Optimal Allocation of SVCs in Transmission Networks Considering System Loadability using Exponential Adaptive Bacterial Foraging Algorithm

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ABSTRACT

Voltage instability is considered as the greatest challenge to power system operation, which often results to total system collapse. The ability of the Static Var Compensator (SVC) to provide uninterrupted reactive power to the system so as to enhance voltage stability and reduce system losses makes it the most widely employed Flexible Alternating Current Transmission System (FACTS) device. In this paper, an Exponential Adaptive Bacterial Foraging Algorithm (EABFA) is proposed for optimal allocation of SVCs in a distribution network considering system loadability.

Power flow analysis using Newton-Raphson method are conducted to ascertain the initial state of the system. The objective function to be minimized consists of total power loss and voltage deviation. The effects of SVCs on the system are studied under normal and three-quarter loading conditions.

The proposed EABFA is demonstrated on the Ward and Hale 6-node system. The results showed improvement in voltage stability and reduction in losses with the placement of SVCs at the appropriate buses. For normal loading condition, 9.76 %, 14.04 % and 17.69 % reduction in active power was achieved with the installation of 1 SVC, 2SVCs and 3 SVCs respectively. Also, 9 %, 12.91 % and 17.64 % voltage profile improvement were recorded for the same number of SVC. Similarly, for three-quarter loading, the proposed approach attained 2.54 %, 3.80 % and 5.08 % reduction in active power loss for 1 SVC, 2 SVCs and 3 SVCs, respectively.

In terms of voltage profile improvement, the approach recorded 2%, 3% and 4.09% improvement as compared to the base case scenario (with-out SVC).

(Keywords: Static Var Compensator, Exponential Adaptive Bacterial Foraging Algorithm, Loadability, Newton-Raphson Power Flow)

NOMENCLATURE

i , j	Bus index
ik	Branch index
N, N_B	Total number of bus and branch
B_{ik}, G_{ik}	Susceptance and conductance at branch *ik*
P_i ,Q_i	Active and reactive powers at bus *i*
P_k ,Q_k	Active and reactive powers at bus *k*
V_i ,δ_i	Voltage magnitude and phase angle at bus *i*
V_k ,δ_k	Voltage magnitude and phase angle of bus *k*
θ_{ik}	Angle between bus *i* and *k*
Y_{ik}	Branch admittance between bus *i* and *k*
ΔP, ΔQ	Incremental active and reactive power changes
$\Delta\delta$, ΔV	Incremental bus voltage angle and magnitude changes
P_i^G,Q_i^G	Active and reactive generation at bus *i*
P_i^L,Q_i^L	Active and reactive load at bus *i*
V_i^{min},V_i^{max}	Minimum and maximum voltage at bus *i*
Q_i^{min},Q_i^{max}	Minimum and maximum SVC size at bus *i*
B_{SVC}	Susceptance of SVC

Symbols not mentioned in the nomenclature are well defined in the text.

INTRODUCTION

The security of power systems is a critical issue in power supply and requires great attention [1]. Transmission and distribution networks constitute the most critical components of power system security, in view of their role in power system stability and quality. In addition, due to high energy demand for both industrial and domestic activities, which often consume reactive power, transmission systems are forced to operate close to their tolerance limit. Thus, transmission lines are becoming more complex and heavily loaded, resulting to high power loss and voltage instability [3]. This could necessitate the need for the transmission line expansion. However, substantial financial, environmental and time factors as well as political issues are associated with setting up new or expanding existing transmission facilities. Hence, the option of applying Flexible AC Transmission Systems (FACTS) devices in existing power systems for enhanced operational capability has attracted considerable attention over the years [2, 3]. The FACTS devices are incorporated at appropriate position(s) on the transmission lines so as to compensate for reactive power loss, improve voltage stability and thereby ensuring better system operation [3-5].

The SVC is a member of the shunt connected FACTS devices and is the most widely used compensating device in power systems due to its excellent performance and affordability [4]. When properly located, the SVC interacts with the system by exchanging capacitive and inductive current to enhance voltage and reduce losses [4]. However, proper allocation of these devices in transmission systems is complicated and remains a major concern [6]. In general, the approaches to the allocation of these devices can be categorized into three: classical, sensitivity-based and heuristics/meta-heuristics approaches.

A number of classical approaches for allocation of SVCs have been reported in [2], [7], [8], [9], [10], [11], [12] and [13]. In [14], sensitivity analysis approach using voltage profile index (VPI) was employed for SVCs placement in power systems for improved voltage stability and loss minimization. The performance analysis was carried out on IEEE 30-bus system. In addition, an approach to determine the optimal location of thyristor controlled series compensators (TSSCs) based on real power performance index and reduction of total system loss was presented in [15]. In [16], a sensitivity based voltage collapse proximity index for appropriate location of SVC position in power systems under normal and over loaded conditions was proposed.

Several meta-heuristics approaches such as Evolutionary Algorithm [17], Genetic Algorithm [18], Differential Evolutionary Algorithm [19], Improved Harmony Search Algorithm [20], Fuzzy-GA [21], Particle Swarm Optimization Algorithm [22], Fuzzy Logic, and Gravitational Search Algorithm [23] have all been developed for optimal placement of SVC in transmission network for the purpose of improving system security. Although all of the above approaches have recorded promising results, there still exists the need for more robust and faster approaches for placement of SVCs in transmission networks for enhanced system operation.

This paper proposes an exponential adaptive bacterial foraging algorithm (EABFA)-based approach for SVCs allocations, considering system loadability on the Ward and Hale 6-node system.

PROBLEM FORMULATION

Classical Power Flow Equations

The objective of classical power flow is to determine the actual operating state of a system by computing the bus voltage magnitudes and phase angles, as well as real and reactive powers. Newton-Raphson is regarded as the most widely employed classical power flow method due to its ability to fully incorporate the system nonlinear characteristics [4, 24]. The system active and reactive power equations are expressed as [24]:

$$P_i = \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right) \qquad \textbf{(1)}$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k| \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right) \qquad \textbf{(2)}$$

Where $\theta_{ik} = (\delta_i - \delta_k)$. Equations (1) and (2) may be expressed as one-dimensional equation for all system buses as [12]:

$$f(x) = y \qquad \textbf{(3)}$$

where $x = \begin{bmatrix} \delta \\ V \end{bmatrix}$, $y = \begin{bmatrix} P \\ Q \end{bmatrix}$ and $f(x) = \begin{bmatrix} P(x) \\ Q(x) \end{bmatrix}$

Taking Taylor's series expansion about an operating point x_o of Equation (3) and considering the first derivatives only, the power flow equations can be expressed in a compact form as [12]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{4}$$

J_1, J_2, J_3 and J_4 are the Jacobian matrix elements of the system. The active power to voltage angle and magnitude are related by J_1 and J_2, while the reactive power to voltage angle and magnitude are closely related by J_3 and J_4.

Mathematical Modelling of SVC

The SVC is a shunt connected FACTS device used for fast control of reactive power in power systems so as to improve transient stability. Just like a variable reactance, the SVC is capable of providing inductive as well as capacitive compensation. When the system voltage level is low (inductive loading), the SVC injects reactive power into the system at the point of common coupling (PCC). On the other hand, when the system voltage level is high (capacitive loading), the SVC absorbs reactive power from the system to control system bus voltages to the specified limits [1, 3, 4, 24]. Figure 1 shows a schematic diagram of SVC connected to a bus.

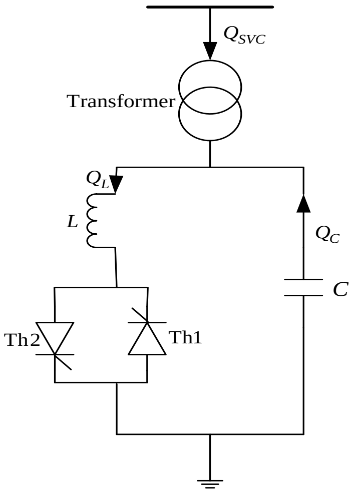


Figure 1: Schematic Diagram of SVC [3].

The reactive power and current injected into the system by the SVC are computed by:

$$Q_{SVC} = -V^2 B_{SVC} \tag{5}$$

$$I_{SVC} = jB_{SVC}V \tag{6}$$

Optimization Model

The objective of allocating SVCs in power systems is to minimize losses and bus voltage deviations. For simplicity, the investment costs of SVCs are not taken into consideration. Thus, the active power loss (P_{Loss}) and voltage deviation (V_D) are given by Equations (7) and (8) [4, 6]:

$$P_{Loss} = \sum_{i=1}^{N} |V_i||V_k||Y_{ik}| cos(\delta_i - \delta_k - \theta_{ik}) \tag{7}$$

$$V_D = \sum_{i=1}^{N} \left(\frac{V_{ref} - V_i}{V_{ref}} \right)^2 \tag{8}$$

where V_{ref} is the reference voltage. The minimization equation (F) is formulated by the weighted summation of Equations (7) and (8):

$$min(F) = min(\mu P_{Loss} + \psi V_D) \tag{9}$$

subject to equality and inequality constraints given by Equations (10) - (11) and (12) - (14) respectively:

$$P_i^G - P_i^D - \sum_{i=1}^{N} |V_i||V_k||Y_{ik}| cos(\delta_i - \delta_k - \theta_{ik}) = 0 \tag{10}$$

$$Q_i^G - Q_i^D - \sum_{i=1}^{N} |V_i||V_k||Y_{ik}| sin(\delta_i - \delta_k - \theta_{ik}) = 0 \tag{11}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{12}$$

$$Q_i^{min} \le Q_i \le Q_i^{max} \tag{13}$$

$$S_{ik} \le S_{ik}^{max} \tag{14}$$

where μ and ψ are unit weighting factors and S is the apparent power of transmission line flow for $ik = 1,2,\ldots N_B$.

BACTERIAL FORAGING ALGORITHM

Bacterial Foraging Algorithm (BFA) is a swarm based nature-inspired algorithm proposed by Kevin Passino in 2002. The algorithm is developed to mimic the foraging behaviors of *Escherichia coli* (E. coli) bacteria found in the intestine. The BFA is modelled based on four principal processes: chemotaxis, swarming, reproduction, and elimination-dispersal [25-27].

Chemotaxis

Chemotaxis explains the movement of bacteria over a landscape of nutrients. The *i*th bacterium movement is explained by:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\phi(i) \tag{15}$$

where $\theta^i(j,i,k)$ is the position of *i*th bacterium at *j*th chemotactic, *k*th is the reproductive, *l*th is the dispersion and elimination step. Also, $C(i)$ is the step size unit and $\phi(i)$ represent the *j*th step direction angle.

The fitness of the *i*th bacterium is determined based on its position represented by $J=J(i,j,k,l)$. The direction angle $\phi(i)$ explains the tumble of the bacteria as:

$$\phi(i) = \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{16}$$

where $\Delta(i) \in R^p$ represents the randomly generated vector.

Swarming

The attractive and repulsive effects of each bacterium are used as a medium of communication to others. Attractants are released by bacteria under stress circumstances to stimulate bacteria to swarm together, while repellent are released to inform others to maintain a reasonable interval from the stressed bacterium. The bacteria cell-to-cell signaling mechanism is given by:

$$\begin{aligned} J_{cc} &= (\theta, P(j,k,l)) \\ &= \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-\omega_{attract}\sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right)\right] \\ &\quad + \sum_{i=1}^{S}\left[h_{repellant}\exp\left(-\omega_{repellant}\sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right)\right] \end{aligned} \tag{17}$$

where $J_{cc}=(\theta,P(j,k,l))$ is the fitness function to be added to the actual fitness function, S is the number of bacteria, *p* is the number of variables to be optimized. $\theta = [\theta_1\ \theta_2\ \ldots\ \theta_p]^T$ represents a point in the *p*-dimensional search field, $d_{attract}$ and $\omega_{attract}$ are the depth and width of the attractant released respectively, while $h_{repellant}$ and $\omega_{repellant}$ represents the height and width of the repellent, respectively.

The fitness of each position is determined using:

$$J(i,j,k,l) = J(i,j,k,l) + J_{cc}(\theta, P(j,k,l)) \tag{18}$$

Reproduction

In the case of reproduction, after N_c chemotaxis steps, the reproduction step is obtained by sorting the health of all bacteria based on their fitness described by:

$$J_{health}^i = \sum_{j}^{N_c+1} J(i,j,k,l) \tag{19}$$

The S_r bacteria (the population of the bacteria divided into two equal halves) with least health due to insufficient nutrient eventually die leaving the healthiest to split into two similar bacteria and positioned at the same location.

Elimination-Dispersal

The process of elimination and dispersion is executed after N_{re} reproduction steps so as to avoid being trapped in local optima. Each bacterium is subjected to the process of dispersal and elimination within the environment according to a probability (P_{ed}). N_{ed} is the number of elimination and dispersal steps. Figure 2 shows a flow chart for the conventional BFA.

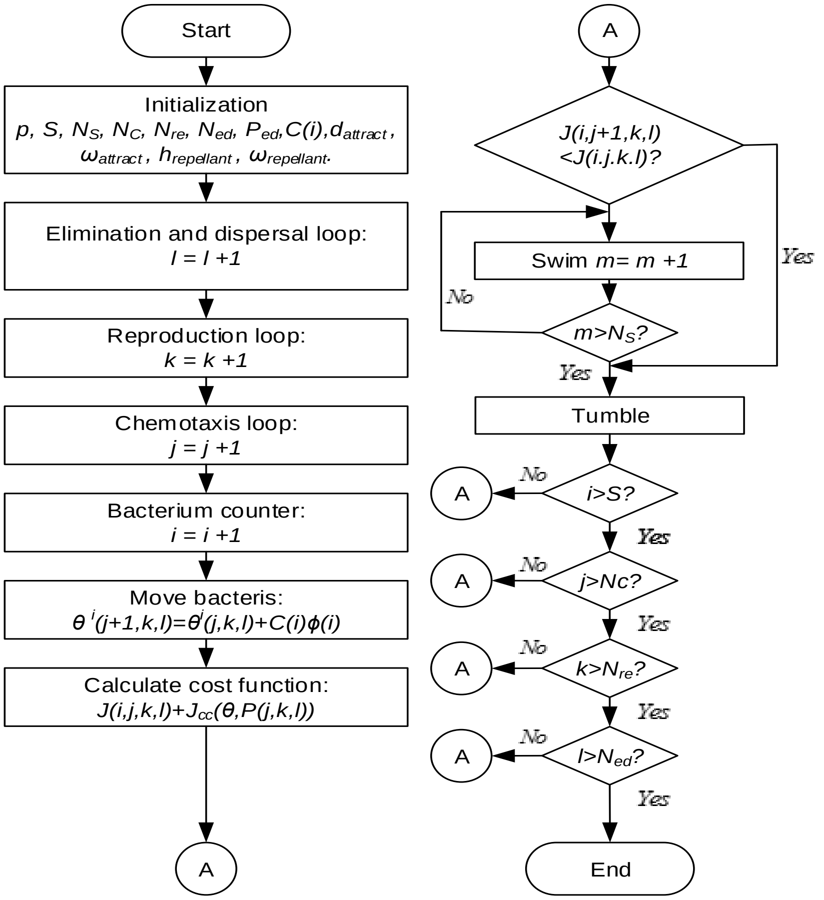


Figure 2: Flow Chart for Conventional Bacterial Foraging Algorithm.

EXPONENTIAL BACTERIAL FORAGING ALGORITHM

Similar to the BFA, the exponential adaptive bacterial foraging algorithm (EABFA) is also modelled based on the four processes of chemotaxis, swarming, reproduction and elimination-dispersal. However, the algorithm step size, *C(i)*, is made adaptive based on the fitness function *J(i)*, and the cell-to-cell signaling mechanism is eliminated [28].

The EABFA step size unit is given by:

$$C_e(i) = \frac{c_{max}}{1 + \frac{\alpha}{\beta e^{|J(i)|}}} \qquad \textbf{(20)}$$

where $C_e(i)$ represents the exponential adaptive step size unit for all bacterium, c_{max} is tunable maximum step size unit, $|J(i)|$ is the absolute cost function of every bacterium, and α and β are positive tunable factor and scaling factor respectively.

A complete pseudo-code of the EABFA is presented below and its flow chart is depicted in Figure 3.

```
[Step 1] Initialize parameters:
$p, S, N_S, N_C, N_{re}, N_{ed} P_{ed}, C(i), \theta^i \; (i = 1,2,...,S)$
    [Step 2] Elimination and the dispersal loop:
    for l = l + 1
        [Step 3] Reproduction loop:
        for k = k + 1
            [Step 4] Chemotaxis loop:
          for j = j + 1
          4.1.for each bacterium i = 1,2,…,S,
          4.2.Determine the cost function J(i,j,k,l) using
              equation (18) without the cell-to-cell
              signaling mechanism
          4.3. $J_{last} = J(i,j,k,l)$
          4.4.Tumbling: Create a random vector set
              $\Delta(i) \in R^p$
          4.5.Move: Compute $\theta^i(j+1,k,l)$ using Equation
              (15)
```

```
4.6.Compute cost function $J(i,j+1,k,l)$ using Equation (18)
4.7.Swim: m=0 (counter for swim length)
        while $m<N_S$
            m= m+1,
        if $J(i,j+1,k,l)<J_{last}$ then
            $J_{last}=J(i,j+1,k,l)$
            Move: Compute $\theta^i(j+1,k,l)$ using Equation (10)
            Compute cost function $J(i,j+1,k,l)$ using Equation (18) without the cell-to-cell signaling mechanism
    else
        $m=N_S$
        end
end
[Step 5] if $j<N_C$, move to step 4
[Step 6] Reproduction
for i = 1,2,…,S ,
        6.1Compute $J^i_{health}$ using Equation (19)
    end
        6.2 Sort bacteria in order of ascending. The smallest healthier bacteria $(S_r)$ die and others divided into two bacteria and placed in the same place.
    end
[Step 7] if $k<N_{re}$ go to step 3
[Step 8] Elimination-dispersal:
for $m=1,2,...,S$ ,
    8.1 if $p_{ed}>rand$ (create a random number for each bacterium and if any number is lower than $p_{ed}$ then discard or destroy the bacterium)
    Create new random locations for the bacteria
        else
    Bacteria remain in their place.
        end
end
if $l<N_{ed}$ , move back to step 2;
else
end.
```

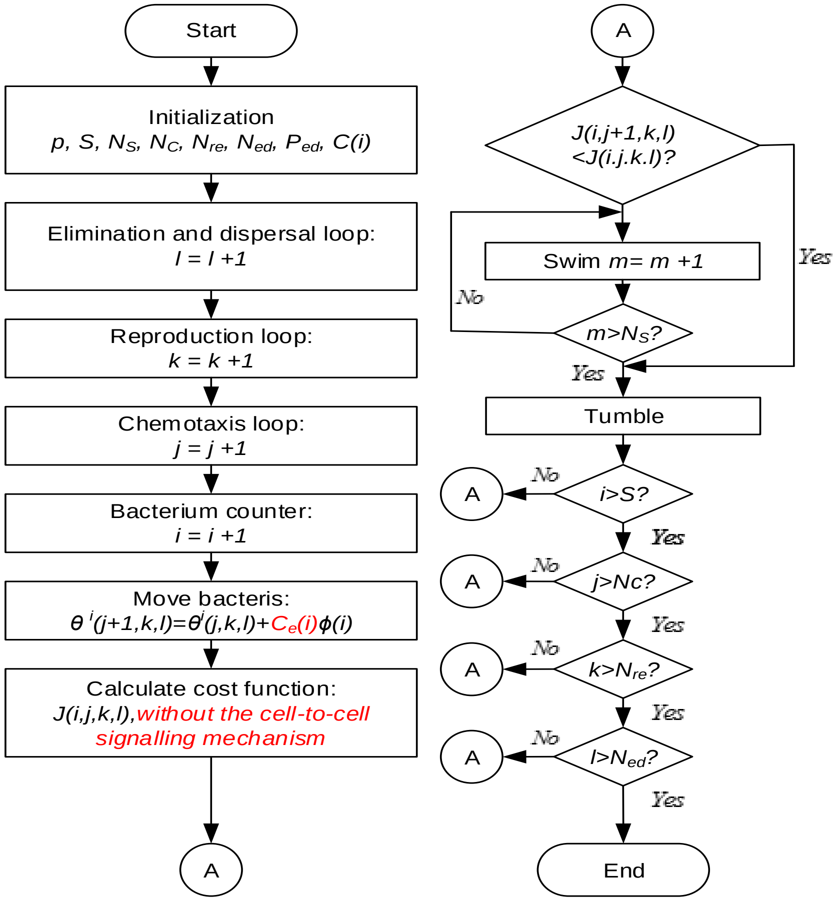


Figure 3: Flow Chart for Exponential Adaptive Bacterial Forging Algorithm.

MATERIALS AND METHODS

The program for implementing the EABFA based approach for SVCs allocation was coded in MATLAB R2013a virtual environment using a HP Elite Book 6930p personal computer with specifications as follows:

- Intel(R) Core(TM) 2Duo CPU P8700;
- 2.53GHz 64-based processor;
- 4GB installed memory (RAM); and
- 32-bit windows 8 Operating System (OS).

Next, the network line data and bus data were loaded, while the base-case power flow analysis was performed using Newton-Raphson method. The EABFA parameters in Table 1 were then Initialized and, the multi-objective function comprising of P_{Loss} and V_D for use in the EABFA was formulated and applied. Finally, the power flow analysis with the optimum sizes of SVCs installed at the appropriate locations was performed and the improved voltage magnitudes at each bus as well as the corresponding reduction in line losses were displayed.

Table 1: Parameter values for EABFA.

Parameters	Values
search space dimensions, p	2
Size of the bacteria, S	10
Total chemotactic steps, N_c	4
Total swim steps, N_s	4
Total reproductive steps, N_{re}	4
Total elimination and dispersal steps, N_{ed}	3
Run-length unit $C(i)$	0.1
Total bacteria reproductions (splits) per generation, S_r	S/2
Probability of elimination and dispersal of bacteria, P_{ed}	0.25
Tuneable factor, α	1
Scaling factor, β	0.01

RESULTS AND DISCUSSION

The effectiveness of the proposed EABFA was tested on Ward and Hale 6-node system. The line and node data of the test system are obtained from [29]. The system load bus voltage limits were set as 0.90 p.u. and 1.00 p.u. as in [29]. Analysis was conducted for two different loading conditions:

- Normal loading condition
- Three-quarter loading condition

The authors have chosen to employ SVCs with allowable compensation range of $0 \leq Q_{SVC} \leq 15$ (MVAr) in this work.

Normal Loading Condition

The single line diagram of the system normal loading condition is shown in Figure 4. Applying the EABFA approach, Table 2 presents the best location(s) and size(s) of SVCs in the test system.

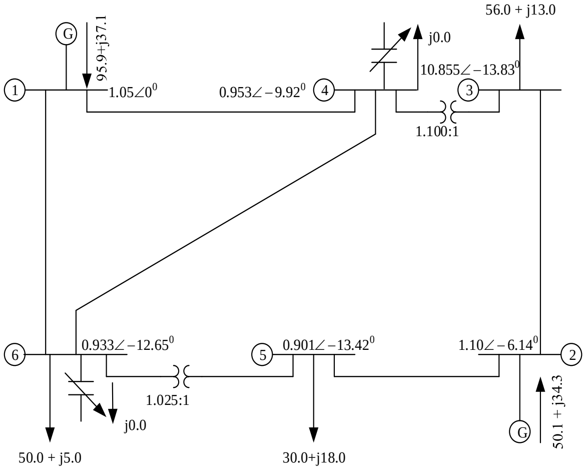


Figure 4: Single Line Diagram for 6-Node System.

The results obtained from the proposed approach without and with SVCs are presented in Table 3. From the table, it can be observed that voltage at bus 3 of column 2 is 0.855 p.u. which clearly violates the set limits for load bus voltage.

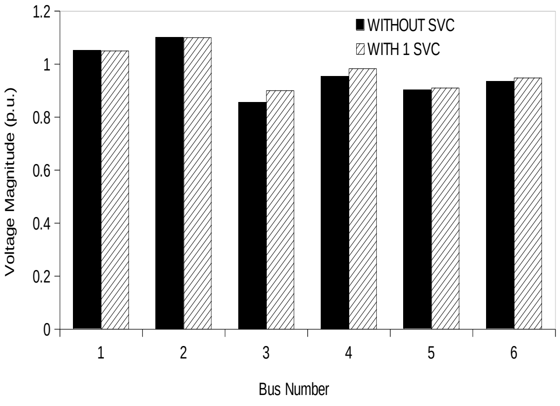
Table 2: SVCs Locations and Sizes using EABFA.

Number of SVCs	Bus Number	SVC Size (MVAr)
1	3	13.841
2	3, 5	13.841, 6.184
3	3, 5, 6	13.841, 6.184, 8.321

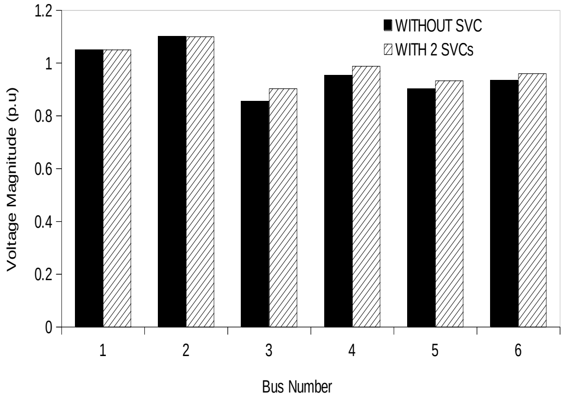
The system active power loss was obtained as 11.6123 MW without SVC. The installation of SVCs using the proposed EABFA approach has further improved the network voltage profile and reduce losses.

Figure 5: a, b and c shows the voltage profile improvement for 1 SVC, 2 SVCs and 3 SVCs respectively. It could be seen from the figures that load bus constraints have been satisfied, as no load bus is below the lower voltage limit of 0.90 p.u. The total active and reactive losses without and with SVCs are shown in Figures 6 and 7, respectively.

It can be observed from the figures that a steady reduction in losses with the increase in number of SVCs has been achieved. Table 4 shows the summary of the simulation results for the test network without and with SVCs.



(a)



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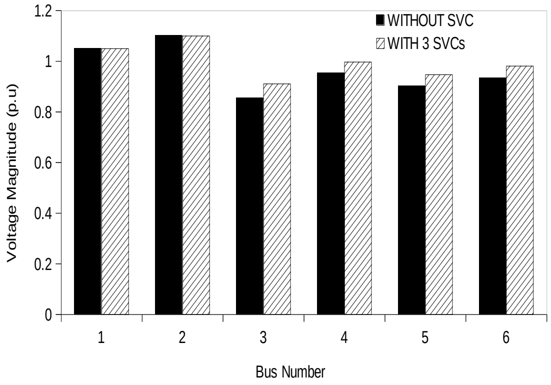


(c)

Figure 5: Voltage Profile Comparison for (a) 1 SVC, (b) 2 SVCs, and (c) 3 SVCs.

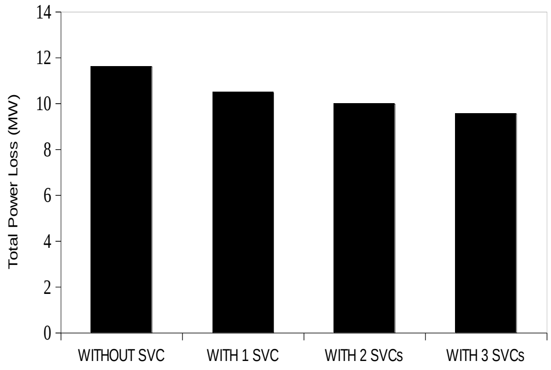


Figure 6: Total Active Power Loss Comparison.

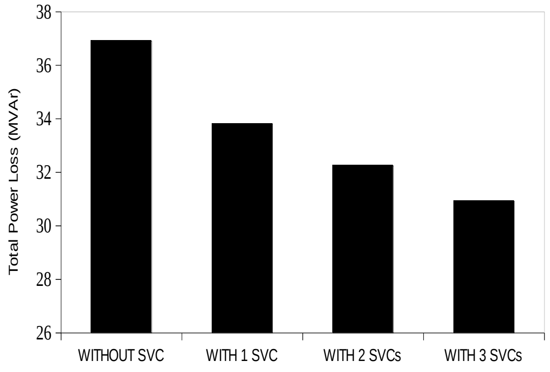


Figure 7: Total Reactive Power Loss Comparison.

Table 3: Bus Voltage Magnitudes.

Bus Number	Without SVCs	With 1 SVC	With 2 SVCs	With 3 SVCs
1	1.050	1.050	1.050	1.050
2	1.100	1.100	1.100	1.100
3	0.855	0.900	0.903	0.911
4	0.953	0.983	0.988	0.997
5	0.901	0.910	0.933	0.947
6	0.933	0.948	0.960	0.981
Mean	0.9653333	0.9818333	0.9890000	0.9976667
Standard Deviation	0.0925347	0.0795146	0.0740486	0.0696547

Table 4: Performance Comparison with and without SVCs.

Parameters	Without SVCs	With 1 SVC	With 2 SVCs	With 3 SVCs
Voltage Magnitude (p.u.)	0.855 (Bus 3)	0.900 (Bus 3)	0.903 (Bus 3)	0.911 (Bus 3)
Overall Voltage Improvement (%)	-	9.00	12.91	17.64
Total P_{Loss} (MW)	11.6123	10.4795	9.9823	9.5583
P_{Loss} Reduction (%)	-	9.76	14.04	17.69
Total Q_{Loss} (MVAr)	36.9113	33.8152	32.2463	30.9263
Q_{Loss} Reduction (%)	-	8.39	12.64	16.21

Three-Quarter Loading Condition

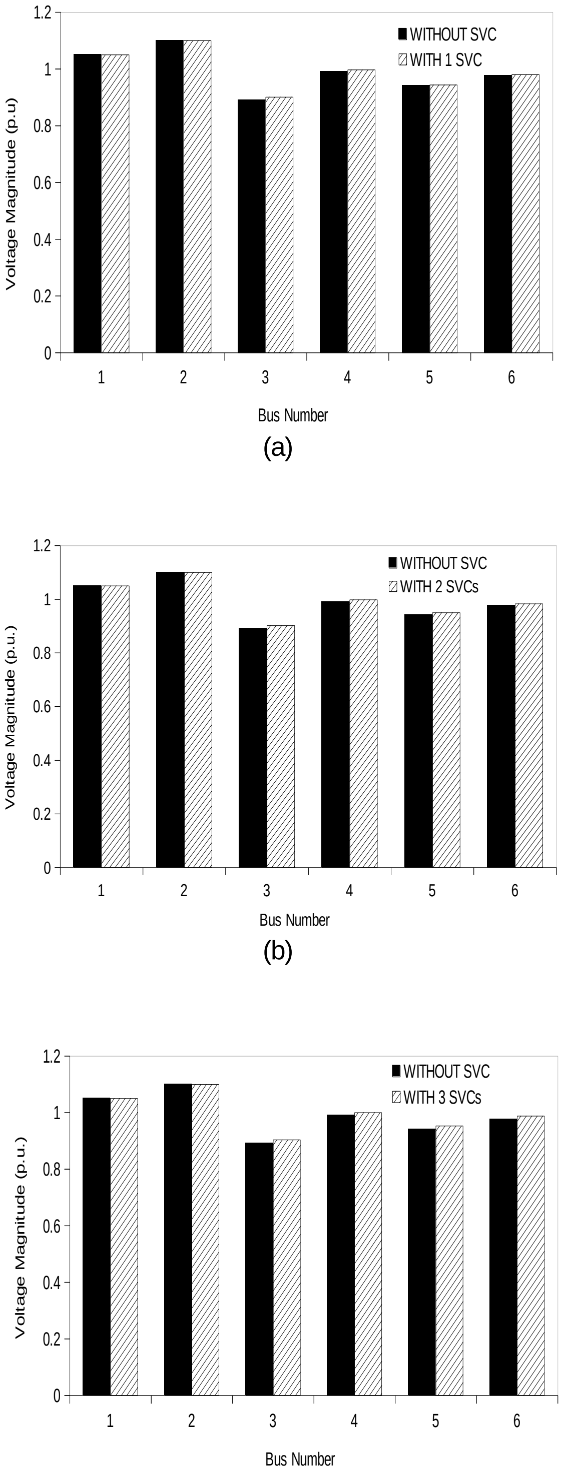
The best SVCs position(s) and size(s) for three-quarter loading condition are shown in Table 5.

Table 5: SVCs Locations and Sizes using EABFA.

Number of SVCs	Bus Number	SVC Size (MVAr)
1	3	4.502
2	3, 5	4.502, 2.201
3	3, 5, 6	4.502, 2.201, 3.016

The results shown in Table 6 indicate that bus number 3 exhibit a lower voltage magnitude of 0.891 p.u. as compared to the acceptable minimum value of 0.90 p.u. An active power loss of 7.4427 MW was recorded without SVC. The application of the proposed EABFA for determination of SVCs positions has mitigated the issue of low bus voltages and also reduced power loss.

Voltage profile enhancement for 1 SVC, 2 SVCs and 3 SVCs are depicted in Figure 8: a, b and c, respectively. Here also, no load bus voltage was found to be below the lower limit of 0.90 p.u. The presence of SVCs has also reduced the system active and reactive losses as shown by Figures 9 and 10, respectively. Just as in normal loading condition, a steady reduction in the both losses with the increase in number of SVCs could be observed. Summaries of the test system simulation results are presented in Table 7.



(a)

(b)

(c)

Figure 8: Voltage Profile Comparison for (a) 1 SVC, (b) 2 SVCs, and (c) 3 SVCs.

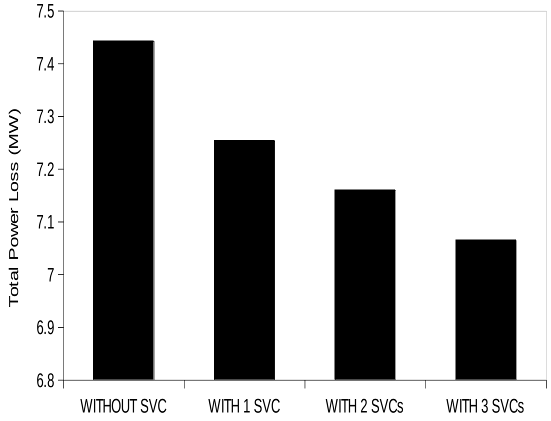


Figure 9: Total Active Power Loss Comparison.

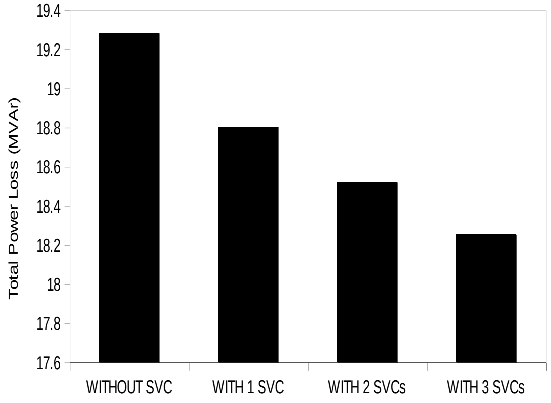


Figure 10: Total Reactive Power Loss Comparison.

CONCLUSION

This paper presents an exponential adaptive bacterial foraging algorithm base approach for allocation of SVCs in transmission lines, considering system loadability. The aim was to improve system security by minimizing losses and voltage deviation. Newton-Raphson classical power flow technique was used to determine the actual state of the system. Based on the outcomes of the base-case power flow analysis, an objective function comprising of P_{Loss} and V_D was formulated. In place of the constant step size employed by the conventional bacterial foraging algorithm, an exponential adaptive step size unit was employed in the proposed EABFA for improved computational speed and also to avoid being trapped in local minima.

Table 6: Bus Voltage Magnitudes.

Bus Number	Without SVCs	With 1 SVC	With 2 SVCs	With 3 SVCs
1	1.050	1.050	1.050	1.050
2	1.100	1.100	1.100	1.100
3	0.891	0.901	0.902	0.904
4	0.990	0.997	0.998	1.000
5	0.942	0.944	0.950	0.953
6	0.977	0.980	0.983	0.988
Mean	0.9916667	0.9953333	0.9971667	0.9991667
Standard Deviation	0.0747761	0.0717152	0.0704966	0.0693755

Table 7: Performance Comparison with and without SVCs.

Parameters	Without SVCs	With 1 SVC	With 2 SVCs	With 3 SVCs
Voltage Magnitude (p.u.)	0.891 (Bus 3)	0.901 (Bus 3)	0.902 (Bus 3)	0.904 (Bus 3)
Overall Voltage Improvement (%)	-	2.00	3.00	4.09
Total P_{Loss} (MW)	7.4427	7.2535	7.1601	7.0645
P_{Loss} Reduction (%)	-	2.54	3.80	5.08
Total Q_{Loss} (MVAr)	19.2829	18.8038	18.5207	18.2535
Q_{Loss} Reduction (%)	-	2.48	3.95	5.94

The proposed method was implemented on Ward and Hale 6-node system. The optimal locations and sizes of SVCs in the test system were determined by using the objective function in the proposed EABFA approach. Analyses were performed for two loading conditions: normal loading and three-quarter loading.

Simulation results indicate that for normal loading condition, 9.76 %, 14.04 % and 17.69 % reduction in active power was achieved with the installation of 1 SVC, 2 SVCs and 3 SVCs respectively. Also, voltage profile improvement of 9 %, 12.91 % and 17.64 % were recorded for the same number of SVCs. Similarly, for three-quarter loading, the proposed approach attained 2.54 %, 3.80 % and 5.08 % reduction in active power loss for 1 SVC, 2 SVCs and 3 SVCs respectively. In terms of voltage profile improvement, the approach recorded 2 %, 3 % and 4.09 % improvement as compared to the base case scenario (with-out SVC).

Future work will consider the effects of hybridizing SVCs with other FACTS devices. The approach will be further tested on larger power systems.

REFERENCES

1. Kang, T., et al. 2017. "A Hybrid Approach for Power System Security Enhancement via Optimal Installation of Flexible AC Transmission System (FACTS) Devices". *Energies*. 10(9): 1305.

2. Le, N.A.B.M., et al. 2017. "The Modeling of SVC for the Voltage Control in Power System". *Indonesian Journal of Electrical Engineering and Computer Science*. 6(3).

3. Choudekar, P., S. Sinha, and A. Siddiqui. 2017. "Optimal Location of SVC for Improvement in Voltage Stability of a Power System under Normal and Contingency Condition". *International Journal of System Assurance Engineering and Management*. 1-7.

4. Gacem, A. and D. Benattous. 2017. "Hybrid GA–PSO for Optimal Placement of Static VAR Compensators in Power System*". International Journal of System Assurance Engineering and Management*. 8(1): 247-254.

5. Hingorani, N.G. and L. Gyugyi. 2000. "Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems". Wiley-IEEE Press: New York, NY.

6. Zhang, X., et al. 2017. "Optimal Allocation of Static Var Compensator via Mixed Integer Conic Programming". arXiv preprint arXiv:1703.09854.

7. Joshi, B.S., O.P. Mahela, and S.R. Ola. 2016. "Reactive Power Flow Control using Static VAR Compensator to Improve Voltage Stability in Transmission System".In: *Recent Advances and Innovations in Engineering (ICRAIE) International Conference* IEEE.

8. Araga, I., A. Anibasa, and I. Alabi. 2017. "Placement of Multiple Svc on Nigerian Grid System for Steady State Operational Enhancement". *American Journal of Engineering Research.* 6(1):78.

9. Alabduljabbar, A.A., et al. 2017. "Implementation Aspects and Comprehensive Assessment of a 16 MVAr Static VAr Compensator Installed for a Weak Distribution Network". *International Transactions on Electrical Energy Systems*.

10. Kumar, S., et al. 2017. "Enhancement of Voltage Profile by Incorporating Static VAR Compensator in IEEE-30 bus system"*. Red Sea University Journal of Basic and Applied Science*. 2 (Special Issue 1).

11. Sikiru, T.H., A.A. Jimoh, and J.T. Agee. 2011. "Optimal Location of Network Devices using a Novel Inherent Network Topology Based Technique". In: *AFRICON*. IEEE.

12. Sikiru, T.H., et al. 2012. "Voltage Profile Improvement based on Network Structural Characteristics. in Transmission and Distribution: Latin America Conference and Exposition (T&D-LA). Sixth IEEE/PES. IEEE.

13. Chakravorty, M. and S. Patra. 2016. "Voltage Stability Analysis using Conventional Methods". In: *Signal Processing, Communication, Power and Embedded System (SCOPES), 2016 International Conference.* IEEE.

14. Jain, P. and R. Dahiya. 2016. Optimal Placement of SVCs based on Sensitivity Analysis using VPI". In: *Electrical, Electronics and Computer Science (SCEECS), 2016 IEEE Students' Conference*. IEEE.

15. Besharat, H. and S.A. Taher. 2008. "Congestion Management by Determining Optimal Location of TCSC in Deregulated Power Systems". *International Journal of Electrical Power & Energy Systems*. 30(10): 563-568.

16. Rao, B.V. and G.N. Kumar. 2014. "Sensitivity Analysis Based Optimal Location and Tuning of Static Var Compensator Using Firefly Algorithm". *Indian Journal of Science and Technology*. 7(8): 1201-1210.

17. Sekhar, A.H. and A.L. Devi. 2017. Optimal Sizing and Placement of Advanced SVC in Transmission System by Using Evolutionary Algorithms". *Manager's Journal on Electrical Engineering*. 10(3): 30.

18. Duraisamy, P. and A. Ponnusamy. 2017. Power System Performance Improvement by Optimal Placement and Sizing of SVC using Genetic Algorithm*. International Journal of Applied Power Engineering (IJAPE)*. 6(2):56-63.

19. Udgir, S., L. Srivastava, and M. Pandit. Optimal Placement and Sizing of SVC for Loss Minimization and Voltage Security Improvement using Differential Evolution Algorithm. *Recent Advances and Innovations in Engineering (ICRAIE),* IEEE.

20. Sirjani, R., A. Mohamed, and H. Shareef. 2011. "Optimal Placement and Sizing of Static Var Compensators in Power Systems using Improved Harmony Search Algorithm*". Przeglad Elektrotechniczny*. 87(7): 214-218.

21. Mohammadi, M., M. Abasi, and A.M. Rozbahani. 2017. Fuzzy-GA Based Algorithm for Optimal Placement and Sizing of Distribution Static Compensator (DSTATCOM) for Loss Reduction of Distribution Network Considering Reconfiguration". *Journal of Central South University.* 24(2): 245-258.

22. Chakravarthy, V.P. and K. Vaisakh. 2017. "Optimal Placement of Shunt and Series Compensators for Minimization of Losses and Maximization of TTC Using PSO"*. Imperial Journal of Interdisciplinary Research*. 3(3).

23. Farsangi, S.E., E. Rashedi, and M.M. Farsangi. 2017. "Multi-objective VAr planning using fuzzy-GSA". *Swarm Intelligence and Evolutionary Computation (CSIEC). 2017 2nd Conference.*. IEEE.

24. Sen, D., S.R. Ghatak, and P. Acharjee. 2017. "Optimal Allocation of Static VAR Compensator by a Hybrid Algorithm"*. Energy Systems*. 1-43.

25. Passino, K.M. 2002. "Biomimicry of bacterial foraging for distributed optimization and control*". Control Systems*, IEEE. 22(3):52-67.

26. Passino, K.M. 2012. "Bacterial foraging optimization. *Innovations and Developments of Swarm Intelligence Applications*. 219.

27. Xing, B. and W.J. Gao. 2014. *Innovative Computational Intelligence: A Rough Guide to 134 Clever Algorithms*. Springer, Berlin, Germany. 62:469.

28. Supriyono, H. and M.O. Tokhi. 2010. "Bacterial Foraging Algorithm with Adaptable Chemotactic Step Size". In: *Second International Conference on Computational Intelligence, Communication Systems and Networks (CICSyN)*. IEEE.

29. Wang, Z., et al. 1996. "A Non-Incremental Model for Optimal Control of Reactive Power Flow*". Electric Power Systems Research*. 39(2):153-159.

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