academicJournals

Vol. 8(24), pp. 1121-1133, 25 June, 2013
DOI 10.5897/SRE2013.5510
ISSN 1992-2248 © 2013 Academic Journals
http://www.academicjournals.org/SRE

Scientific Research and Essays

Full Length Research Paper

Static synchronous series compensator and static var compensator interaction on voltage stability limit enhancement and active power loss minimization through differential evolution algorithm

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Accepted 18 June, 2013

This paper proposes an application of differential evolution (DE) algorithm based extended voltage stability margin and minimization of real power loss incorporating static synchronous series compensator (SSSC) and static var compensator (SVC) devices. A new circuit element based model of SSSC and variable susceptance model of SVC are utilized to control the line power flows and bus voltage magnitudes for voltage stability limit improvement. The line stability index is used to assess the voltage stability of a power system. Voltage profile improvement values, real power loss minimization values and the location and size of SSSC and SVC devices were optimized by differential evolution algorithm. The results are obtained from the IEEE-30 Bus test case system and were analyzed with the voltage and real power loss under normal loading, critical loading and single line outage contingency conditions.

Key words: Differential evolution algorithm (DEA), voltage stability, static synchronous series compensator (SSSC), static var compensator (SVC), line stability index, FACTS devices, load flow.

INTRODUCTION

The recent power systems are undergoing numerous changes and becoming more complex from operation, control and stability maintenance stand points when they meet ever-increasing load demand (Kundur, 1994). 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. 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 (Van Cutsem, 2000). Excessive voltage decline can occur following some severe system contingencies and this situation could be aggravated, possibly leading to voltage collapse, by further tripping of more transmission facilities, var sources or generating units due to over

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loading. Many large interconnected power systems are increasingly experiencing abnormally high or low voltages or voltage collapse.

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 (Dobson and Chiang, 1989). Voltage instability is one of the phenomena which have result in a major blackout. Recently, several network blackouts have been related to voltage collapses (Technical Analysis of August 14, 2003; A Report). The Flexible AC Transmission System (FACTS) controllers are capable of supplying or absorption of reactive power at faster rates (Xu and Chen, 2000). The introduction of Flexible AC Transmission System (FACTS) controllers are increasingly used to provide voltage and power flow controls. Insertion of FACTS devices is found to be highly effective in preventing voltage instability (Hingorani and Gyugyi, 2000). Series and shunt compensating devices are used to enhance the static voltage stability margin.

Voltage stability assessment with appropriate representations of FACTS devices are investigated and compared under base case of study (Canizares and Faur, 1999; Sode-Yome and Mithulanathan, 2005; Musunuri and Dehnavi, 2010). One of the shortcomings of those methods only considered the normal state of the system. 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 (Jafari and Afsharnia, 2007).

The generalized power injection model of SSSC needs modification of the Jacobian matrix and makes quiet complex in coding. 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 (Zhang and Zhang, 2006). 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 to implement SSSC model based on the circuit elements is used in this paper (Motie-Birjandi and Sabzawari, 2010). The SVC is modeled as a variable reactive power source/sink at the connected bus. The author (Jebaraj et al., 2012) makes use of the same model of SSSC and SVC incorporation through shuffled frog leaping algorithm under stressed conditions. Line stability indices provided important information about the proximity of the system to voltage instability and can be used to identify the weakest bus as well the critical line with respect to the bus of the system. The LQP line stability index is used in this paper for stability assessment (Reis et al., 2009). From the family of evolutionary computation, differential evolution (DE) algorithm is used to solve a problem of real power loss minimization and voltage stability maximization of the system.

The DE algorithm is a population based algorithm like genetic algorithms using the similar operators of crossover, mutation and selection. Several transformer tap positions along with numbers of reactive power injections at some selected buses in a power system are simultaneously optimized as control variables, so that the multiple objectives are fulfilled, keeping an eye to all specified constraints (Price and Storn, 1995). The authors (Vasan and Siminovic, 2010) make a successful implementation of DEA to water resource distribution network. Because of higher cost of the SSSC and SVC, the installation is not recommended to all possible line outages. Hence line outage contingency screening and ranking carried out to identify the most critical line during whose outage SSSC and SVC controllers can be positioned and system can be operated under stable condition (Reppen et al., 1993; Ejebe et al., 1995; Vaahedi et al., 1995). The prime objective of this paper is to improve the voltage stability limit and real power limit of a power system during critical loading and single line outage contingency conditions performed by insertion of SSSC and SVC devices through differential evolution algorithm.

STATIC MODEL OF FACTS DEVICES

Static 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 1 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

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

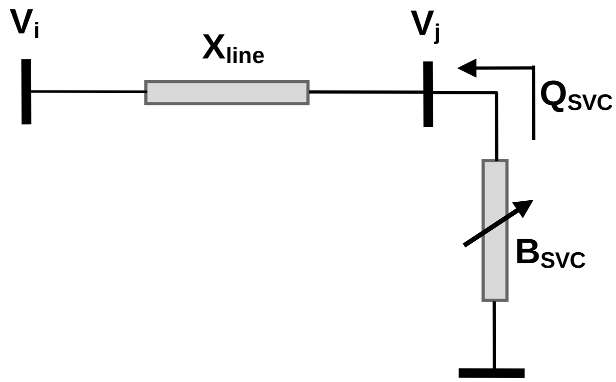

Figure 1. Variable susceptance model of SVC.

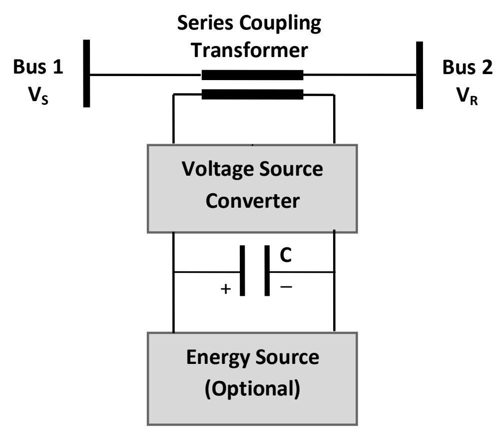

Figure 2. SSSC configuration.

And the reactive power is

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

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

$$\begin{bmatrix} \Delta Pj \\ \Delta Qj \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \theta_j \end{bmatrix} \begin{bmatrix} \Delta\theta j \\ \Delta Bsvc/Bsvc \end{bmatrix} \tag{3}$$

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

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + (\Delta B_{SVC}/B_{SVC})^{(i)} B_{SVC}^{(i-1)} \tag{4}$$

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).

Static model of SSSC

The static synchronous series compensator (SSSC) can be operated without an external energy source as reactive power source with and fully controllable 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 2. The model of SSSC is also shown in Figure 3. The real and reactive powers exchanged with the line by the series voltage inserted by SSSC are

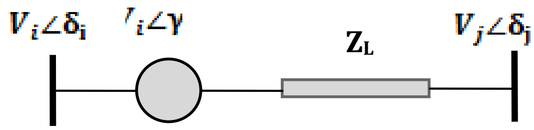

Figure 3. Model of SSSC.

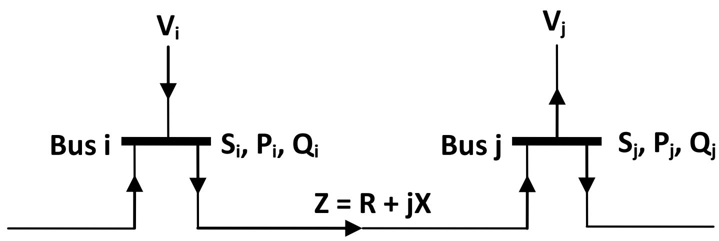

Figure 4. Single line concept of power transmission.

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

$$S_e = V_{se} I \tag{5}$$

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

$$I = \frac{V_i\angle\delta_i + V_{se}\angle\gamma - V_j\angle\delta_j}{Z_L} \tag{6}$$

The active and reactive powers exchanged with the line are modeled as resistance and reactance associated as in Equations 7 and 8.

$$R = \frac{V_{se}^2}{P_{se}} \tag{7}$$

$$X = \frac{V_{se}^2}{Q_{se}} \tag{8}$$

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

$$R = \frac{V_{se} Z_L}{V_i \sin(\delta_i - \delta_j - \gamma) + V_j \sin\gamma} \tag{9}$$

$$X = \frac{V_{se} Z_L}{V_i \cos(\delta_i - \delta_j - \gamma) - V_j \cos\gamma + V_{se}} \tag{10}$$

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 (X_L) and the R_{SSSC} and X_{SSSC} denoting the SSSC.

$$R_{SSSC} = \frac{RX^2}{R^2 + X^2} \tag{11}$$

$$X_{SSSC} = \frac{XR^2}{R^2 + X^2} \tag{12}$$

Line quality proximity index

Voltage stability can be assessed in a system by calculating the line based voltage stability index. The line stability index (LQP) 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:

$$\frac{X}{V_i^2} Q_i^2 - Q_i + \left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \tag{13}$$

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:

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \tag{14}$$

Problem formulation

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

$$F = \min\{P_L + wVD + (1 - w)LQP\} \tag{15}$$

Where w is the weighing factor for voltage deviation and LQP index and is set to 10.

Real power loss minimization (P_L)

The total real power of the system can be calculated as follows

$$P_L = \sum_{k=1}^{N_L} G_k[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \tag{16}$$

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; δ_i and δ_j are angles of the sending and receiving end voltages.

Load bus voltage profile deviation minimization (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).

$$VD = \sum_{k=1}^{N_{PQ}} |(V_i - V_{ref})| \tag{17}$$

where V_K is the voltage of a specified load bus, V_{ref} is the voltage of the reference bus and N_{PQ} is the total number of load buses in the proposed test system.

Line voltage stability index minimization (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 (LPQ) is given as:

$$LQP = \sum_{j=1}^{N_L} LQP_j \tag{18}$$

where N_L is the total number of lines in the proposed test system.

Constraints

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

Equality constraints:

1. Load flow constraints:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij}\cos(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{19}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij}\sin(\delta_{ij} + \gamma_j - \gamma_i) = 0 \tag{20}$$

where P_{Gi} is the real power generated power at bus I, P_{Di} is the real power demand at bus I, Q_{Gi} is the reactive power generated power at bus I, Q_{Di} is the reactive power demand at bus I, V_i is the voltage magnitude at bus I, V_j is the voltage magnitude at bus j, Y_{ij} is the admittance of the line conductor between bus i and j, δ_{ij} is the load angle of the line between bus i and j, γ_i is the magnitude of injected voltage at bus I, and γ_j is the magnitude of injected voltage at bus j.

Inequality constraints:

1. Reactive power generation limit of SVCs:

$$Q_{SVCi}^{min} \le Q_{SVCi} \le Q_{SVCi}^{max}; i \in N_{SVC} \tag{21}$$

2. Reactance limits of TCSCs:

$$-0.8X_{ij} \le X_{TCSC\,k} \le 0.2X_{ij}; k \in N_{TCSC} \tag{22}$$

3. Voltage constraints:

$$V_i^{min} \le V_i \le V_i^{max}; i \in N_B \tag{23}$$

4. Transmission line flow limit:

$$S_i \leq S_i^{max}; i \in N_l \qquad (24)$$

Where Q_{SVCi} is the reactive power generation of i^{th} SVC (i = 1, 2…N), N_{SVC} is the number of SVC connected to the system, X_{TCSCk} is the reactance of the k^{th} TCSC (k=1, 2…N), N_{TCSC} is the number of TCSC connected to the system, V_i is the voltage magnitude of bus i (i = 1, 2…N_B), S_i is the transmission line flow of the i^{th} line (i = 1, 2…N_L).

Differential evolution algorithm

Overview

Differential evolution (DE) is a population based evolutionary algorithm, capable of handling non-differentiable, nonlinear and multi-modal objectives functions. DE generates new offspring by forming a trial vector of each parent individual of the population. The population is improved iteratively, by three basic operations namely mutation, crossover and selection. A brief description of different steps of DE algorithm is given below.

Initialization: The population is initialized by randomly generating individuals within the boundary constraints

$$X_{ij}^0 = X_j^{min} + rand\left(X_j^{max} = X_j^{min}\right); i = 1,2,3, \ldots NP, j = 1,2,3, \ldots D \quad (25)$$

where "rand" function generates random values uniformly in the interval (0, 1); NP is the size of the population; D is the number of decision variables. X_j^{min} and X_j^{max} are the lower and upper bound of the j^{th} decision variable, respectively.

Mutation: As a step of generating offspring, the operations of "Mutation" are applied. "Mutation" occupies quite an important role in the reproduction cycle. The mutation operation creates mutant vectors V_i^k by perturbing a randomly selected vector X_a^k with the difference of two other randomly selected vectors X_b^k and X_c^k at the k^{th} iteration as per the following equation:

$$V_i^k = X_a^k - (X_b^k - X_c^k); i = 1,2,3 \ldots\ldots NP \qquad (26)$$

X_a^k, X_b^k and X_c^k are randomly chosen vectors at the K^{th} iteration and $a \neq b \neq c \neq i$ and are selected a new for each parent vector. *F* is the scaling constant that controls the amount of perturbation in the mutation process and improves convergence.

Crossover: Crossover represents a typical case of a "genes" exchange. The trial one inherits genes with some probability. The parent vector is mixed with the mutated vector to create a trial vector, according to the following equation:

$$U_{ij}^k = \begin{cases} V_{ij}^k, \text{if rand} < CR \text{ or } j = q \\ X_{ij}^k, \text{Otherwise} \end{cases} \qquad (27)$$

Where *i=1, 2, 3……………NP*; *j=1, 2, 3…………..D*. X_{ij}^k, V_{ij}^k U_{ij}^k are the j^{th} individual of target vector, mutant vector, and trial vector at k^{th} iteration, respectively. *q* is a randomly chosen index in the range (*1,D*) that guarantees that the trial vector gets at least one parameter from the mutant vector. CR is the cross over constant that lies between 0 and 1.

Selection: Selection procedure is used among the set of trial vector and the updated target vector to choose the best one. Selection is realized by comparing the fitness function values of target vector and trial vector. Selection operation is performed as per the following equation:

$$X_i^{k+1} = \begin{cases} U_i^k, \text{if } \left(U_i^k\right) \leq f\left(X_i^k\right); i = 1,2,3 \ldots\ldots NP \\ X_i^k, \text{Otherwise} \end{cases} \qquad (28)$$

Implementation

Representing an Individual: Each individual in the population is defined as a vector containing the values of control parameters including the size of the SSSC and SVC.

Number of individuals: There is a trade-off between the number of individuals and the number of iterations of the population and each individual fitness value has to be evaluated using a power flow solution at each iteration; thus, the number of individuals should not be large because computational effort could increase dramatically. Individuals of 10, 20 and 50 are chosen as an appropriate population sizes.

Feasible region definition: There are several constraints in this problem regarding the characteristics of the power system and the desired voltage profile. Each of these constraints represents a limit in the search space. Therefore the DE algorithm has to be programmed so that the individual can only move over the feasible region. For instance, the network in Figure 5 has 4 transmission lines with tap changer transformer. These lines are not considered for locating SSSC, leaving 37 other possible locations for the SSSC. In terms of the algorithm, each time that an individual's new position includes a line with tap setting transformer, the position is changed to the geographically closest line (line

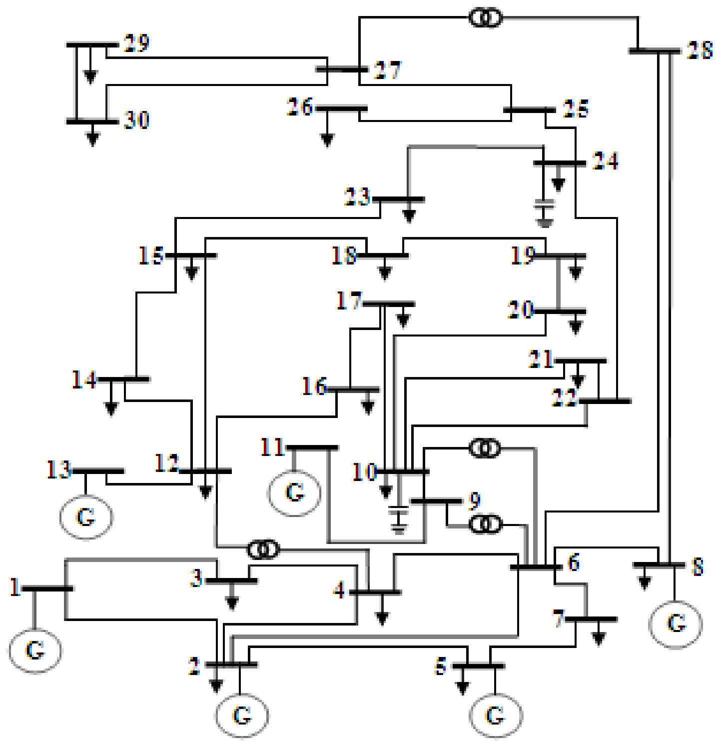

Figure 5. One line diagram of IEEE 30 Bus test system.

Table 1. Optimal values of differential evolution parameters.

Parameter	Optimal values
Number of individuals	50
Cross over constant	0.6
Scaling constant	0.3
Number of iterations	100

without transformer). Finally, in order to limit the sizes of the SSSC units, the restrictions of level of compensation is applied to the individuals. The optimal parameter values of differential evolution algorithm shown in Table 1.

Integer DE: For this particular application, the position of individuals is determined by an integer number (line number). Therefore the individuals' movement is approximated to the nearest integer numbers. Additionally, the location number must not be a line with tap setting transformer. If the location is in line with tap setting transformer, then the individual component regarding position is changed to the geographically closest line without a tap setting transformer.

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 30 bus test system as shown in Figure 5. The line data and bus data are taken from the standard power system test case archive. The system has 6 generator buses, 24 load buses and 41 transmission lines. System data and results are based on 100 MVA and bus no 1 is the reference bus. In order to verify the presented models and illustrate the impacts of SSSC and SVC 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, resulting in poor voltage profile in the load buses and unacceptable real power loss level.

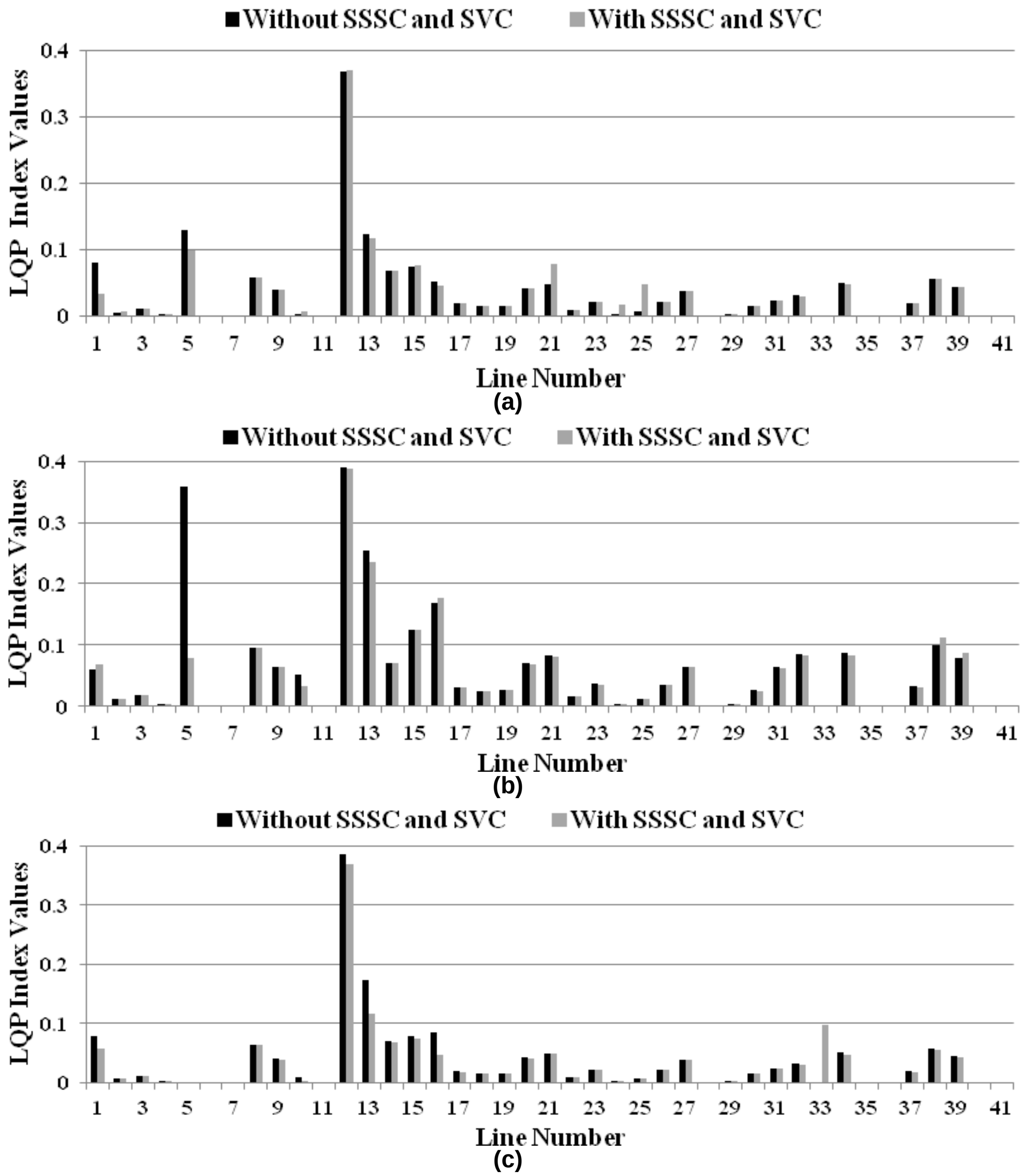

Figure 6. LQP Index values under (a) normal conditions (b) critical loading conditions (c) single line outage contingency condition.

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 presence and absence of SSSC and SVC devices. The voltage stability limit improvement is assessed by the value of LQP index. The LQP values of all lines under normal conditions with and without FACTS devices are depicted in Figure 6(a). Figure 6(b) compares the index value of all the lines in the system under critical loading condition. It is evident from the figures that LQP values of most of the lines are reduced after placement of FACTS devices in the system.

In case 3, the line outage is ranked according to the severity and the severity is taken on the basis of the line stability index values (LQP) 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 is carried out on the test system and the results are shown in Table 2. It is clear from the results that outage of line number 5 is the most critical line outage and this condition is considered for voltage stability improvement. Outage of other lines has no much impact on the system and therefore they

Table 2. Contingency ranking.

Rank	Line number	LQP values
1	5	0.9495
2	9	0.6050
3	2	0.4993
4	4	0.4968
5	7	0.4693

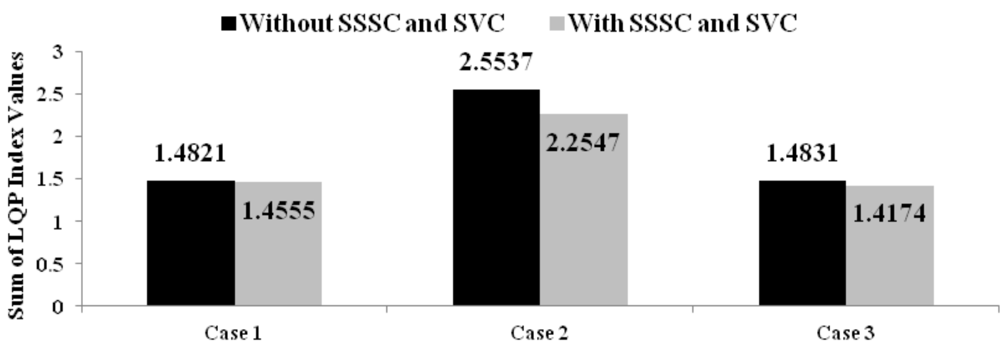

Figure 7. Sum of LQP index values in all cases.

are not given importance. Load flow is run on the system with line 5 outaged. Outage of this line 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 FACTS devices at suitable locations can relieve the system much from stressed conditions (reduced line losses).

LQP values of the lines before and after insertion of FACTS are compared in Figure 6(c) during contingency condition. The reduction in LQP values is encouraging in all the lines in this case. 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 optimization process is compared in Figure 7. The reduction in the index value indicates the voltage stability limit improvement.

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 bound of allowable value). These bus voltages are improved after the FACTS devices are installed. It is obvious from Table 3, that voltage profile of the system in all the three cases are improved better during post insertion of FACTS devices as compared with PSO. The comparison of average value of load bus voltage also proves the enhancing behavior of voltage stability limit incorporating SSSC and SVC devices of all cases shown in Figure 9. Table 4 exposes the comparison of minimum and maximum load bus voltages both absence and presence of FACTS devices under all cases. In loss minimization point of view through insertion of SSSC and SVC, the real power loss under normal loading is decreased by 1.36 MW which is 7.76% of total real power loss. Similarly under critical loading and line outage contingency conditions, the real power loss decreased by 5.64 and 9.37 MW respectively. The percentages of reduction under these cases are 12.03 and 28.73% respectively. The comparison of real power losses with PSO under all cases are shown in Table 5. The line wise real power loss are also depicted in Figure 8(a) under normal conditions, Figure 8(b) and 8(c) under critical loading and single line outage contingency conditions respectively. It is clear from these figures that the real power loss reduction is higher in buses nearer to generator than remote buses.

Reduction in reactive power loss indicates that power flow through the heavily loaded lines are diverted through the under loaded lines and the result is improved voltage profile. The reactive power loss is increased due to the presence of FACTS devices under normal loading by 2.652 MVAR which is 3.86% of total reactive power loss. But under critical loading and line outage contingency conditions, the reactive power loss is decreased by 25.154 MVAR and 28.131 MVAR respectively.

The percentages of reduction under these cases are 13.91 and 25.06% respectively. The comparison of

Table 3. Voltage profile values in p.u of all cases.

Bus No.	Case 1			Case 2			Case 3		
	Without SSSC and SVC	With SSSC and SVC [DE]	With SSSC and SVC [PSO]	Without SSSC and SVC	With SSSC and SVC [DE]	With SSSC And SVC [PSO]	Without SSSC and SVC	With SSSC And SVC [DE]	With SSSC And SVC [PSO]
1	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
2	1.0430	1.0330	1.0291	1.0030	1.0030	1.0030	1.0430	1.0330	1.0330
3	1.0217	1.0195	1.0189	0.9745	0.9785	0.9749	1.0069	1.0218	1.0101
4	1.0129	1.0103	1.0101	0.9581	0.9624	0.9599	0.9958	1.0218	1.0167
5	1.0100	1.0000	0.9988	0.9600	0.9600	0.9601	0.9600	0.9602	0.9607
6	1.0121	1.0109	1.0105	0.9553	0.9584	0.9557	0.9909	1.0128	1.0210
7	1.0035	0.9986	0.9932	0.9438	0.9455	0.9451	0.9661	0.9738	0.9721
8	1.0100	1.0100	1.0084	0.9600	0.9600	0.9603	0.9900	1.0100	0.9986
9	1.0507	1.0521	1.0498	0.9923	0.9965	0.9961	1.0388	1.0525	1.0422
10	1.0438	1.0472	1.0396	0.9722	0.9791	0.9784	1.0306	1.0471	1.0395
11	1.0820	1.0826	1.0822	1.0520	1.0531	1.0550	1.0820	1.0823	1.0820
12	1.0576	1.0589	1.0577	1.0004	1.0083	1.0037	1.0495	1.0586	1.0502
13	1.0710	1.0710	1.0668	1.0410	1.0510	1.0503	1.0710	1.0710	1.0699
14	1.0429	1.0453	1.0431	0.9754	0.9833	0.9806	1.0339	1.0444	1.0386
15	1.0385	1.0417	1.0389	0.9670	0.9751	0.9740	1.0282	1.0407	1.0310
16	1.0445	1.0467	1.0447	0.9769	0.9844	0.9828	1.0341	1.0465	1.0381
17	1.0387	1.0417	1.0411	0.9650	0.9722	0.9699	1.0262	1.0416	1.0411
18	1.0282	1.0357	1.0301	0.9489	0.9568	0.9061	1.0167	1.0308	1.0257
19	1.0252	1.0352	1.0299	0.9434	0.9510	0.9502	1.0131	1.0281	1.0120
20	1.0291	1.0403	1.0374	0.9493	0.9568	0.9533	1.0167	1.0321	1.0199
21	1.0293	1.0326	1.0311	0.9489	0.9569	0.9557	1.0163	1.0332	1.0254
22	1.0353	1.0385	1.0381	0.9572	0.9662	0.9611	1.0215	1.0409	1.0408
23	1.0291	1.0324	1.0302	0.9488	0.9570	0.9518	1.0163	1.0332	1.0330
24	1.0237	1.0265	1.0264	0.9369	0.9484	0.9481	1.0091	1.0321	1.0292
25	1.0202	1.0216	1.0211	0.9328	0.9523	0.9522	1.0023	1.0389	1.0379
26	1.0025	1.0040	1.0029	0.9034	0.9236	0.9233	0.9844	1.0216	1.0010
27	1.0265	1.0271	1.0269	0.9446	0.9688	0.9681	1.0068	1.0399	1.0071
28	1.0109	1.0102	1.0103	0.9510	0.9556	0.9560	0.9901	1.0127	1.0108
29	1.0068	1.0073	1.0095	0.9109	0.9476	0.9491	0.9866	1.0204	0.9987
30	0.9953	0.9959	0.9954	0.8915	0.9415	0.9410	0.9750	1.0091	0.9925

reactive power losses with PSO under all cases are shown in Table 6. The line wise reactive power loss are also depicted in Figure 10(a) under normal conditions, Figure 10(b) and 10(c) under critical loading and single line outage contingency conditions respectively. It is clear from these figures that the reactive power loss reduction is higher in buses nearer to generator than remote buses under cases 2 and 3 with presence of FACTS devices.

From Table 7, the most suitable location for SSSC to control power flow is found to be line number 6 for both normal loading and single line outage contingency conditions and line number 5 for critical loading condition. Similarly SVC to improve voltage profile are found to be bus number 20 for normal loading, bus number 30 for critical loading and bus number 25 for single line outage contingency condition. The much reduction in real power loss and increase in voltage magnitudes after the insertion of SSSC and SVC proves that FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability limit.

Conclusion

In this paper, optimal location of SSSC and SVC for voltage stability limit improvement and loss minimization are demonstrated. The voltage stability limit improvement and real power loss minimization are done under normal, critical loading and line outage contingency conditions. The LQP index is used for voltage stability assessment.

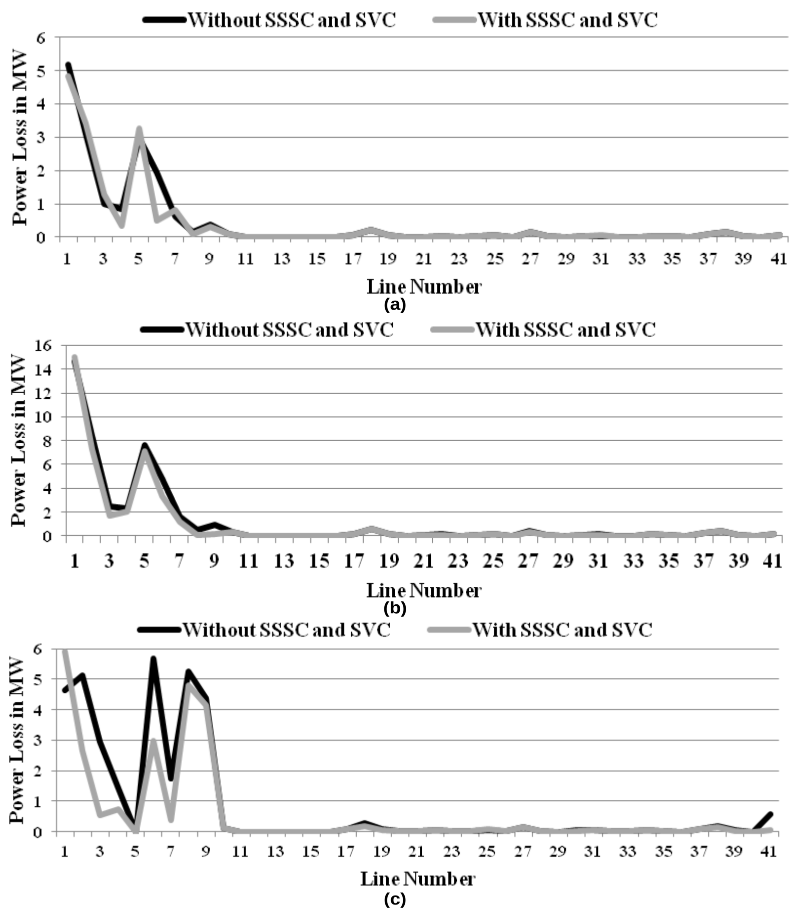

Figure 8. Line wise real power loss under (a) Case 1, (b) Case 2, (c) Case 3.

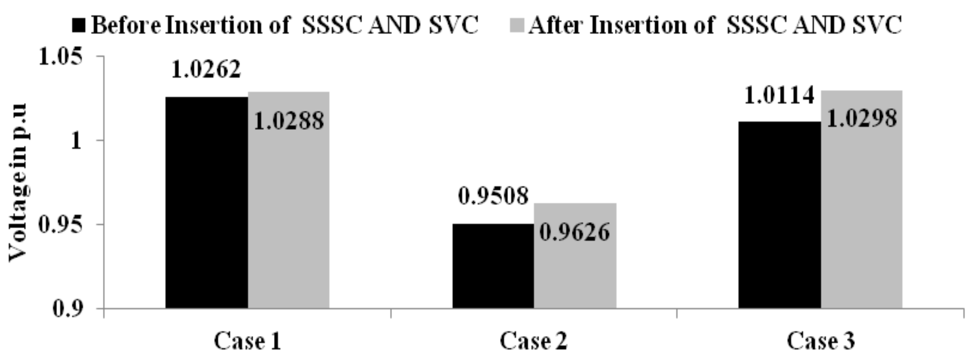

Figure 9. Average load bus voltage values in p.u.

Table 4. Minimum maximum load bus voltage values in p.u.

Cases	V_{MIN}		V_{MAX}	
	Before insertion of SSSC and SVC	After insertion of SSSC and SVC	Before insertion of SSSC and SVC	After insertion of SSSC and SVC
Case 1	0.9953	0.9959	1.0576	1.0589
Case 2	0.8915	0.9236	1.0004	1.0083
Case 3	0.9661	0.9738	1.0495	1.0586

Table 5. Real power loss values in MW.

Cases	Without SSSC and SVC	With SSSC and SVC	
		DE	PSO
Case 1	17.517	16.157	16.504
Case 2	46.898	41.258	43.272
Case 3	32.600	23.234	25.561

Table 6. Reactive power loss values in MVAR.

Cases	Without SSSC and SVC	With SSSC and SVC	
		DE	PSO
Case 1	68.692	71.344	74.981
Case 2	180.831	155.677	163.762
Case 3	112.229	84.098	94.754

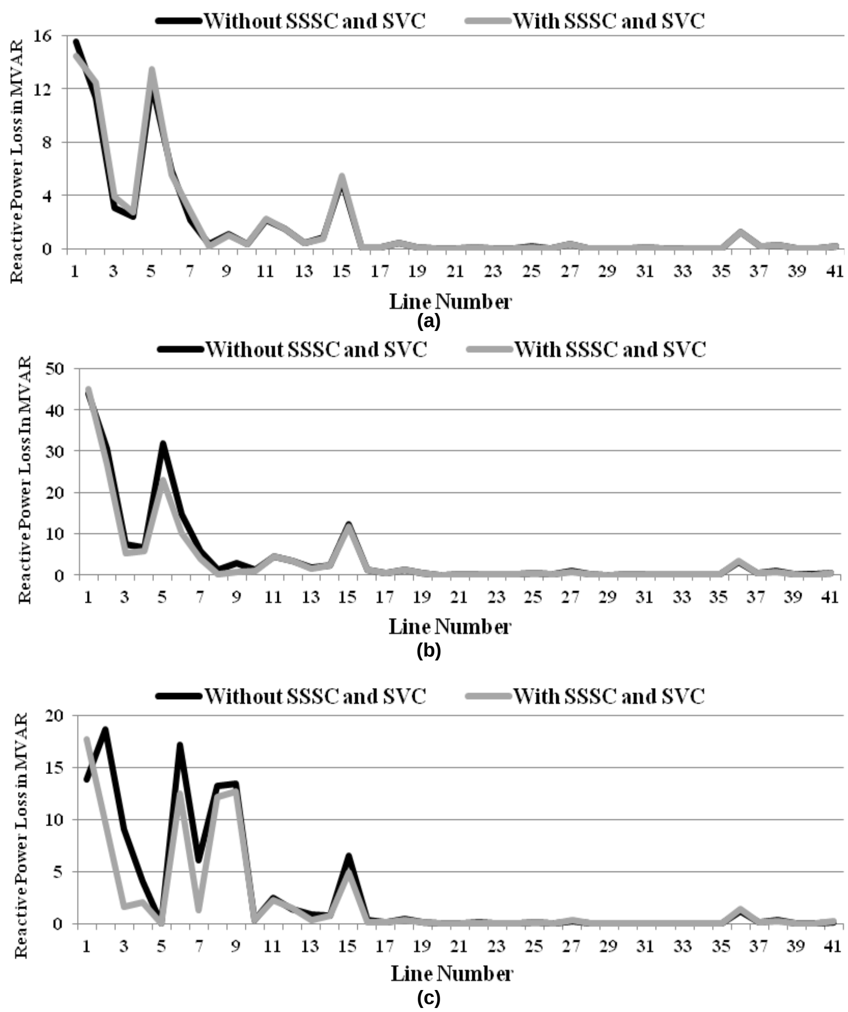

Figure 10. Line wise reactive power loss under (a) Case 1, (b) Case 2, (c) Case 3.

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 performance of SSSC and SVC combination in optimal power flow control for

Table 7. Best location and size of TCSC and SVC of all cases.

Cases	SSSC		SVC	
	Location	**Size [R + jX]**	**Location**	**Size [MVAR]**
Case 1	Between buses 2 and 6 (Line No. 6)	0.0239 + j0.2664	Bus No. 20	5.8131
Case 2	Between buses 2 and 5 (Line No. 5)	0.0289 + j0.0931	Bus No. 30	6.2554
Case 3	Between buses 2 and 6 (Line No. 6)	0.0112 + j0.0478	Bus No. 25	5.8559

voltage stability limit improvement is proved in the results by comparing the system real power loss and voltage profile with and without the devices. It is clear from the numerical results that voltage stability limit improvement and real power loss minimization are highly encouraging. The voltage stability limit improvement is by the combined action of power flow control of SSSC and reactive power compensation by SVC.

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