to reduce the power losses [13][14]. In [15] Teaching Learning Based Optimization (TLBO) is applied to locate and to change the setting of the SVC with an objective to reduce losses and cost of installation. SA in combination with goal attainment method is used to optimally size and allocate either TCSC or SVC such that the losses and cost are minimized with an increase in system security against voltage instability [16]. Non-dominated Sorting PSO is applied to obtain the location and setting of TCSC and SVC optimally and to minimize the active power losses and voltage variation [17]. Hybrid PSO is used to reduce the complexity of the problem formulation. Setting and allocation of FACTS are defined by PSO whereas sequential quadratic programming is employed to gain control over various operational states of the considered network [18].

Modal analysis is used to identify the weak areas and SA is used to obtain the level of compensation required [19]. In [20] Differential Evolution Algorithm (DEA) is used to locate and set the SVC to safeguard the system and to reduce the losses. Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC) and Optimal Unified Power Flow Controller (OUPFC) are considered to reduce the losses and overload factor [21]. A method using PSO and GA is combined to plan the VAR compensation [22]. Non-linear programming and mixed-integer nonlinear programming are applied to allocate and set the rating of FACTS optimally [23]. The modal analysis is used to identify the locations for SVC in order to withstand utmost load with reduced investment cost. The risk index value for various contingencies is presented [24].A detailed survey for the allocation of FACTS using PSO in terms of objectives, constraints, parameter settings is performed [25].

A survey on integration of renewable energy in real time applications for power quality issues is performed and is presented. Photovoltaic plant in grid connection is considered and the variation of voltages that occur abruptly is measured [26]. A hybrid genetic algorithm and linear programming are employed to give protection to micro grid through optimal rating and curve of relays [27]. A coordinated control accomplished by PID controller in a hybrid system consisting of wind generators, diesel engine, solar generation, battery storage and superconducting magnetic energy storage is discussed. Flower pollination algorithm is used to optimize the parameters of the controller [28]. The control of grid connected photovoltaic system is discussed. An inverter with maximum power point tracking is involved for the optimal real and reactive power injection to the grid[29]. Genetic algorithm is used to optimize the sort and rating of renewable generators in Hokkaida in japan [30]. A Control strategy for SVC is formulated to improve power quality and stability for unbalanced loads [31]. The solar management of Van in turkey is investigated. The parameter such as temperature of air, insolation period are considered in addition to solar radiation [32]. A new technique is proposed for STATCOM which depends on ac side voltage doubling voltage source inverter as a result of which reactive power support can be increased [33].

Dragon fly algorithm (DA) and its implementation for single objective and multi objective is discussed in [34]. The significance of basic circuit laws and its impact on Y admittance matrix for the given power system network is discussed. Based on the circuit concepts and the electrical attractions existing between generator to generator, generator to load and load to load, Y admittance matrix is partitioned. Eigenvalue decomposition is implemented on load to load attraction sub matrix in order to identify the weak buses [35]. The possibility of classification of a given network either as a weak network or as a strong network based on their electrical distance and circuit laws are shown [36][37].

The main aim of this paper is to obtain the optimal location for SVC using Eigen Value Decomposition (EVD) technique on partitioned Y-admittance matrix. This EVD technique determines the eigenvalues for all the load buses and the load buses are ranked based on the ascending order of the eigenvalues. The buses with least values are the weak buses and these are the optimal locations to implement the reactive power compensators. The optimization of size and cost of SVC for voltage profile improvement in transmission system is obtained using dragonfly algorithm. In the formulation of the objective function line flows, voltage deviation and reactive power limit are considered as the design constraints. The algorithm is implemented on IEEE 14 and 30 bus systems. The results thus obtained with and without the placement of SVCs are compared with other algorithms such as PSO, TLBO and Hybrid PSO in order to show its effectiveness. A solar generation of 2 MW is installed at one of the weak buses of IEEE 30 bus system and the improvement in voltage profile with reduced losses is shown.

The paper is organized as follows: section 2 gives the problem formulation of the objective function. Section 3 describes the dragon fly algorithm. Section 4 describes the implementation of eigenvalue decomposition technique on partitioned Y-admittance matrix to identify the weak buses. Section 5 shows the implementation details of the dragonfly algorithm on various test systems such as IEEE 14 and 30 bus systems. Section 6 discusses the results obtained using DA and gives its comparison with that of the other existing algorithms. Section 7 gives the conclusion and the future scope.

2. Problem Formulation

The main aim of the proposed method is to minimize the size and cost of the SVC and to reduce the line losses and voltage deviation so as to improve the voltage profile of the considered power transmission system. The optimal location for SVC is determined by EVD technique on partitioned Y-admittance matrix which is discussed in section 4.

2.1 Objective function:

$$Minimize F = (I_{SVC} + Pf * \|R-1\|) \quad (1)$$

where F is the value of fitness function

R – violation limit of line flows and bus voltages and is given in eqn (5)

Pf – penalty factor

$$I_{svc} = C_{svc} * S * 1000 in USD \quad (2)$$

where

I_{svc} is the optimal cost of installation of SVC in USD

The cost of SVC, C_{svc} in USD/KVAR is given by [38]:

$$C_{svc} = 0.003S^2 - 0.3051S + 127.38(USD/KVAR)$$
(3)

where

S - Operating range of SVC in MVAR

$$S = |Q_2| - |Q_1| in MVAR \quad (4)$$

In equation (4) Q_2 and Q_1 denote the line reactive power after and before the SVC installation respectively.

2.2. Constraints considered for optimization are as follows:

Violation limit of line flows and bus voltages, R is given by

$$R = \prod_{line} LOF_{line} * \prod_{bus} VSI_{bus} \quad (5)$$

where

LOF_{line} -line overload factor

VSI_{bus} - voltage stability index

2.2.1 Line Overload Factor

$$LOF_{line} = \begin{cases} 1; P_{ab} \le P_{ab}^{\max} \\ e\left(\psi\left|1 - \frac{P_{ab}}{P_{ab}^{\max}}\right|\right); P_{ab} \phi P_{ab}^{\max} \end{cases} \quad (6)$$

where

P_{ab} - power flow between buses a and b

2.2.2. Voltage Stability Index:

$$VSI_{bus} = \begin{cases} 1, (0.95 \le V_{bus} \le 1.1) \\ e^{\vartheta|1-V_{bus}|} otherwise \end{cases} \quad (7)$$

where V_{bus} - bus voltage in p.u.

υ and ψ –positive constants both with value 0.1.

2.2.3. FACTS device constraint:

$$-100MVAR \le Q_{svc} \le 100MVAR \quad (8)$$

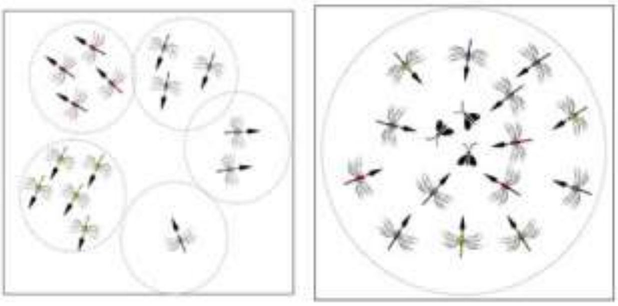
where

Q_{svc} - reactive power of SVC in MVAR

3. Overview of Dragonfly Algorithm

Dragonfly algorithm is proposed in 2015 by Seyedali Mirjalili. Dragonfly algorithm is a resultant algorithm for particle swarm optimization technique. This algorithm is grounded on the imitation of the swamped performance of dragonflies. Dragonflies are scavenging the insects like mosquitoes as food. Dragonflies basically undergo two phases, nymph and adults. In the first phase as nymph they consume aquatic insects and live for years whereas as adults on their wings they live only for few weeks. The algorithm includes both the static and dynamic activities of the dragonflies. In static behavior the swarms join in much smaller groups and hunt for small insects within a smaller boundary. In dynamic state the swarms form bigger groups and fly in a direction for longer distances. Dragonflies swarm for two major reasons such as hunting and migration. This algorithm pretends the problem as the source of food and the search agents as dragonflies. Exploration and exploitation behaviors are much similar to the two main phases of meta-heuristic optimization. These two phases are exhibited with utmost care so as to attain the optimization globally.

The illustrative demonstration of exploration and exploitation of dragonfly algorithm is given below in Fig. 1.



(a) Exploration (b) Exploitation

Fig. 1 Exploration and exploitation of Dragonfly algorithm

The three primitive principles proposed by Reynolds are the separation, alignment and the cohesion which describe the behaviour of the dragon flies along with its equations.

a) Separation denotes the collision avoidance among the individuals in the surrounding.
b) Alignment signifies the velocity matching among the individuals in the surrounding.
c) Cohesion refers to the individual tendency towards the mass centre in the surrounding.

In general the main aim of any swarm is survival for which it gets attracted towards the prey and gets distracted from the enemies. Based on the above phenomena five factors are considered so as to update the position vectors of the swarms and are given as follows.

a) Separation is given by

$$S_j = -\sum_{i=1}^{N} Y - Y_i \tag{9}$$

Where Y is the considered swarm giving the i^{th} position of the swarm in the surrounding and N is the total number of swarms.

b) Alignment is given by

$$A_j = \frac{\sum_{i=1}^{N} V_i}{N} \tag{10}$$

Where V_i gives the velocity of i^{th} swarm in the surrounding.

c) Cohesion is given by

$$C_j = \frac{\sum_{i=1}^{N} Y_i}{N} - X \tag{11}$$

Where Y is the position of the considered individual, N is the total number of surroundings, and Y_j shows the position of j^{th} individual.

d) Attraction towards the food is given by

$$F_j = Y^{+} - Y \tag{12}$$

Where Y is the position of the current individual, and Y^{+} displays the food position.

e) Distraction from an enemy is given by

$$E_j = Y^{-} + Y \tag{13}$$

Where Y is the considered individual position, and Y^{-} Shows the enemy position.

To update the position of artificial dragon flies in the search space two vectors are required : they are step (ΔY) and position (Y) vectors.

$$\Delta Y_{t+1} = (sS_j + aA_j + cC_j + fF_j + eE_j) + W\Delta Y_t A = P(1+\frac{r}{n})^{nt} \tag{14}$$

where s, a, c, are the separation weight, alignment weight and cohesion weight respectively. S_j, A_j, C_j, are the separation, alignment and cohesion of j^{th} individual. f and e are the food and the enemy factors respectively. F_j and E_j are the position of food and enemy of jth individual. w is the inertia weight, and t is the iteration count.

After calculating the step vector, the position vectors are calculated as follows:

$$X_{t+1} = X_t + \Delta X_{t+1} \tag{15}$$

Where t is the current iteration.

When the dragonflies fly using a random walk (Levy flight) when there is no solutions possible in the surrounding, the position is updated as

$$Y_{t+1} = Y_t + Levy(d) * Y_t \tag{16}$$

Where t is the considered iteration, and d is the vector dimension of the position.

3.1 Steps to implement the Dragon fly algorithm:

1. Population of the dragonflies are initialized as Y_j (j = 1, 2, ..., n).
2. Step vectors are initialized ΔY_j (j = 1, 2, ..., n) **while** the end condition is not fulfilled.
3. Objective values are calculated for all the individuals considered.
4. Food sources and enemies are updated.
5. All the weight factors such as w, s, a, c, f, and e are reorganized.
6. All the position vectors such as S, A, C, F, and E are updated using Equations from (9) to (13).
7. Surrounding radius is updated.

8. The velocity and position vectors are updated using the equations (10) and (15) respectively, if the considered individual has atleast one individual in its surrounding.

9. Else update the position vector using (16) and end if.

10. Updated positions are checked and corrected based on the boundaries of the variables.

11. End while

The flowchart of the Dragonfly algorithm for optimization of size and cost of SVC is given in Fig. 2

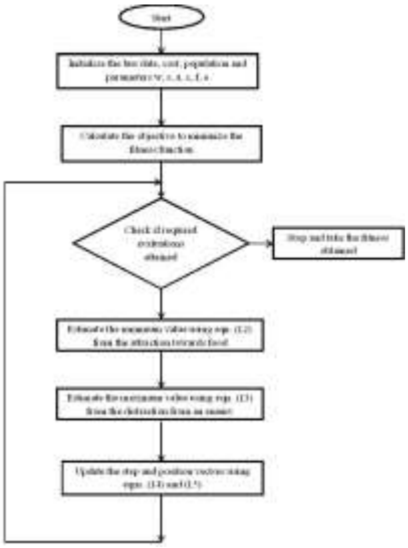


Fig. 2 Flowchart for optimization of size and cost of FACTS using DA algorithm

Dragonfly algorithm starts the optimization problem by initiating a set of solutions. The optimization problem considered in this work is to optimize the size and the cost of the SVC. The position and the step vectors of dragonflies are initialized by random values which are defined within the lower and upper bounds of the reactive power ranges. In every iteration, update of position and the step vector of every individual is carried by choosing a surrounding at an Euclidean distance between the individuals and selecting all number of individuals. This procedure is carried until the final criteria are attained.

4. Eigenvalue Decomposition Technique on Partitioned Y-admittance Matrix [35]

Circuit theory approach is an accurate method when it is required to find the weakest buses to implement the reactive power compensators. This approach is advantageous without the need for the repetitive load flow analysis unlike the other methods like voltage stability indices and continuation power flow. The circuit theory approach involves the basic circuit laws in which the maximum power that a given network can support is considered. The weakest buses thus identified are highly reliable and remain the permanent locations for the reactive power compensators until the structure of the given power system network is altered. In general the structure of a network changes either due to any contingency or outage hence until then the locations thus identified for the compensators remain the same. The circuit theory approach is a suitable method even to classify the given power system network either as a weak or strong network in terms of transmission capacity, voltage stability and transmission losses.
As per circuit theory,

$$V = Z * I \tag{17}$$

Where,
V – Voltage
I - Current
Z - Impedance of the line

From which I is given by

$$I = Z^{-1} * V \tag{18}$$

Where $Z^{-1} = Y_{bus}$

$$\text{Hence} \quad I = Y_{bus} * V \tag{19}$$

Equations (17) to (19) denote the relationship between current, voltages and the transmission impedances of the corresponding generator and load buses as per the basic circuit laws.

Y_{bus} is partitioned with respect to generator and load buses as shown in equation (20)

$$Y_{bus} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \tag{20}$$

Where,
Y_{GG} - coupling of generator-generator with dimension G × G
Y_{LG} - Load-generator coupling with dimension L x G
Y_{GL} - Generator-load coupling with dimension G x L
Y_{LL} - Load-load coupling with dimension L × L
L and G - Numbers of load and generator buses respectively

Equation (20) denotes the partitioning of the Y_{bus} matrix based on their interconnections that exist between generators and load buses without affecting the Y_{bus} elements.

Substituting (20) into (19), the equation is

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{21}$$

Where,
I_L – Load currents
I_G – generator currents
V_G – Generator voltages
V_L – Load voltages

On rearranging the equation (21)

$$\begin{bmatrix} V_G \\ I_L \end{bmatrix} = \begin{bmatrix} Z_{GG} & E_{GL} \\ N_{LG} & R_{LL} \end{bmatrix} \begin{bmatrix} I_G \\ V_L \end{bmatrix} \quad (22)$$

Where,

$Z_{GG} = Y_{GG}^{-1}$, total generator impedances accounting for total generator losses

$E_{GL} = -Y_{GG}^{-1}Y_{GL}$, generators influence over load buses which is termed as generator affinity

$N_{LG} = Y_{LG}Y_{GG}^{-1}$, negative transpose of E_{GL} matrix

$R_{LL} = Y_{LL} - Y_{LG}Y_{GG}^{-1}Y_{GL}$, Schur complement of Y_{GG} in Y and defines the electrical property of load-load attraction region.

Relationship between the Schur complement and Y-admittance matrix is given below

$$\det Y = \det Y_{GG} \det R_{LL} \quad (23)$$

Equation (23) does not change the value of the basic circuit equations (17) to (20) above, in any way.

Matrix R_{LL} denotes the equivalent admittance of load buses with influences of all generator buses eliminated. Impact of the structure of load-load electrical attraction region on load flow is the important information present in this matrix.

Equations (21) to (23) discuss the matrix manipulation involved in isolation of load to load attraction region making it suitable to apply eigenvalue decomposition technique to find the weak buses.

Eigen value decomposition of R_{LL} matrix is given by (24)

$$R_{LL} = VNV^* = \sum_{i=1}^{n} v_i \lambda_i v_i^* \quad (24)$$

where V is an orthonormal matrix with eigenvectors v_i, v_i^* and N is the diagonal matrix with eigenvalues $\lambda_i, i = 1,2,\ldots n$ as the diagonal elements.

On expanding (22) and applying eigenvalue decomposition on R_{LL} matrix

$$[V_L] = [R_{LL}]^{-1}[I_L - N_{LG}I_G] \quad (25)$$

$$\|V_L\| = \left\| \sum_{i=1}^{n} \frac{v_i v_i^*}{\lambda_i}[I_L - N_{LG}I_G] \right\| \quad (26)$$

where

λ_i are the eigenvalues.

Equations (24) to (26) show the implementation of EVD and determination of eigenvalues.

The buses with least eigenvalues are the weak buses based on their reciprocal relationship between the eigenvalues and the load bus voltages. These are the weak buses which are responsible for the decline in voltage in particular and become the suitable locations to place the reactive power compensators.

5. Implementation of the Dragonfly Algorithm for the Optimal Location and Sizing of the SVC

a) Input the test system data consisting of bus data, which includes total number of buses, sending end bus, receiving end bus, bus real power (P), bus Reactive power (Q), bus voltage (V_{bus}), bus voltage angle (Ɵ) and the line data which gives the line (R/X) ratio and the tap setting.

b) The location of the SVC is determined by eigenvalue decomposition technique on partitioned Y-admittance matrix using equations (17) to (26).

c) The Dragon fly algorithm is used for optimizing the size and cost of the SVCs.

d) The following parameters are initialized. Maximum number of dragonflies is set to 30. Minimum number of dragonflies is set to 0. Total number of dragon flies in population is 100. The acceptable limit of voltage is considered between 0.95 p. u and 1.1 p. u. and the voltage stability index in equation (7) is included in the design constraints. The line overload factor in equation (6) is included in the fitness function which is based on line flow data obtained from load flow analysis so as to reduce the SVC cost for better reactive power support to maintain a better voltage profile with reduced losses.. Reactive power range of SVC is set to ± 100MVAR.

e) The objective function values are calculated for all the dragon flies such that to minimize the fitness function.

f) The population is ranked in descending order and consider the population with minimum fitness until maximum population is attained and the fitness of new population is calculated. Repeat the algorithm steps from 1 to 11 which is discussed in section 3.1 for maximum number of iterations.

5.1 Implementation results and discussion on various test systems:

Dragon fly algorithm is implemented on IEEE 14 and IEEE 30 bus systems. The weak buses to implement the SVCs are determined using eigenvalue decomposition technique on sub matrix R_{LL}, resulting from the partitioned Y-admittance matrix. When SVCs of rating ± 100 MVAR are placed at these buses it is observed that there is a significant improvement in voltage profile and in real power transfer with a remarkable reduction in real power losses and voltage deviation .

5.1.1. Results of IEEE 30 bus system:

The system consists of 5 generators and 25 load buses and 41 lines. The first three weak buses thus identified using EVD are 19, 20 and 24 respectively. The total voltage deviation without placement of SVC is 1.0765 p. u. It is observed that the voltage deviation is more than 1 p. u. When a single SVC is placed at bus 20 the deviation in voltage has reduced significantly. The implementation of two SVCs has given a voltage deviation of 0.8675 p.u, whereas the voltage deviation with three SVCs at buses 19, 20 and 24 has reduced the deviation to 0.8608 p. u. The total real and reactive power losses, the total generation and the reactive power support obtained when the required number of SVCs are implemented at these weak buses are shown in Table.1.

Table.1 Performance analysis of IEEE 30 bus system

No of SVCs	SVCs installed at Bus No.	Q (MVAR)	Total voltage deviation in p. u	Installation cost in US$	Total losses		Total generation	
					P_L (MW)	Q_L (MVAR)	P_G (MW)	Q_G (MVAR)
1	19	26.4611	1.0765	119.4	9.6527	35.4905	198.8525	98.3128
	20	28.5028	1.0406	118.8	9.6070	35.0499	198.8088	73.4955
	24	16.6303	1.4470	122	9.9970	37.4069	199.1967	110.7574
2	19,20	34.5665	0.8675	117.4	9.5877	34.5083	198.7873	88.7968
3	19,20,24	34.9084	0.8608	116.8	9.5532	34.4490	198.7530	88.5833

5.1.2. IEEE 14 bus system results:

IEEE 14 bus system has 5 generators and 9 load buses and has 20 lines. The first three weak buses identified by EVD are 9, 11and 14 respectively. The improvement in voltage profile on implementation of SVC at the weak buses 9 and 11 individually is shown in the Fig. 3. From Fig. 3 it is obvious that the voltage profile improves better when SVC is placed at 9th bus rather than at11th bus.

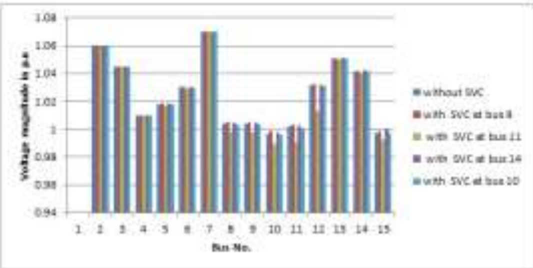


Fig. 3 Variation of voltage profile with and without SVC

6. Comparison of Dragonfly Algorithm Results with Other Algorithms

Comparison of the results obtained for IEEE 14 bus system is given in Table. 2. It is observed that the cost of SVC and the installation cost increases with the loading condition.

Table.2 Comparison of IEEE 14 bus system results with other algorithms

Methodology	Real power losses (MW)	Voltage deviation (p. u)	SVC location [bus No.]	SVC size (MVAR)
PSO [11]	18.9657	0.8952	12	10
TLBO [15]	13.4377	0.4993	5	-40.89
Hybrid PSO [18]	–	–	12	10.330
DA	11.903	0.35296	9	16.6

The real power loss is 11.903 MW on implementing DA whereas it is 18.9657 and 13.4377 MW for PSO and TLBO respectively. Hence the reduction in real power losses obtained using DA is remarkable when compared to PSO and TLBO and is shown in Fig. 4.

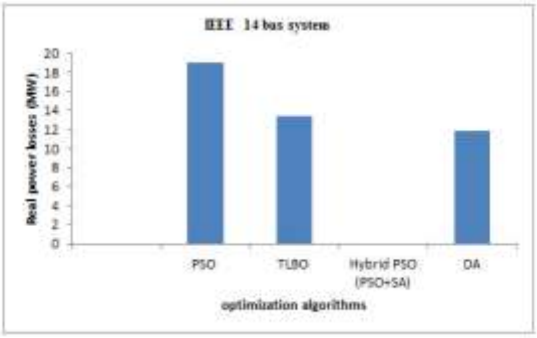


Fig. 4 Comparison of real power losses of various algorithms

The reduction in voltage deviation is significant using DA with a value of 0.35296 p. u. rather than PSO and TLBO which give the values of 0.8952 p. u. and 0.4993 p. u. respectively and is shown in Fig. 5.

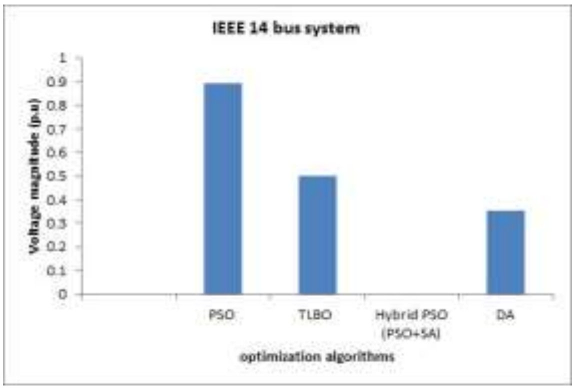


Fig. 5 Comparative analysis of voltage deviation for IEEE 14 bus system

6.1 IEEE 30 bus system:

In IEEE 30 bus system three SVCs are placed at 19, 20 and 24. The line losses thus obtained with SVC implementation is compared with the result without SVC and is shown in Fig. 6. It is evident from Fig. 6 that the line losses have reduced substantially. The overall voltage profile also has improved to greater extent and is shown in Fig. 7.

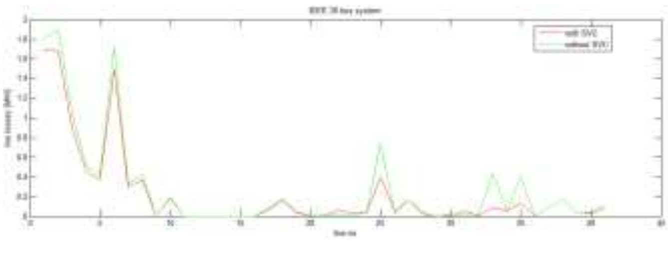


Fig. 6 Line losses of IEEE 30 bus system with and without SVC

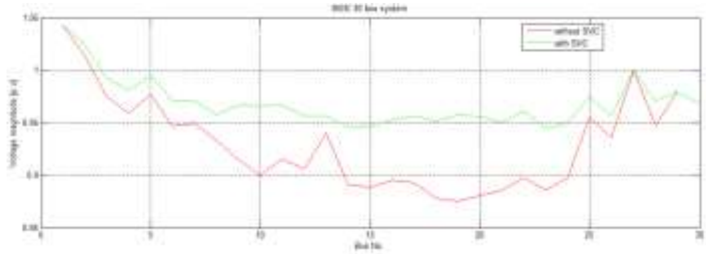


Fig. 7 voltage profile of IEEE 30 bus system with and without SVC

Table . 3 Comparison of IEEE 30 bus system results with other algorithms

No of SVCs	Methodology	Objective functions considered	Real power losses (MW)	SVC location	SVC size (MVAR)
1	PSO [11]	SVC installation cost and power losses	17.6283	24	7.0346
	Hybrid PSO[18]	Installation cost and voltage control	-	30	13.27
	DA	Installation cost and loss reduction	9.6527	19	26.46
3	PSO[11]	SVC installation cost and power losses	17.5283	9, 17, 24	27.5171 (9) 1.6888 (17) 7.0346 (24)
	DA	Installation cost and loss reduction	9.5532	19, 20, 24	26.4611 (19) 28.5028 (20) 16.6303 (24)

Table.3 gives the comparative analysis of the results obtained for IEEE 30 bus system. It is obvious from Table.3 that the reduction in real power losses is significant with 9.6527 MW using DA algorithm whereas it is of about 17.6283 MW in PSO with implementation of single SVC. This major difference in the real power losses shows the effectiveness of the SVC location thus identified by EVD. It is because the location identified by EVD is based on structural characteristics of the given network which satisfies the basic circuit concepts as discussed in section.4.

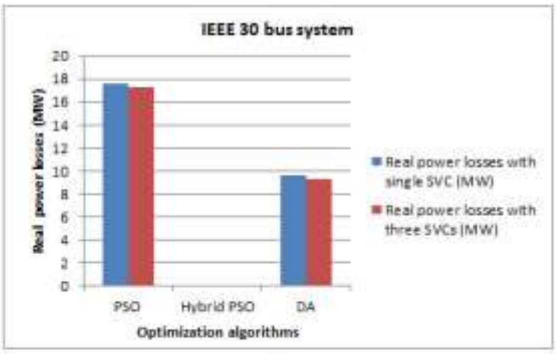


Fig. 8. Comparison of real power losses of various algorithms for IEEE 30 bus system

The reactive power support provided by the SVCs in a DA is better when compared with PSO and is evident from Fig. 8.

6.2 Implementation of Solar generation in IEEE 30 bus system

In addition to the implementation of 3 SVCs at first three weak buses, a 2 MW solar generation is installed at bus 20, the second weak bus. This results in better reduction of real power losses. In particular bus 20 is chosen as the location for installation of solar generation since it has the interconnections with bus 19, the first weakest bus and with many other load buses with larger power demand. It is obvious that the power demand is met in a better way particularly in the zone which is more prone to cause a voltage collapse. The significance of solar generation is illustrated in Table. 4 from which it is clear that the voltage profile has improved significantly with reduced voltage deviation. Hence there is a greater possibility for the inclusion of few more solar panels even at other weak buses which consecutively will reduce the reactive power requirement as the load demand can be satisfied locally. This effect the VAR rating of the SVCs which is one of the design constraints and results in optimal size and cost of the FACTS involved.

Table . 4 Comparison of results with and without Solar Panel of 2 MW

Summer season	With SVC at buses 19, 20, 24 (first three weakest buses)	With 3 SVCs and 2 MW solar generation at bus 20 (one of the weakest buses)
P_L (MW)	9.5532	9.4235
Q_L (MVAR)	34.4490	34.0293
Voltage deviation (p.u)	0.8608	0.8572
Q_c(MVAR)	88.3831	88.3786

The variation of SVC cost with reactive power is given in Fig. 9. The optimal location and size is obtained using eigenvalue decomposition technique and DA respectively. The variation of Installation cost with reactive power is shown in Fig. 10.

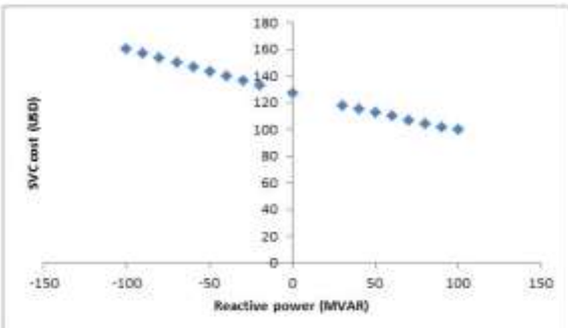


Fig. 9 Variation of SVC cost with reactive power

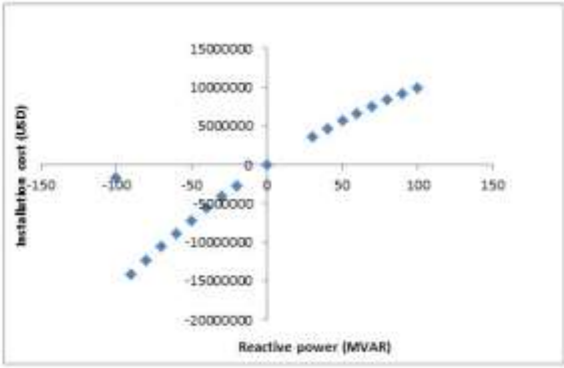
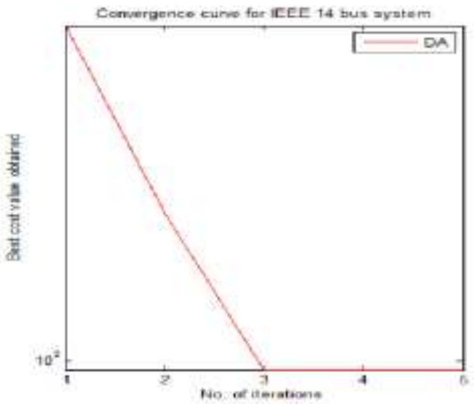
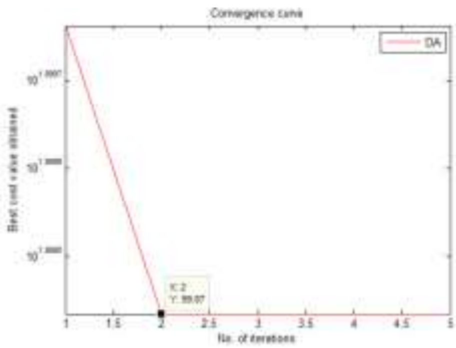


Fig. 10 Variation of Installation cost with reactive power

The convergence of cost function for IEEE 14 and 30 bus systems are shown in Fig. 11. The minimum value of the fitness function is 99.87 and it is observed that the convergence of the fitness function is with less number of iterations when compared with other algorithms. The variation of fitness function with reactive power is shown in Fig. 12. From the figure it is clear that the installation cost varies linearly with reactive power demand in MVAR.



a. convergence curve of IEEE 14 bus system



b. convergence curve of IEEE 30 bus system

Fig. 11 Convergence curve of the fitness function

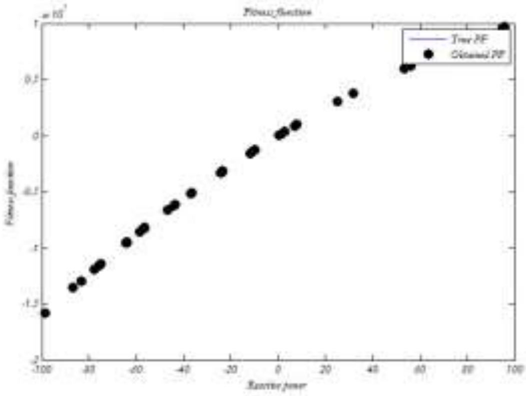


Fig. 12 Variation of fitness function with reactive power demand

7. Conclusion

The proposed method is implemented on IEEE 14 and IEEE 30 bus systems. The optimal location and size of SVC are defined using eigenvalue decomposition method and DA respectively. The results thus obtained are compared with that of PSO, Hybrid PSO (PSO+SA) and TLBO algorithms. The results show that the voltage deviation is reduced much in DA when compared with other algorithms. The line losses are also minimized significantly. The convergence of the objective function is with less number of iterations in DA when compared with other algorithms. Hence this method is highly suitable for optimal location and size of SVC. Inorder to demonstrate the possibility to integrate the renewable energy a 2MW solar generation is installed at bus 20 which is one of the weak buses of IEEE 30 bus system and the improvement in voltage profile is presented. The further scope of this work is to employ the wind generators at the weak buses instead of SVC so as to reduce the electrical distance between the generators and the farthest load buses to observe the improvement in voltage profile and power transfer with reduced losses.

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