Research Article

Application of Firefly Algorithm in Voltage Stability Environment Incorporating Circuit Element Model of SSSC with Variable Susceptance Model of SVC

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This paper proposes an application of firefly algorithm (FA) based extended voltage stability margin and minimization of active (or) real power loss incorporating Series-Shunt flexible AC transmission system (FACTS) controller named as static synchronous series compensator (SSSC) combined with static var compensator (SVC). A circuit model of SSSC and variable susceptance model of SVC are utilized to control the line power flows and bus voltage magnitudes, respectively, for real power loss minimization and voltage stability limit improvement. The line quality proximity index (LQP) is used to assess the voltage stability of a power system. The values of voltage profile improvement, real power loss minimization, and the location and size of FACTS devices were optimized by FA. The results are obtained from the IEEE 14- and 30-bus test case systems under different operating conditions and compared with other leading evolutionary techniques such as shuffled frog leaping algorithm (SFLA), differential evolution (DE) and particle swarm optimization (PSO).

1. Introduction

Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all buses in the system under normal conditions and after being subjected to a disturbance [1]. The recent day power systems are undergoing numerous changes and becoming more complex from the standpoints of operation, control, and stability maintenance when they meet ever-increasing load demand [2]. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [3, 4]. The authors [5, 6] discuss methods to assess voltage stability of a power system to find possible ways to improve the voltage stability.

Abnormal voltages and voltage collapse pose a primary threat to power system stability, security, and reliability.

Moreover, with the fast development of restructuring, the problem of voltage stability has become a major concern in deregulated power systems. To maintain security of such systems, it is desirable to plan suitable measures to improve power system security and increase voltage stability margins [7]. Voltage instability is one of the phenomena which have resulted in major blackouts. Recently, several network blackouts have been related to voltage collapse [8]. The only way to counteract this problem is by reducing the reactive power load in the system or by adding new reactive power generation systems in the weakest points of the system, thereby, increasing the voltage at those points.

The flexible AC transmission system (FACTS) controllers are capable of supplying or absorbing reactive power at faster rates [9]. The introduction of FACTS controllers are increasingly used to provide voltage and power flow controls [10]. Insertion of FACTS devices is found to be highly effective in preventing voltage instability and minimize the active or real power loss on transmission lines [11, 12]. Series and shunt

compensating devices are used to enhance the static voltage stability margin and reduce the real power loss appreciably [13, 14].

The generalized power injection model of SSSC needs modification of the Jacobian matrix and makes quite complex in coding. In the SSSC control parameters, voltage magnitude and angle of the series converters are presented as independent variables and their values are found through the traditional load flow iterative process [15]. In this case, the size of the Jacobian matrix increases to incorporate the additional independent variables. The new model of the SSSC changes only the bus admittance matrix and consequently reduces the coding of load flow problem incorporating SSSC simple. The SSSC control parameters, voltage magnitude and angle of the series converters, are presented as independent variables and their values are found through the traditional load flow iterative process. In this case, the size of the Jacobian matrix increases to incorporate the additional independent variables. Hence, a simple and easy way to implement SSSC model based on the circuit elements is used in this work [16].

Voltage stability assessment with appropriate representations of FACTS devices is investigated and compared under base case of study [17–19]. One of the shortcomings of those methods only considered the normal state of the system [20]. The author [21] presented the different computational techniques for voltage stability assessment and control. The author [22] focused on the contingency ranking obtained with respect to overloads in large power systems. Abdelaziz et al. [23] proposed the process of contingency ranking through fuzzy logic approach. However, voltage collapses are mostly initiated by a disturbance like line outages. Voltage stability limit improvement needs to be addressed during network contingencies. So, to locate FACTS devices, consideration of contingency conditions is more important than consideration of normal state of system and some approaches are proposed to locate FACTS devices with considerations of contingencies too [24, 25].

Line stability indices provide important information about the proximity of the system to voltage instability and can be used to identify the weakest bus as well as the critical line with respect to the bus of the system [26]. Different types of line stability indices are proposed to evaluate the proximity of the system to voltage instability [27, 28]. The line quality proximity index is used in this work for stability assessment [29, 30]. From the family of bioluminescence inspired computation, FA is used to solve the problem of real power loss minimization and voltage stability maximization of the system. In the firefly algorithm, the objective function of a given optimization problem is based on differences in light intensity. It helps the fireflies to move towards brighter and more attractive locations in order to obtain optimal solutions. All fireflies are characterized by their light intensity associated with the objective function [31–33].

Because of higher cost of the FACTS devices, the installation is not recommended to all possible line outages. Hence, line outage contingency screening and ranking were carried out to identify the most critical line during which outage FACTS controllers can be positioned and system can be operated under stable condition [34–36]. The prime objective

FIGURE 1: SSSC configuration.

FIGURE 2: Circuit element model of SSSC.

of this work is to obtain the results from standard IEEE 14- and 30-bus test cases through FA incorporating circuit element model of SSSC combined with variable susceptance model of SVC and to compare the results of these series-shunt FACTS controllers with other important evolutionary techniques such as SFLA, DE, and PSO under normal, critical loading and single-line outage conditions.

2. Static Model of FACTS Devices

2.1. Circuit Element Model of SSSC. The SSSC can be operated without an external energy source as reactive power source and is fully controllable and independent of transmission line current for the purpose of increasing or decreasing the overall reactive voltage drop across the transmission line and thereby controlling the electric power flow. The widely used power injection model of SSSC requires modification of the Jacobian matrix and makes the Newton-Raphson load flow (NRLF) coding more complex. A new circuit elements based model of SSSC is utilized to control the line power flows and bus voltage magnitudes for voltage stability limit improvement. The new model of the SSSC changes only the bus admittance matrix and consequently reduces the coding of load flow problem incorporating SSSC simple. This converter performs the main function of injecting a controllable series voltage. The basic configuration of SSSC is depicted in Figure 1. The circuit element model of SSSC is also shown in Figure 2.

The real and reactive powers exchanged with the line by the series voltage inserted by SSSC are modeled as a negative resistance and reactance connected in parallel. The negative resistance represents injection of real power and the reactance may be either capacitive or inductive depending on whether reactive power is delivered or absorbed.

The complex power exchanged by the series converter with the line is expressed as

$$S_e = V_{se} I, \quad (1)$$

where V_{se} is the complex voltage injected by the converter and I the current through the line given by

$$I = \frac{V_i \angle \delta_i + V_{se} \angle \gamma - V_j \angle \delta_j}{Z_L}. \quad (2)$$

The active and reactive powers exchanged with the line are modeled as resistance and reactance associated as represented by

$$R = \frac{V_{se}^2}{P_{se}}, \quad (3)$$

$$X = \frac{V_{se}^2}{Q_{se}}.$$

The elements R and X can be calculated by directly using the following equations:

$$R = \frac{V_{se} Z_L}{V_i \sin(\delta_i - \delta_j - \gamma) + V_j \sin \gamma}, \quad (4)$$

$$X = \frac{V_{se} Z_L}{V_i \cos(\delta_i - \delta_j - \gamma) - V_j \cos \gamma + V_{se}}.$$

The resistance R and the reactance X representing the effect of series voltage are transformed into their equivalent series combination. This makes the line simple with only series-connected elements of the line (Z_L) and the R_{SSC} and X_{SSC} denoting the resistance and reactance of SSC:

$$R_{SSC} = \frac{RX^2}{R^2 + X^2}, \quad (5)$$

$$X_{SSC} = \frac{XR^2}{R^2 + X^2}.$$

2.2. Variable Susceptance Model of SVC. A variable susceptance B_{SVC} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. This model is an improved version of SVC models. Figure 3 shows the variable susceptance model of SVC which is used to derive its nonlinear power equations and the linearised equations required by Newton's load flow method.

In general, the transfer admittance equation for the variable shunt compensator is

$$I_{SVC} = jB_{SVC} V_j. \quad (6)$$

And the reactive power of SVC is

$$Q_{SVC} = -V_j^2 B_{SVC}. \quad (7)$$

FIGURE 3: Variable susceptance model of SVC.

FIGURE 4: Single-line concept of power transmission.

(a) 14-bus system

(b) 30-bus system

FIGURE 5: One-line diagram of IEEE test system.

FIGURE 6: Sum of LQP index values comparison.

In SVC susceptance model, the total susceptance B_{SVC} is taken to be the state variable; therefore the linearised equation of the SVC is given by

$$\begin{bmatrix} \Delta P_j \\ \Delta Q_j \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \theta_j \end{bmatrix} \begin{bmatrix} \Delta \theta_j \\ \frac{\Delta B_{SVC}}{B_{SVC}} \end{bmatrix}, \quad (8)$$

where ΔP_j , ΔQ_j , and $\Delta \theta_j$ are the change in real, reactive power, and voltage angle at j th bus.

At the end of iteration i , the variable shunt susceptance B_{SVC} is updated according to

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}} \right)^{(i)} B_{SVC}^{(i-1)}. \quad (9)$$

This changing susceptance value represents the total SVC susceptance which is necessary to maintain the nodal voltage magnitude at the specified value (1.0 p.u. in this paper).

3. Line Quality Proximity Index

Voltage stability can be assessed in a system by calculating the line based voltage stability index. The LQP index based on a power transmission concept is used in this paper. The value of line index shows the voltage stability of the system. The value close to unity indicates that the respective line is close to its stability limit and value much close to zero indicates light load in the line. The formulation begins with the power equation in a power system. Figure 4 illustrates a single line of a power transmission concept.

The power equation can be derived as

$$P_i = \sqrt{\frac{V_i^2}{X} (Q_i - Q_j) - Q_i^2}. \quad (10)$$

The line stability factor is obtained by setting the discriminant of the reactive power roots at bus 1 to be greater than or equal to zero, thus defining the line stability factor, LQP, as

$$LQP = 4 \left(\frac{X}{V_i^2} \right) \left(\frac{X}{V_i^2} P_i^2 + Q_j \right). \quad (11)$$

4. Problem Formulation

The objective function of this work is to find the optimal rating and location of FACTS devices combination which minimizes the real power loss, minimizes voltage deviation, and maximizes the voltage stability limit. Hence, the objective function can be expressed as

$$F = \min \{P_L + wVD + (1 - w) LQP\}, \quad (12)$$

where w is the weighing factor for voltage deviation and is set to 10.

4.1. *Minimization of Real Power Loss (P_L)*. The total real power of the system can be calculated as follows:

$$P_{loss} = \sum_{k=1}^{N_L} G_k [V_i^2 + V_j^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j)], \quad (13)$$

where N_L is the total number of lines in the system; G_k is the conductance of the line “ k ”; V_i and V_j are the magnitudes of the sending end and receiving end voltages of the line; and δ_i and δ_j are angles of the end voltages.

4.2. *Minimization of Load Bus Voltage Deviation (VD)*. Bus voltage magnitude should be maintained within the allowable range to ensure quality service. Voltage profile is improved by minimizing the deviation of the load bus voltage from the reference value (it is taken as 1.0 p.u. in this work):

$$VD = \sum_{k=1}^{N_{PQ}} |V_i - V_{ref}|, \quad (14)$$

where V_i is the voltage at i th bus and V_{ref} is the reference voltage.

4.3. *Minimization of Line Quality Proximity Index (LQP)*. Voltage stability limit of a power system is increased by minimizing voltage stability index value. The indicator takes values between 0 (no load) and 1 (full load). The line based stability index (LQP) is given as

$$LQP = \sum_{j=1}^{N_L} LQP_j. \quad (15)$$

FIGURE 7: (a) Voltage profile values comparison for 14-bus system. (b) Voltage profile values comparison for 30-bus system.

4.4. Constraints. The minimization problem is subject to the following equality and inequality constraints.

4.4.1. Equality Constraints

Load Flow Constraints. Consider

$$\begin{aligned} P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \cos(\delta_{ij} + \gamma_j - \gamma_i) &= 0, \\ Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \sin(\delta_{ij} + \gamma_j - \gamma_i) &= 0, \end{aligned} \quad (16)$$

where P_{Gi} and Q_{Gi} are the active and reactive powers of i th generator and P_{Di} and Q_{Di} are the active and reactive powers of i th load bus.

4.4.2. Inequality Constraints

Reactive Power Generation Limit of SVCs. By choosing small-sized compensator, capital cost involved can be minimum.

The size limit of SVC has been taken from minimum of 5 MVAR to maximum of 20 MVAR:

$$Q_{SVCi}^{\min} \leq Q_{SVCi} \leq Q_{SVCi}^{\max}; \quad i \in N_{SVC}, \quad (17)$$

where $Q_{SVCi}^{\min}$ and $Q_{SVCi}^{\max}$ are the minimum and maximum VAR injection limits of i th shunt capacitor.

Voltage Constraints. The acceptable voltage limits in all load buses are taken from 0.95 p.u. to 1.05 p.u. to avoid voltage instability:

$$V_i^{\min} \leq V_i \leq V_i^{\max}; \quad i \in N_B, \quad (18)$$

where $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum value voltage of bus " i ".

Transmission Line Flow Limit. Consider

$$S_i \leq S_i^{\max}; \quad i \in N_l, \quad (19)$$

where S_i is the apparent power flow of i th branch and $S_i^{\max}$ is the maximum apparent power flow limit of i th branch.

FIGURE 8: Percentage of real power loss reduction under all cases.

TABLE 1: Optimal values of FA parameters.

Parameters	Optimal Values
Number of fireflies	30
β_0	0.1
γ	0.2
α	0.25
m	4.0
d	2.0
Maximum iterations	100

5. Firefly Algorithm

5.1. Overview. The firefly algorithm (FA) is a metaheuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions. It was developed by Dr. Xin-She Yang at Cambridge University in 2007, and it is based on the swarm behavior such as fish, insects, or bird schooling in nature. In particular, although the firefly algorithm has many similarities with other algorithms which are based on the so-called swarm intelligence, such as the famous particle swarm optimization (PSO), artificial bee colony optimization (ABC), and bacterial foraging algorithms (BFA), it is indeed much simpler in both concept and implementation. Furthermore, according to recent bibliography, the algorithm is very efficient and can outperform other conventional algorithms, such as genetic algorithms, for solving many optimization problems, a fact that has been justified in a recent research, where the statistical performance of the firefly algorithm was measured against other well-known optimization algorithms using various standard stochastic test functions. Its main advantage is the fact that it uses mainly real random numbers and it is based on the global communication among the swarming particles (i.e., the fireflies), and as a result, it seems more effective in multiobjective optimization such as the economic emissions load dispatch problem in our case.

The firefly algorithm has three particular idealized rules which are based on some of the major flashing characteristics of real fireflies. These rules are the following.

- (i) All fireflies are unisex, and they will move towards more attractive and brighter ones regardless their sex.
- (ii) The degree of attractiveness of a firefly is proportional to its brightness which decreases as the distance from the other firefly increases due to the fact that the air absorbs light. If there is no brighter or more attractive firefly than a particular one, it will then move randomly.
- (iii) The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem. For maximization problems, the light intensity is proportional to the value of the objective function.

5.2. Implementation

5.2.1. Attractiveness. In the firefly algorithm, the form of attractiveness functions of a firefly is the following monotonically decreasing function:

$$\beta(r) = \beta_0 * \exp(-\gamma r^m), \quad \text{with } m \geq 1, \quad (20)$$

where r is the distance between any two fireflies, β_0 is the initial attractiveness at $r = 0$, and γ is an absorption coefficient which controls the decrease of the light intensity.

5.2.2. Distance. The distance between any two fireflies i and j , at positions x_i and x_j , respectively, can be defined as a Cartesian or Euclidean distance as follows:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2}, \quad (21)$$

where $x_{i,k}$ is the k th component of the spatial coordinate x_i of the i th firefly and d is the number of dimensions we have, for $d = 2$; we have

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}. \quad (22)$$

However, the calculation of distance r can also be defined using other distance metrics, based on the nature of the problem, such as Manhattan distance.

TABLE 2: Voltage stability index values of most stressed lines.

(a) For 14-bus system						
Cases	Line number	Preinsertion of FACTS	FA	Postinsertion of FACTS		
				SFLA	DE	PSO
Case 1	14	0.1122	0.0714	0.0818	0.0807	0.0829
	20	0.0776	0.0582	0.0537	0.0544	0.0617
	1	0.0688	0.0447	0.0511	0.0491	0.0519
	17	0.0593	0.0310	0.0388	0.0408	0.0503
	9	0.0515	0.0291	0.0346	0.0307	0.0401
Case 2	10	0.2580	0.1106	0.1722	0.1651	0.1995
	14	0.1815	0.0994	0.0991	0.1012	0.1244
	20	0.1494	0.0912	0.0941	0.1109	0.1286
	9	0.1393	0.0833	0.0994	0.1081	0.1120
	1	0.0799	0.0517	0.0604	0.0597	0.0661
Case 3	10	0.1904	0.1014	0.0941	0.1057	0.1129
	15	0.1160	0.0809	0.0802	0.0914	0.0956
	6	0.0914	0.0529	0.0317	0.0441	0.0582
	4	0.0793	0.0447	0.0406	0.0533	0.0551
	9	0.0648	0.0361	0.0304	0.0369	0.0408
(b) For 30-bus system						
Cases	Line number	Preinsertion of FACTS	FA	Postinsertion of FACTS		
				SFLA	DE	PSO
Case 1	12	0.3691	0.3664	0.3687	0.3700	0.3683
	5	0.1284	0.0695	0.1264	0.0987	0.1282
	13	0.1226	0.0722	0.0114	0.1169	0.1095
	15	0.0749	0.0713	0.0748	0.0752	0.0749
	14	0.0678	0.0667	0.0674	0.0676	0.0672
Case 2	12	0.3899	0.3861	0.3877	0.3874	0.3881
	5	0.3596	0.0884	0.3310	0.0793	0.3312
	13	0.2549	0.2115	0.2355	0.2351	0.2390
	16	0.1687	0.1241	0.1735	0.1767	0.1610
	15	0.1255	0.1167	0.1245	0.1244	0.1249
Case 3	12	0.3851	0.3688	0.3864	0.3686	0.3793
	13	0.1732	0.1159	0.1766	0.1152	0.1711
	16	0.0836	0.0445	0.0855	0.0475	0.0833
	1	0.0786	0.0540	0.0810	0.0568	0.0694
	15	0.0775	0.0741	0.0776	0.0749	0.0771

5.2.3. *Movement.* The movement of a firefly i which is attracted by a more attractive (i.e., brighter) firefly j is given by the following equation:

$$x_i = x_i + \beta_0 * \exp(-\gamma r_{ij}^2) * (x_i - x_j) + \alpha * \left(\text{rand} - \frac{1}{2}\right), \quad (23)$$

where the first term is the current position of a firefly, the second term is used for considering a firefly's attractiveness to light intensity seen by adjacent fireflies, and the third term issued for the random movement of a firefly in case there are no any brighter ones. The coefficient α is a randomization parameter determined by the problem of interest, while rand is a random number generator uniformly distributed in the

space (0,1). As we will see in this implementation of the algorithm, we use $\beta_0 = 0.1$, $\alpha \in [0, 1]$, and the attractiveness or absorption coefficient $\gamma = 0.2$, which guarantees a quick convergence of the algorithm to the optimal solution. The optimal values of firefly parameters are in Table 1.

6. Results and Discussion

The proposed work is coded in MATLAB 7.6 platform using 2.8 GHz Intel Core 2 Duo processor based PC. The method is tested in the IEEE 14- and 30-bus test systems shown in Figure 5. The line data and bus data are taken from the standard power system test case archive. The 14-bus system has 5 generator buses, 9 load buses, and 20 transmission lines.

TABLE 3: Contingency ranking.

Rank	14-bus system		30-bus system	
	Line number	LQP values	Line number	LQP values
1	1	0.5795	5	0.9495
2	3	0.3826	9	0.6050
3	10	0.3449	2	0.4993
4	2	0.3157	4	0.4968
5	15	0.1984	7	0.4693

TABLE 4: Average load bus voltage values in p.u.

(a) For 14-bus system

Cases	Preinsertion of FACTS	Postinsertion of FACTS			
		FA	SFLA	DE	PSO
Case 1	1.0438	1.0517	1.0494	1.0483	1.0460
Case 2	0.9890	1.0082	1.0013	1.0051	0.9966
Case 3	1.0243	1.0409	1.0363	1.0331	1.0308

(b) For 30-bus system

Cases	Preinsertion of FACTS	Postinsertion of FACTS			
		FA	SFLA	DE	PSO
Case 1	1.0260	1.0296	1.0306	1.0288	1.0265
Case 2	0.9520	0.9961	0.9664	0.9626	0.9602
Case 3	1.0109	1.0380	1.0108	1.0298	1.0222

The 30-bus system has 6 generator buses, 24 load buses, and 41 transmission lines. System data and results are based on 100 MVA and bus number 1 is the reference bus. In order to verify the presented models and illustrate the impact of circuit element model of SSSC with variable susceptance model of SVC combination study, three different operating conditions are considered as mentioned below.

Case 1. The system with normal load in all the load buses is considered as normal condition and the Newton-Raphson load flow is carried out with loading factor value equal to 1.

Case 2. The system with 50% increased load in all the load buses is considered as a critical condition. Loading of the system went beyond this level and results in poor voltage profile in the load buses and unacceptable real power loss level.

Case 3. Contingency is imposed by considering the most critical line outage in the system. This is the most suitable condition for voltage stability analysis of a power system as voltage stability is usually triggered by line outages.

Newton-Raphson program is repeatedly run with the absence and presence of FACTS device combination. The voltage stability limit improvement is assessed by the value of LQP index. The voltage stability index values of top five stressed lines under all cases with preinsertion and postinsertion of FACTS devices are shown in Table 2. It is evident from the table that LQP values of the stressed lines are reduced after placement of FACTS devices in the system.

For quick assessment of voltage stability limit improvement of the system under the three different operating conditions, sum of the LQP index values of all the lines before and after the insertion of FACTS devices combination is compared in Figure 6. The reduction in the index value through the proposed method indicates the best voltage stability limit improvement.

The line outage is ranked according to the severity and the severity is taken on the basis of the line quality proximity index values and such values are arranged in descending order. The maximum value of index indicates most critical line for outage. Line outage contingency screening and ranking are carried out on the test systems and the results are shown in Table 3.

It is clear from Table 3 that outage of lines numbers 1 and 5 are the most critical line outages of 14- and 30-bus systems, respectively. This situation is considered for voltage stability improvement. Outage of other lines has not much impact on the system and therefore they are not given importance. Load flow is run on the system with the lines that have outages. Outage of these lines results in large real power loss and voltage profile reduction in most of the load buses. The system is under stressed conditions and needs to be relieved by some means. Installation of FACTS devices at suitable locations can relieve the system much from stressed conditions (reduced line losses).

FACTS devices help the system to maintain acceptable voltage profile in the load buses. Under normal operating conditions, most of the bus voltage magnitudes are within the normal value. During critical and contingency conditions, voltage magnitude of remote load buses are below 0.95 (lower

TABLE 5: Minimum-maximum load bus voltage values in p.u.

(a) For 14-bus system												
Cases	Preinsertion of FACTS	Bus number	V_{MIN}				Preinsertion of FACTS	Bus number	V_{MAX}			
			Postinsertion of FACTS						Postinsertion of FACTS			
			FA	SFLA	DE	PSO			FA	SFLA	DE	PSO
Case 1	1.0173	4	1.0252	1.0211	1.0203	1.0143	1.0604	7	1.0696	1.0673	1.0642	1.0617
Case 2	0.9656	14	1.0004	0.9884	0.9933	0.9824	1.0101	7	1.0211	1.0176	1.0199	1.0155
Case 3	0.9913	5	1.0264	1.0208	1.0104	1.0111	1.0350	13	1.0496	1.0490	1.0460	1.0438
(b) For 30-bus system												
Cases	Preinsertion of FACTS	Bus number	V_{MIN}				Preinsertion of FACTS	Bus number	V_{MAX}			
			Postinsertion of FACTS						Postinsertion of FACTS			
			FA	SFLA	DE	PSO			FA	SFLA	DE	PSO
Case 1	0.9953	30	0.9978	0.9976	0.9959	0.9954	1.0576	11	1.0820	1.0820	1.0820	1.0822
Case 2	0.8915	30	0.9662	0.9035	0.9415	0.9410	1.0004	11	1.0667	1.0620	1.0520	1.0550
Case 3	0.9661	5	1.0121	0.9600	0.9600	0.9607	1.0495	11	1.0820	1.0820	1.0820	1.0820

TABLE 6: Real power loss values comparison (in MW).

(a) For 14-bus system					
Conditions	Preinsertion of FACTS (initial)	Postinsertion of FACTS			
		FA	SFLA	DE	PSO
Case 1	13.401	11.014	11.409	11.693	12.106
Case 2	35.042	28.018	28.991	28.875	29.019
Case 3	24.183	18.046	19.255	19.389	19.771

(b) For 30-bus system					
Conditions	Preinsertion of FACTS (Initial)	Postinsertion of FACTS			
		FA	SFLA	DE	PSO
Case 1	17.514	13.467	14.852	16.157	16.504
Case 2	46.900	40.990	45.797	41.258	43.272
Case 3	32.569	22.801	29.272	23.234	25.561

bound of allowable value). These bus voltages are improved after the FACTS devices are installed. Voltage profile value comparison under all cases incorporating the series-shunt FACTS devices combination is depicted separately in Figures 7(a) and 7(b) under both test cases. It is obvious from the figure that voltage profile comparison of the system is improved better with the proposed method incorporating FACTS devices combination. The comparison of average value of load bus voltage also proves the enhancing behavior of voltage stability limit incorporating with FACTS devices of all cases shown in Table 4. Table 5 exposes the comparison of minimum and maximum load bus voltages in both the absence and presence of FACTS devices under all cases.

In real power loss minimization point of view through insertion of FACTS devices, the real power loss under Case 1 is decreased by 2.387 and 4.047 MW, respectively, for 14- and 30-bus systems. In Case 2, the reduction in real power loss rate is 7.024 and 5.910 MW, respectively. The reduction rate in real power loss is 6.137 and 9.768 MW,

respectively, under Case 3 operation. The real power loss values of proposed method compared with other important evolutionary techniques under all cases are shown in Table 6.

The percentage of reduction in real power loss comparison under all cases including both combinations is depicted in Figure 8. Obviously from the results shown in Table 6, the proposed method is more efficient than other evolutionary techniques given here to reduce the real power loss minimization application. The much reduction in real power loss and increase in voltage magnitudes after the insertion of FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability limit. The most suitable size and location of combinations of FACTS devices to improve the voltage stability limit and real power loss minimization are also given in Table 7 under all cases with 14- and 30-bus systems, respectively. The optimized size of SVC inserted with both combinations is not in larger value which helps to reduce in cost.

TABLE 7: Best location and size of FACTS devices.

(a) For 14-bus system

Cases			Series	Shunt	
		Location (line number)	Size (degrees of compensation)	Location (bus number)	Size (MVar)
Case 1	FA	10	$0.0722 + j0.1464$	5	7.2015
	SFLA	4	$0.0377 + j0.0916$	12	8.6554
	DE	15	$0.0461 + j0.1540$	10	6.9988
	PSO	3	$0.0622 + j0.1067$	12	8.3037
Case 2	FA	12	$0.0823 + j0.0961$	13	11.211
	SFLA	1	$0.0536 + j0.1642$	11	10.6217
	DE	9	$0.0507 + j0.1145$	12	9.9654
	PSO	11	$0.0727 + j0.0836$	10	7.2510
Case 3	FA	12	$0.0769 + j0.0810$	13	9.6817
	SFLA	10	$0.0421 + j0.1162$	5	10.6528
	DE	2	$0.0489 + j0.0773$	11	8.9207
	PSO	7	$0.0673 + j0.1286$	10	11.4368

(b) For 30-bus system

Cases		Series		Shunt	
		Location (line number)	Size (degrees of compensation)	Location (bus number)	Size (MVar)
Case 1	FA	5	$0.0159 + j0.0924$	12	8.6962
	SFLA	1	$0.0086 + j0.0833$	19	6.9688
	DE	6	$0.0239 + j0.2664$	20	5.8131
	PSO	12	$0.0191 + j0.0977$	23	15.0806
Case 2	FA	6	$0.0137 + j0.0384$	17	9.0607
	SFLA	9	$0.0170 + j0.1243$	21	14.1058
	DE	5	$0.0289 + j0.0931$	30	6.2554
	PSO	8	$0.0281 + j0.0447$	18	19.0106
Case 3	FA	11	$0.0311 + j0.1417$	26	8.0115
	SFLA	9	$0.0115 + j0.1302$	28	6.7499
	DE	6	$0.0112 + j0.0478$	25	5.8559
	PSO	8	$0.0291 + j0.1189$	3	18.2640

7. Conclusion

In this paper, optimal location and size of series-shunt FACTS devices for voltage stability limit improvement and loss minimization through firefly algorithm are demonstrated. The voltage stability limit improvement and real power loss minimization are done under three operating cases such as normal, critical loading, and line outage contingency conditions. The LQP index is used for voltage stability assessment. The circuit element model of SSSC is considered to improve the voltage stability limit by controlling power flows and maintaining voltage profile. This model is easy to incorporate the effect of SSSC into Newton-Raphson load flow program coding. The variable susceptance model of SVC is used in a combined manner with SSSC. It is clear from the numerical results that voltage stability limit improvement and real power loss minimization are highly encouraging. The real power loss minimization and voltage stability limit improvement is remarkable by the combined action of power flow control of SSSC and reactive power compensation by SVC through firefly algorithm over other evolutionary optimization techniques given in this paper.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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