Turkish Journal of Electrical Engineering & Computer Sciences
http://journals.tubitak.gov.tr/elektrik/
Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 1092 – 1106

doi:10.3906/elk-1111-12

OPF-based reactive power planning and voltage stability limit improvement under single line outage contingency condition through evolutionary algorithms

Sakthivel PADAIYATCHI,[1,*] **Mary DANIEL**[2]
[1]Department of Electrical and Electronics Engineering, V.R.S. College of Engineering and Technology, Villupuram, TN, India
[2]Department of Electrical and Electronics Engineering, Government College of Engineering, Bargur, TN, India

Received: 06.11.2011 • **Accepted:** 19.03.2012 • **Published Online:** 03.06.2013 • **Printed:** 24.06.2013

Abstract: Reactive power planning is vital for maintaining the voltage stability of power systems and evolutionary algorithms are highly useful for achieving this task. This paper compares the effectiveness of the differential evolution (DE) and evolutionary programming (EP) algorithms in optimizing the reactive power planning of power systems under line outage contingency conditions. DE is efficient in exploration through the search space of the problem, while EP is simple and easy to implement. The low cost but fast response thyristor-controlled series capacitor (TCSC) flexible alternating current transmission system (FACTS) device is incorporated to control the power flows. The optimal settings of the control variables of the generator voltages, transformer tap settings, and location and parameter settings of the TCSC are considered for reactive power planning and the resultant reactive power reserves. The effectiveness of the proposed work is tested on the IEEE-30 Bus test system under the most critical line outage condition.

Key words: FACTS devices, TCSC, reactive power planning, evolutionary programming, differential evolution

1. Introduction

Present day power systems are forced to be operated at much closer to the stability limits due to there being a greater increase in the demand for electric power than ever before. In such a stressed condition, the system may enter into a voltage instability problem, which has been found to be responsible for many system blackouts in many countries around the world [1]. Voltage instability is primarily caused by insufficient reactive power support under stressed conditions.

In the emerging scenario of the deregulation of power system networks, the optimum generation bidders are chosen based on the real power cost characteristics and this results in reactive power shortage, and hence the loss of the voltage stability of the system. Various methods have been reported [2,3] to assess the voltage stability of power systems and to find possible ways to improve the voltage stability limit.

A power system needs to have sufficient reactive reserves to meet the increased reactive power demand under heavily loaded conditions and to avoid voltage instability problems. The reactive reserve of the generators can be managed by optimizing the reactive power dispatch. Generator bus voltages and transformer tap settings are the control parameters in the optimization of the reactive power dispatch. The amount of reactive power reserves at the generating stations is a measure of the degree of voltage stability. Several papers [4] have been published on reactive power reserve management with the perspective of ensuring voltage stability by providing an adequate amount of reactive power reserves.

---

*Correspondence: sithansakthi@gmail.com

A strategy to improve the voltage stability by dynamic Var source scheduling was proposed by Menezes [5]. In [6], the authors introduced a methodology to reschedule the reactive power injection from generators and synchronous condensers with the aim of improving the voltage stability margin. This method is formulated based on modal participations factors and an optimal power flow (OPF), wherein the voltage stability margin, as computed from the eigenvectors of a reduced Jacobian, is maximized by reactive rescheduling. However, the authors avoided using a security-constrained OPF formulation, and thus the computed voltage stability margin from the Jacobian would not truly represent the situation under a stressed condition.

The authors in [7] discussed a hierarchical reactive power optimization scheme that optimizes a set of corrective controls, such that the solution satisfies a given voltage stability margin. Bender's decomposition method was employed to handle the stressed cases. Evolutionary algorithms (EAs) like the genetic algorithm (GA), differential evolution (DE), and evolutionary programming (EP) [8,9] have been widely exploited during the last 2 decades in the field of engineering optimization. They are computationally efficient in finding the global best solution for optimization problems and will not easily get trapped in the local minima. Such intelligent algorithms were used for optimal reactive power dispatch in recent works [10–13]. Abou El Ela et al., in their work [14], have adopted the DE algorithm for reactive power and voltage control to improve the system stability.

Modern power systems are facing increased power flow due to increasing demand and are difficult to control. The rapid development of fast-acting and self-commutated power electronics converters, well known as flexible alternating current transmission system (FACTS) controllers, introduced in 1988 by Hingorani [15], are useful in taking fast control actions to ensure the security of power systems. FACTS devices are capable of controlling the voltage angle and voltage magnitude [16] at selected buses and/or line impedance of transmission lines. A thyristor-controlled series capacitor (TCSC) is a series-connected FACTS device that is inserted into a transmission line to vary its reactance, and thereby reduce the reactive losses and increase the transmission capacity. However, the conventional power flow methods need to be modified to take into account the effects of the FACTS devices. Lu et al. [17] presented a procedure to optimally place TCSCs in a power system to improve the static security. The TCSC has been proven to be efficient in improving the stability of a power system [18–20].

Most of the works [16,21,22] on voltage stability limit improvement consider the system under normal conditions, which is not sufficient since voltage instability is usually triggered by faults like line outages. Therefore, it would be more meaningful to consider a system under contingency conditions for voltage stability limit improvement. Recently, few works [23] have been done on voltage stability improvement under contingency conditions.

The proposed algorithm for the optimal reactive power flow control achieves the goal by setting suitable values for the generator terminal voltages, transformer tap settings, and reactance of the TCSCs. The optimal location of the TCSCs is done based on different factors, such as the loss reduction, voltage stability enhancement, and reactive power generation reduction. The cost of FACTS devices is high and therefore care must be taken while selecting their position and number of devices. With a view to reduce the cost of the FACTS devices only, the low-cost TCSC alone is considered, but the results obtained are encouraging.

2. Reactive power reserves

The different reactive power sources of a power system are the synchronous generators and shunt capacitors or FACTS devices. During a disturbance or contingency, the real power demand does not change considerably but the reactive power demand increases dramatically. This is due to the increased voltage decay with increasing line losses and reduced reactive power generation from the line charging effects. A sufficient reactive power reserve should be made available to supply the increased reactive power demand, and hence improve the voltage stability limit.

The reactive power reserve of a generator is how much more reactive power that it can generate and this can be determined from its capacity curves [1]. Simply speaking, the reactive power reserve is the ability of the generators to support the bus voltages under increased load conditions or system disturbances. The reserves of the reactive sources can be considered as a measure of the degree of the voltage stability.

3. Model of the TCSC

TCSC is a series compensation component that consists of a series capacitor bank shunted by a thyristor-controlled reactor. The basic idea behind the power flow control with the TCSC is to decrease or increase the overall lines' effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly. The TCSC is modeled as a variable reactance, where the equivalent reactance of line X_{ij} is defined as:

$$X_{ij} = -0.8X_{Line} \leq X_{TCSC} \leq 0.2X_{Line} \tag{1}$$

where X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive, as in Eq. (1).

4. Static voltage stability index

Controlling the decision variables and location of the TCSC is done based on the performance using the voltage stability index of each line for the same operating conditions. The static voltage stability index (SVSI) technique is applied as the tool to indicate the optimal values of the control parameters for voltage stability limit improvement. The concept of the SVSI is demonstrated through a simple 2-bus system [24] and the mathematical expression for the SVSI is as follows:

$$SVSI_{ij} = \frac{2\sqrt{\left(R_{ij}^2 + X_{ij}^2\right)\left(P_j^2 + Q_j^2\right)}}{\left|V_i^2 - 2X_{ij}Q_j\right|} \tag{2}$$

where 'i' is the sending end bus and 'j' the receiving end bus of the line $i-j$, and P_j and Q_j are the receiving end real and reactive powers. The SVSI takes values between '0' and '1', where '1' represents the voltage instability condition and '0' represents the no load condition. The value of the SVSI should be kept at well below '1' to ensure that the power system is under voltage stability conditions.

5. Differential evolution algorithm

DE is a population-based evolutionary algorithm [8] that is capable of handling nondifferentiable, nonlinear, and multimodal objectives functions. DE generates new offspring by forming a trial vector of each parent individual of the population. The population is improved iteratively by 3 basic operations, namely mutation, crossover, and selection. A brief description of the different steps of the DE algorithm is given below.

5.1. Initialization

The population $S_i^0 = [s_{i1}, s_{i2}, s_{i3}..........s_{iD}]$ is initialized by randomly generating individuals within the boundary constraints:

$$s_{ij}^0 = s_j^{\min} + rand\left(s_j^{\max} - s_j^{\min}\right) \tag{3}$$

$$i = 1, 2, 3\ldots\ldots.NP; j = 1, 2, 3\ldots\ldots.D$$

where the "*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, and $s_j^{\min}$ and $s_j^{\max}$ are the lower and upper bounds of the jth decision variable, respectively.

5.2. 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 $T_i^k = [t_{i1}, t_{i2}, t_{i3}..........t_{iD}]$ by perturbing a randomly selected vector, S_a^k, with the difference of 2 other randomly selected vectors, S_b^k and S_c^k, at the kth iteration, as per the following equation:

$$t_{ij}^k = s_{aj}^{k-1} + F\left(s_{bj}^{k-1} - s_{cj}^{k-1}\right); i = 1, 2, 3.....NP \tag{4}$$

$s_{aj}^{k-1}, s_{bj}^{k-1}$, and s_{cj}^{k-1} are randomly chosen vectors at the *(k – 1)*th iteration and $a \neq b \neq c \neq i$and are selected anew for each parent vector. F is the scaling factor that controls the amount of perturbation in the mutation process and improves convergence.

5.3. Crossover

Crossover represents a typical case of a "gene" exchange. The trial one $U_i^k = [u_{i1}, u_{i2}, u_{i3}..........u_{iD}]$ inherits genes with some probability. The parent vector is mixed with the mutated vector to create a trial vector, according to the following equation:

$$u_{ij}^k = \begin{cases} t_{ij}^k, & \text{ifrand} < Corj = q \\ s_{ij}^{k-1}, & \text{Otherwise} \end{cases} \tag{5}$$

where $i =$ *1,2,3...............NP; j = 1,2,3.............D.* s_{ij}^k, t_{ij}^k, and u_{ij}^k are the jth individuals of the target vector, mutant vector, and trial vector at the kth iteration, respectively; 'q' is a randomly chosen index in the range of *(1,D)*, which guarantees that the trial vector gets at least 1 parameter from the mutant vector; and C is the cross over constant that lies between '0' and '1'.

5.4. Selection

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

$$S_i^k = \begin{cases} U_i^{k-1}, iff\left(U_i^{k-1}\right) \leq f\left(S_i^{k-1}\right); i = 1, 2, 3.....NP \\ S_i^{k-1}, otherwise \end{cases} \tag{6}$$

6. Evolutionary programming algorithm

6.1. Overview

EP is an evolutionary based optimization algorithm and it uses probability transition rules to select the generations. Each individual competes with other individuals in a combined population of the parents and the offspring. The winners of the same number as the individuals in the parent's generation constitute the next generation [9]. The different operations involved in EP are briefly explained below:

6.2. Initialization

The initial population is generated randomly within the feasible search space. Next, the fitness $f(U_i)$ of each individual is calculated according to the objective function and the environment.

$$u_{ij}^{0} = u_{j}^{\min} + rand\left(u_{j}^{\max} - u_{j}^{\min}\right) \tag{7}$$

$$i = \mathit{1,2,3} \ldots\ldots NP;\; j = \mathit{1,2,3} \ldots\ldots D$$

where the "*rand* " function generates random values uniformly in the interval of (0, 1), NP is the size of the population, D is the number of decision variables, and $u_j^{\min}$ and $u_j^{\max}$ are the lower and upper bounds of the jth decision variable, respectively.

6.3. Statistics

The maximum fitness $f^{\max}(U)$, minimum fitness $f^{\min}(U)$, sum of the fitness $f^{sum}(U)$, and average fitness $f^{ave}(U)$ of this generation are calculated.

6.4. Mutation

Each probabilistically selected parent is mutated; for example, U_{ij} is mutated and added to its population as in the following the equation:

$$u_{ij}^{k} = u_{ij}^{k-1} + N(0, \beta\sigma^2) \tag{8}$$

where

$$\sigma = \left(u_{ij}^{\max} - u_{ij}^{\min}\right) \frac{f\left(U_i\right)}{f^{\max}\left(U\right)},$$

where 'k' is the current iteration count, $N(\mu, \sigma^2)$ represents a Gaussian random variable with the mean μ and variance σ^2, and β is the mutation scale, $0 < \beta \leq 1$, that could be adaptively decreased during the generations. If any mutated value exceeds its limit, it will be given the limit value. The mutation process allows an individual with a larger fitness to produce more offspring for the next generation.

6.5. Competition

Competition is created between the parents and their offspring by the tournament selection method. The parents and offspring are combined as a single vector *(2NP)* and arranged in the ascending order of their fitness for a minimization problem. The first half *(NP)* of the combined population is chosen as the parents for the next generation.

6.6. Convergence criterion

If the convergences condition is not met, the mutation and the competition process will run again. The maximum generation number can be used for the convergence condition. Other criteria, such as the ratio of the average and the maximum fitness of the population, are computed and the generations are repeated until

$$\frac{f^{ave}(U)}{f^{\max}(U)} \geq \delta \tag{9}$$

where δ should be very close to '1', which represents the degree of satisfaction. If the convergence has reached a given accuracy, an optimal solution has been found for an optimization problem.

7. Implementation of EP or DE for reactive power control

7.1. Representing an individual

Each individual in the population is defined as a vector containing the values of the control parameters, including the reactance of the TCSC.

Individual $= (P_{G1}.P_{G2},\ldots P_{Gn}, V_{G1}, V_{G2}\ldots V_{Gn}, T_{P1}, T_{P2}\ldots T_{Pn}, X_{TCSC}, X_{TCSC2}\ldots X_{TCSCn})$

The TCSC device is positioned at a possible location (line), and the OPF is run and the reduction in the line losses and improvement in the voltage stability limit (fitness) are observed. This procedure is repeated for all of the individuals in the population iteratively until the convergence criterion is not met.

7.2. Number of individuals

One generation is complete only when the fitnesses of all of the individuals in the population are obtained by running a load flow. Therefore, when the number of individuals is more computational, the effort is also more and to lessen the computational effort a suitable number of individual selections is important. Populations of 10, 20, and 30 individuals are chosen as an appropriate population size.

7.3. 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 EP or DE algorithms have to be programmed so that the individuals can move only over the feasible region. For instance, the network in Figure 1 has 4 transmission lines with a tap changer transformer. These lines are not suitable for locating the TCSC, leaving 37 other possible locations for the TCSC. 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 without transformer).

7.4. Optimal parameter values

The performances of the EP and DE algorithms are greatly influenced by the values of their parameters. Therefore, proper selection of values for the parameters is vital. The algorithms are run several times and the parameters are tuned for the optimum performance of the algorithms. The most suitable values obtained for the objectives considered are tabulated in Tables 1 and 2.

Table 1. Optimal values of the EP parameters.

Parameter	Optimal values
Number of individuals	20
Mutation constant	0.3
Number of iterations	500

Table 2. Optimal values of the DE parameters.

Parameter	Optimal value
Number of individuals	20
Scaling factor	0.5
Crossover constant	0.4
No of iterations	500

7.5. Fitness function

The goal of optimal reactive power planning is to minimize the reactive power generation and real power loss by the optimal positioning of the TCSC and its corresponding parameters. Hence, the objective function can be expressed as:

$$F = \min\left\{P_{loss} + \lambda_1 VD + \lambda_2 SVSI\right\} \tag{10}$$

The terms in the objective function are:

$$P_{loss} = \sum_{k=1}^{N_L} G_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_i - \delta_j\right)\right] \tag{11}$$

$$VD = \sum_{i=1}^{N_{PQ}} \left(V_i - V_{ref}\right)^2 \tag{12}$$

$$SVSI = \sum_{i=1}^{N_L} SVSI_i \tag{13}$$

where λ_1 and λ_2 are the penalty coefficients and are set to 500.

Subject to

Equality constraints

1. Real power balance equation:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij(X_{TCSC})}\cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{14}$$

2. Real power balance equation:

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij(X_{TCSC})}\sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{15}$$

Inequality constraints

3. Real power limit:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}; i \in N_{PV} \tag{16}$$

4. Reactive power limit:

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}; i \in N_{PV} \tag{17}$$

5. Load bus voltage limit:

$$V_i^{\min} \leq V_i \leq V_i^{\max}; i \in N_{PQ} \tag{18}$$

6. Line flow limit:

$$S_i \leq S_i^{\max}; i \in N_L \tag{19}$$

7. TCSC reactance limit:

$$X_{TCSC}^{\min} \leq X_{TCSC} \leq X_{TCSC}^{\max} \tag{20}$$

8. Simulation results and discussion

The proposed algorithm is developed in a MATLAB environment and a 2.9 GHz, Intel Core 2 Duo processor-based PC is used. The effectiveness of the proposed approach has been illustrated using a medium-sized IEEE 30-bus test system [25]. The loading level is taken as a 40% increase in the total load, maintaining the power factor constant.

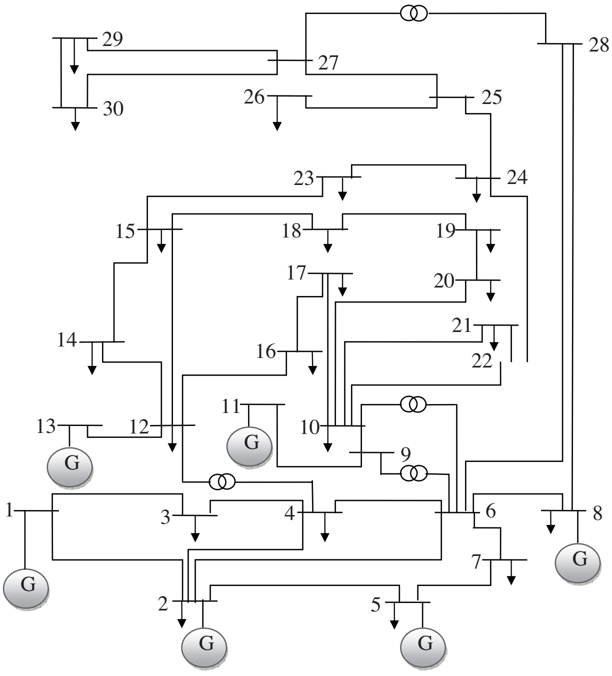

Figure 1. One-line diagram of the IEEE 30-bus system.

The system has 6 generator buses (1-slack and 5 PV buses), 24 load buses, and 41 transmission lines. Transmission lines 6–9, 6–10, 4–12, and 28–27 have tap changer transformers. The system base load conditions are as follows:

$$P_{Load} = 2.834_{PU} Q_{Load} = 1.0445 \text{ pu on a } 100 MVA \text{base}$$

The reactive power flow in the system is optimized by controlling the parameters of the real power generation, generator bus voltages, tap settings of the transformers, and reactance of the TCSCs. These control parameters are varied within their respective limits, as given in Table 3.

Table 3. Limits of the control parameters.

Sl no.	Parameter	Allowable range
1	P_{G2}	(20–80) MW
2	P_{G5}	(15–50) MW
3	P_{G8}	(10–35) MW
4	P_{G11}	(10–30) MW
5	P_{G13}	(12–40) MW
6	Generator voltage magnitude (V_G)	0.9–1.1
7	Transformer tap setting (T_P)	0.9–1.1
8	TCSC reactance (X_{TCSC})	(–0.8X_L)–(0.2X_L)

Reactive power optimization is done under 2 different cases, one being the optimization without the TCSCs, while the other is with the TCSCs. The effectiveness of these cases in reactive power planning is analyzed.

Voltage instability is usually triggered by faults like line outages. As such, voltage stability improvement under contingency conditions is more meaningful than that under the normal conditions of a power system. Line outage contingency screening and ranking is carried out first to identify the critical line outages for the consideration of the voltage stability improvement. All of the possible line outages of the system are considered one at a time. The line whose outage leaves the system with a decreased voltage level at the load buses, increased reactive power generation from the generator buses, and increased line losses is identified as the most critical line. The step-by-step procedure for the contingency ranking [26] is given below:

Step1: Read the system data.

Step2: Run the load flow program considering only one line outage at a time and calculate the total reactive power generation and total line losses.

Step3: The reactive power generation and losses corresponding to different line outages are arranged in descending order.

Step4: The most critical line is identified as the line whose outage results in the highest value of reactive power generation and losses (highly stressed condition).

The line outage contingency screening and ranking results, carried out on the test system, are shown in Table 4. The line outage is ranked according to the severity and the severity is taken on the basis of increased reactive power generation and real power losses. It is clear from Table 4 that the outage of lines 2–5 is the most critical line outage and only this condition is considered for voltage stability improvement.

Table 4. Contingency ranking in the IEEE 30-bus system.

Rank	Outaged line	Total P_{loss} MW	Total Q_{gen} MVAR
1	2–5	80.554	352.866
2	1–3	63.492	309.035
3	3–4	62.301	304.707
4	4–6	47.986	267.767
5	2–6	46.040	263.012

Case a: Reactive power planning without FACTS devices

OPF is run several times considering the real power generation, generator bus voltages, and transformer tap settings as control variables. Both the slack bus power generation and voltage magnitude are considered as fixed. The 2 SVCs located at bus numbers 10 and 24 are fixed at 19 MVAR and 4.3 MVAR. The objectives are to minimize the real power loss, voltage deviation, and voltage stability limit improvement. The best solution for the minimization of the objectives is found by implementing the evolutionary-based EP and DE algorithms.

The values of the real power generation, generator terminal voltages, and tap settings are allowed to vary within their respective limits during the optimization process and the best values with the EP and DE algorithms are shown in Table 5.

Table 5. Optimal values of the control parameters (case a).

Control variables	Buses	Value	
		With EP	With DE
P_{G1}	1	214.006	222.805
P_{G2}	2	75.8378	64.2602
P_{G5}	5	46.5863	46.5967
P_{G8}	8	26.2411	32.5690
P_{G11}	11	22.4542	24.7534
P_{G13}	13	39.9103	32.6548
V_{G1}	1	1.06	1.06
V_{G2}	2	1.0337	1.0782
V_{G5}	5	0.9529	1.0161
V_{G8}	8	0.9731	1.0983
V_{G11}	11	1.0749	1.0545
V_{G13}	13	1.0976	1.0489
T_{P1}	6–9	1.0352	1.0460
T_{P2}	6–10	1.0708	1.0987
T_{P3}	4–12	1.0140	0.9377
T_{P4}	28–27	0.9714	0.9965

Coordinated control of the decision variables greatly reduces the line losses and reactive power generation. The values of the reactive power generation, reactive power loss, and real power loss by the EP and DE algorithm are compared in Table 5. The reduction in the reactive power generation is an indication that the system is relieved from the stressed condition. The amount of reactive power generation reduction can be seen as a reactive power reserve and it may be used when the system needs it again in the future. The voltage stability limit improvement is obvious from the reduction in the value of sum of the SVSI.

It is clear from Table 6 that DE finds a better solution than EP. The reduction in the reactive power generation and real power loss minimization obtained with DE is highly encouraging.

Table 6. Reduction in the Q_{gen}, P_{loss}, Q_{loss}, and SVSI (case a).

IEEE 30-bus system	Total reactive power generation (MW)	Total real power loss (MW)	Total reactive power loss (MVAR)	Sum of SVSI	CPU time (s)
With EP	183.721	28.275	100.366	1.0702	64.57
With DE	173.951	26.879	94.192	0.9521	55.36

The optimization of the control variables yields reduced line losses and reactive power generation but the voltage profile of the load buses in this case is not acceptable, since many of the load bus voltages are below 0.95 pu, as shown in Figure 2. The poor voltage profile is because of an unoptimized reactive power flow through the lines under stressed conditions. Moreover, the system reactive power is optimized considering only the normal condition (no outage). This necessitates the reactive power flow control and thus TCSCs are considered in case b.

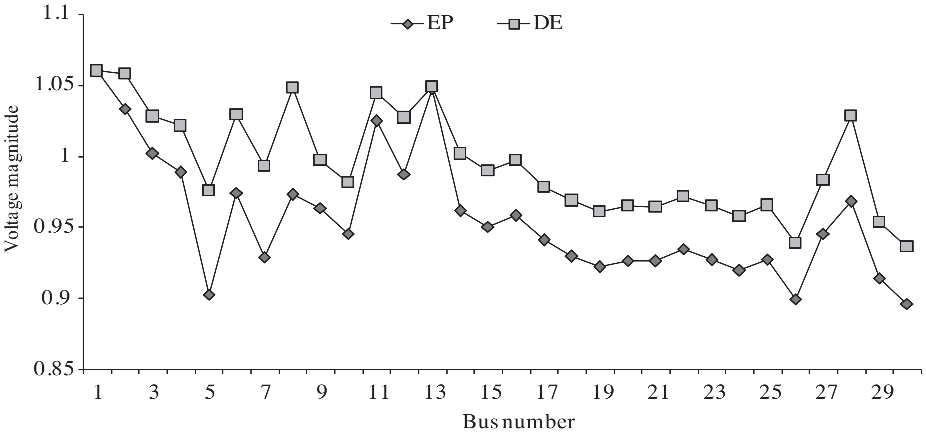

Figure 2. Voltage profile improvement (case a).

Case b: Reactive power planning with FACTS devices

The OPF is run several times considering 2 TCSCs at 2 different lines and the reductions in the real power loss and reactive power generation (objectives) are observed. The TCSC devices are located in the global best positions (lines) to improve the voltage stability by controlling the reactive power flow through the transmission lines of the system. The reactive power flow control is achieved so that the total real power loss and reactive power generation are reduced. The optimum values of the control parameters identified by the EP and DE algorithms are shown in Table 7.

Two TCSCs are located in 2 different lines of the system to adjust the power flow for minimizing the reactive power generation. The reactive power control variables of the generator bus voltages and transformer tap settings are controlled in a coordinated manner along with the reactance of the TCSC.

The EP algorithm determines the optimal locations of the 2 TCSCs as lines 10–21 and lines 12–16, and the line reactances are modified as given in Table 8. The optimal locations for the 2 TCSCs suggested by DE are different and are given in Table 8. It is ensured that the locations of the TSCSs are lines without tap changer transformers.

Table 7. Optimal values of control parameters (case b).

Control variables	Buses	Value	
		With EP	With DE
P_{G1}	1	200.444	188.108
P_{G2}	2	73.1939	78.9201
P_{G5}	5	49.9335	49.3700
P_{G8}	8	30.4006	34.5500
P_{G11}	11	27.5412	29.6400
P_{G13}	13	39.9595	39.4960
V_{G1}	1	1.06	1.06
V_{G2}	2	1.0579	1.0964
V_{G5}	5	0.9820	1.0874
V_{G8}	8	1.0807	1.0954
V_{G11}	11	1.0144	1.0764
V_{G13}	13	1.0514	1.0864
T_{P1}	6–9	0.9583	0.976
T_{P2}	6–10	1.0079	0.959
T_{P3}	4–12	0.9060	0.952
T_{P4}	28–27	0.9381	0.978

Table 8. Global best position of the TCSC devices (case b).

Device number	Global best position		Degree of compensation		Line reactance			
					X_{old}		X_{new}	
	EP	DE	EP	DE	EP	DE	EP	DE
TCSC1	10–21	10–17	0.2445	0.2447	0.0749	0.0845	0.0566	0.0638
TCSC2	12–16	9–11	0.4785	0.6950	0.1987	0.2080	0.1036	0.0634

The values of the reactive power generation, reactive power loss, and real power loss obtained by EP and DE are compared in Table 9. The positioning of 2 TCSCs helps the system to be relieved of much of the stress by way of minimizing the reactive power generation and real power loss. The reduction in the reactive power generation is an indication that the system is relieved from the stressed condition. The amount of reactive power generation reduction in this case is considerable and this proves that FACTS devices are capable of voltage stability improvement. The voltage stability limit improvement is obvious from the reduction in the value of sum of the SVSI after the TCSCs are located.

Table 9. Reduction in the Q_{gen}, P_{loss}, Q_{loss}, and SVSI (case b).

IEEE 30-bus system	Total reactive power generation (MW)	Total real power loss (MW)	Total reactive power loss (MVAR)	Sum of SVSI	CPU time (s)
With EP	166.281	24.712	84.443	0.9071	145.78
With DE	156.714	23.325	79.323	0.8360	123.97

Voltage profile improvement is part of the reactive power optimization. The bus voltage deviation is also minimized considerably after the installation of the TCSC devices and the resultant improvement in the voltage profile is illustrated in Figure 3, where it is clearly seen that the voltage profile is better with DE than with EP. In this case, both the real power loss minimization and voltage profile improvement are better. A power system is with increased real power loss and decreased bus voltage magnitudes especially during disturbance/contingency condition (under highly stressed conditions). A larger reduction in the real power loss and increase in the voltage magnitudes after the insertion of TCSC proves that FACTS devices are highly efficient in relieving a power network from stressed conditions and improving the voltage stability improvement.

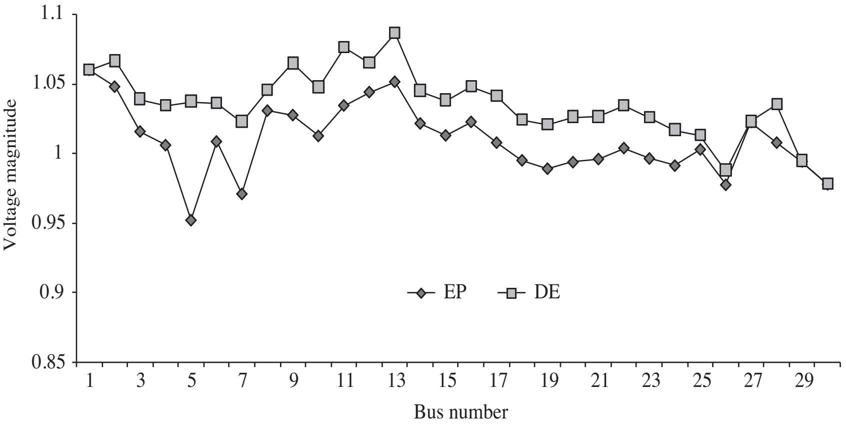

Figure 3. Voltage profile improvement (case b).

Voltage stability improvement is assessed by observing the value of the SVSI, i.e. the reduction in the value of the SVSI is an indication that the voltage stability limit is improved. The SVSI values of all of the lines in the system, optimized by EP and DE, are compared in Figure 4. The improvement in the voltage stability limit is due to the change in the power flow through the lines caused by the insertion of the TCSCs.

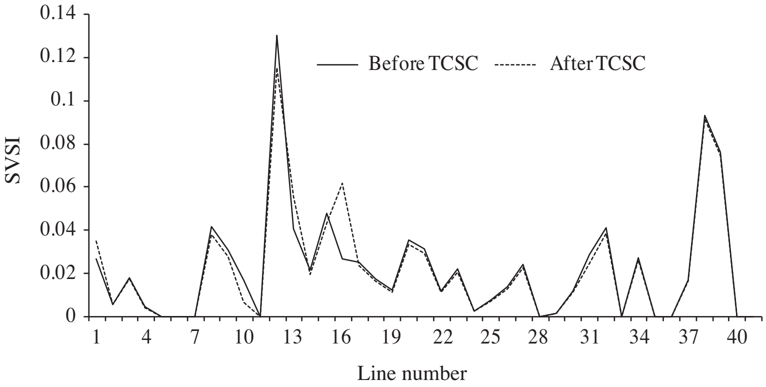

Figure 4. Reduction in the SVSI values of the lines using the EP and DE algorithms (case b).

9. Conclusion

This work compares the application of the DE and EP algorithms to solve the problem of optimal reactive power planning, including the placement and sizing of TCSC devices for voltage stability limit improvement by controlling the reactive power flow and reducing the real power loss. This work proves that the voltage stability limit improvement is more effective when it is done both by the reactive power generation and reactive power flow controls. Reactive power generation control is indicated by the control of the generator bus voltages and the reactive power flow is indicated by the control of the tap setter positions and reactance of the TCSCs. It is clear from the simulation results that the TCSC device is good at controlling the reactive power flow through different transmission lines of the system and it results in reduced reactive power generation or reactive power planning. The reduction in the reactive power generation can be used as a reactive power reserve when the system needs it again. That is, the system is left with a reactive capability and thereby is under a voltage secured condition. The DE algorithm is found to be better than EP in optimal reactive power reserve management. The searching process of DE is efficient due to the mutation operation and it cannot be easily trapped in the local minima.

Nomenclature

R_{ij}	Resistance of the line between buses 'i' and 'j'
X_{ij}	Reactance of the line between buses 'i' and 'j'
V_i	Voltage magnitude of load bus 'i'
G_k	Conductance of line 'k'
δ_i	Voltage angle of bus 'i'
P_{Gi}	Real power generation at the ith generator
Q_{Gi}	Reactive power generation at the ith generator
P_{Di}	Real power demand at the ith generator
Q_{Di}	Reactive power demand at the ith generator
N_B	Number of buses in the system
N_L	Number of lines in the system
N_{PV}	Number of generator buses in the system
N_{PQ}	Number of load buses in the system
Y_{ij}	Admittance of the line between bus 'i' and bus'j'
δ_{ij}	Voltage angle difference $(\delta i - \delta j)$
S_i	MVA flow through line 'i'
X_L	Line reactance
X_{TCSC}	Reactance of the TCSC
P_{loss}	Total real power loss in the system
V_{Gi}	Voltage magnitude of generator bus 'i'
T_{Pi}	Tap setter position of transformer 'i'

References

[1] C.W. Taylor, Power System Voltage Stability, New York, McGraw-Hill, 1994.

[2] P. Kessel, H. Glavitsch, "Estimating the voltage stability of a power system", IEEE Transactions on Power Delivery, Vol. 1, pp. 346–354, 1986.

[3] H. Wan, J.D. McCalley, V. Vittal, "Risk based voltage security assessment", IEEE Transaction on Power Systems,Vol. 15, pp. 1247–1254, 2000.

[4] F. Capitanescu, "Assessing reactive power reserves with respect to operating constraints and voltage stability", IEEE Transactions on Power Systems, Vol. 26, pp. 2224–2234, 2011.

[5] T. Menezes, L.C. da Silva, V.F. da Costa, "Dynamic VAR sources scheduling for improving voltage stability margin", IEEE Transactions on Power Systems, Vol. 18, pp. 969–971, 2003.

[6] S. Granville, "Optimal reactive dispatch through interior point methods", IEEE Transactions on Power Systems, Vol. 9, pp. 136–146, 1994.

[7] E. Vaahedi, Y. Mansour, C. Fuchs, S. Granville, M.D.L. Latore, H. Hamadanizadeh, "Dynamic security constrained optimal power flow/var planning", IEEE Transactions on Power Systems, Vol. 16, pp. 38–43, 2001.

[8] K. Price, R. Storn, "Differential evolution – a simple and efficient adaptive scheme for global optimization over continuous spaces", Technical Report, International Computer Science Institute, Berkley, 1995.

[9] D.B. Fogel, Evolutionary Computation: Toward a new Philosophy in Machine Intelligence, IEEE Press, 1995.

[10] P. Subbaraj, P.N. Rajnarayanan, "Hybrid particle swarm optimization based optimal reactive power dispatch", International Journal of Computer Applications, Vol. 1, pp. 65–70, 2010.

[11] K. Mahadevan, P.S. Kannan, "Comprehensive learning particle swarm optimization for reactive power dispatch", Electric Power Systems Research, Vol. 10, pp. 641–652, 2010.

[12] P. Aruna Jeyanthy, D. Devaraj, "Optimal reactive power dispatch for voltage stability enhancement using real coded genetic algorithm", International Journal of Computer and Electrical Engineering, Vol. 2, pp. 734–740, 2010.

[13] M.Z.M. Idrus, I. Musirin, Z. Zainuddin, "Biological computing technique for optimal reactive power dispatch", Colloquium on Signal Processing and its Application, pp. 112–118, 2006.

[14] A.A. Abou El Ela, M.A. Abido, S.R. Spea, “Differential evolution algorithm for optimal reactive power dispatch”, Electric Power Systems Research, Vol. 81, pp. 458–464, 2011.

[15] N.G. Hingorani, L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, New York, IEEE Press, 2000.

[16] N. Yorino, E.E. El-Araby, H. Sasaki, S. Harada, “A new formulation for FACTS allocation for security against voltage collapse”, IEEE Transactions on Power Systems, Vol. 18, pp. 3–10, 2003.

[17] L. Yunqiang, A. Ali, “Improving system static security via optimal placement of thyristor controlled series capacitor (TCSC)”, IEEE Power Engineering Society Winter Meeting, Vol. 2, pp. 516–521, 2001.

[18] R. Billinton, M. Fotuhi-Firuzabad, S.O. Faried, “Power system reliability enhancement using a thyristor controlled series capacitor”, IEEE Transactions on Power Systems, Vol. 14, pp. 369–374, 1999.

[19] G. Huang, T. Zhu, “TCSC as a transient voltage stabilizing controller”, IEEE Power Engineering Society Winter Meeting, Vol. 2, pp. 628–633, 2001.

[20] Y. Lu, A. Abur, “Static security enhancement via optimal utilization of thyristor-controlled series capacitors”, IEEE Transactions on Power Systems, Vol. 17, pp. 324–329, 2002.

[21] C.A. Caizares, Z.T. Faur, “Analysis of SVC and TCSC controllers in voltage collapse”, IEEE Transactions on Power Systems, Vol. 14, pp. 158–165, 1999.

[22] A. Bhattacharya, P.K. Chattopadhyay, “Application of biogeography-based optimisation to solve different optimal power flow problems”, IET Generation, Transmission & Distribution, Vol. 5, pp. 70–80, 2011.

[23] P.S. Venkataramu, T. Ananthapadmanabha, “Installation of unified power flow controller for voltage stability margin enhancement under line outage contingencies”, Iranian Journal of Electrical and Computer Engineering, Vol. 5, pp. 90–96, 2006.

[24] L. Qi, “AC system stability analysis and assessment for shipboard power systems”, PhD Thesis, University of A&M, Texas, 2004.

[25] Power Systems Test Case, The University of Washington Archive, http://www.ee.washington.edu/research/pstca/, 2000.

[26] S. Sakthivel, D. Mary, “Voltage stability limit improvement incorporating SSSC and SVC under line outage contingency condition by loss minimization”, European Journal of Scientific Research, Vol. 59, pp. 44, 2011.