Reactive Power Optimization for Voltage Stability Limit Improvement Incorporating TCSC Device through DE/PSO under Contingency Condition

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Abstract: Modern power systems are at risks of voltage instability problems due to highly stressed operating conditions caused by increased load demand. This paper proposes a hybrid Differential Evolution (DE)/Particle Swarm Optimization (PSO) algorithm based optimal reactive power flow control task incorporating only one type of FACTS device. DE is efficient in exploration through the search space of the problem but not so good in exploitation while PSO is highly efficient in exploitation of the solutions. The hybrid algorithm combines the features of both DE and PSO and is capable of finding the global best solution without easily trapping in to the local minima. Optimal settings of control variables of generator voltages, transformer tap settings and location and parameter setting of TCSC is considered for optimal solution for reactive power flow control and the resultant reactive power reserves. The effectiveness of the proposed work is tested on IEEE-30 Bus test system.

1. Introduction

The present day power systems are forced to be operated much closer to stability limits due to the increased demand for electric power than ever before. In such a stressed condition, the system may enter into voltage instability problem and it has been found responsible for many system block outs in many countries across the world [1]. Voltage instability is primarily caused by insufficient reactive power support under stressed conditions.

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

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

In [5], T. Menezes,et.al.propose a strategy to improve the voltage stability by dynamic Var sources scheduling . In [6], the authors introduce 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 eigenvectors of a reduced Jacobian, is maximized by reactive rescheduling. However, the authors avoid 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] discuss a hierarchical reactive power optimization scheme which optimizes a set of corrective controls such that the solution satisfies a given voltage stability margin. Bender's decomposition method is employed to handle stressed cases. Evolutionary algorithms (EAs) like Genetic Algorithm (GA), Differential (DE) and Particle Swarm Optimization (PSO) [8]-[9] are widely exploited during last two decades in the field of engineering optimization. They are computationally efficient in finding global best solution for optimization problems and will not easily trap into local minima. Such intelligent algorithms are used for optimal reactive power dispatch is considered in [10]-[13]. H. Yoshida,et.al in their work [14] have adopted the easy to implement search algorithm, the Particle Swarm Optimization (PSO) for reactive power and voltage control to improve system stability.

The 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 FACTS controllers, introduced in 1988 by Hingorani [15] are useful in taking fast control actions to ensure security of power systems. FACTS devices are capable of controlling the voltage angle, voltage magnitude [16] at selected buses and/or line impedance of transmission lines. Thyristor controlled series capacitor (TCSC) is a series connected FACTS device inserted in transmission lines to vary its reactance and thereby reduces the reactive losses and increases the transmission capacity. But the conventional power flow methods are to be modified to take into account the effects of FACTS devices. Lu et.al [17] presented a procedure to optimally place TCSCs in a power system to improve static security. TCSC has been proved to be efficient in improving stability of a power system [18]-[20].

Most of the works [21]-[23] on voltage stability limit improvement takes the system in normal condition and it 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 condition for voltage stability limit improvement. Recently, few works [24] have been done on

voltage stability improvement under contingency condition.

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

2. Reactive Power Reserves

The different reactive power sources of a power system are synchronous generators and shunt capacitors. During a disturbance or contingency the real power demand does not change considerably but reactive power demand increases dramatically. This is due to increased voltage decay with increasing line losses and reduced reactive power generation from line charging effects. Voltage instability is due to insufficient reactive power capacity of power systems. 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 it can be determined from its capacity curves [1]. Simply speaking, the reactive power reserve is the ability of the generators to support bus voltages under increased load condition or system compensation component which consists of a series capacitor bank shunted by thyristor controlled reactor. The basic idea behind the power flow control with the TCSC is to decrease or increase the overall reactance of the line and thereby minimize the reactive power loss. The resultant reactive power reserves can be thought of enhancement in voltage stability improvement as the system is left with reactive capability.

3. Model of TCSC

TCSC is a low cost but rapid response FACTS controller and is a series connected FACTS device that decreases or increases the effective line reactance, by adding a capacitive or inductive reactance correspondingly. TCSC is highly suitable for line flow control by changing the transfer reactance of the line. The TCSC is modeled as a variable reactance, where the equivalent reactance of line X_{ij} is defined as:

$$X_{ij} = X_{Line} + X_{TCSC} \qquad 1$$

where, X_{line} is the transmission line reactance before insertion of TCSC, and X_{TCSC} is the TCSC reactance. The degree of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive to avoid over compensation $(-0.8X_{Line} \le X_{TCSC} \le 0.2X_{Line})$. The load flow studies model of a TCSC is shown in figure 1.
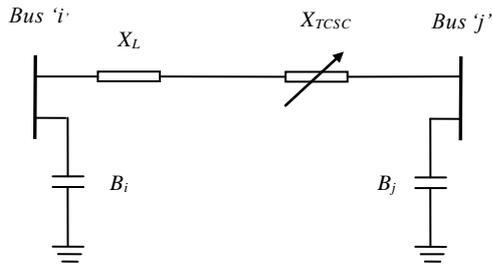
Figure 1.Model of TCSC

The addition of TCSC changes only the elements corresponding to the buses *i* and *j* of the admittance matrix and therefore modeling of TCSC for load flow studies is simple.

4. Static Voltage Stability Index (SVSI)

Controlling of decision variables and location of TCSC are done based on the performance using the voltage stability index of each line for the same operating conditions. The SVSI technique is applied as the tool to indicate the optimal values of control parameters for voltage stability limit improvement. The concept of SVSI is demonstrated through a simple 2 bus system [25] and the mathematical expression for SVSI is as follows:

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

Where *i* is the sending end bus and *j*, the receiving end bus of the line *i-j*, R_{ji} and X_{ji} are resistance and reactance of the line, P_j and Q_j are the receiving end real and reactive powers. SVSI takes values between 0 and 1. 1 represents the voltage instability condition while 0, no load condition. The value of SVSI should be kept well below 1 to ensure the power system under voltage stability condition. Though a number of voltage stability indicators are available, this static voltage stability indicator is considered for assessing the stability of a power system as its value can be easily calculated and the accuracy is also acceptable.

5. Differential Evolution Algorithm (DE)

Differential evolution (DE) is a population based evolutionary algorithm [8], 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.

5.1. Initialization

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

$$X_{ij}^0 = X_j^{\min} + rand \ \ X_j^{\max} - X_j^{\min} \qquad 3$$

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

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 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 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 kth iteration as per the following equation:

$$V_i^k = X_a^k + F \ \ X_b^k - X_c^k \ \ ; i = 1,2,3\ldots NP \qquad 4$$

$X_a{}^k$, $X_b{}^k$ and $X_c{}^k$ are randomly chosen vectors at the Kth iteration and $a \ne b \ne c \ne i$ and are selected anew for each parent vector. *F* is the scaling factor that controls the amount of perturbation in the mutation process and improve convergence.

5.3. 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:

$$U_{ij}^k = \begin{cases} V_{ij}^k, & if \ rand < C \ or \ j = q \\ X_{ij}^k, & Otherwise \end{cases} \qquad 5$$

Where *i=1,2,3…………….NP*; *j=*1,2,3………….*D*. $X_{ij}{}^k$, $V_{ij}{}^k$ $U_{ij}{}^k$ are the jth 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. C is the cross over constant that lies between 0 and 1.

5.4. 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:

$$X_i^{k+1} = \begin{cases} U_i^k, & if \ f\ U_i^k \le f\ X_i^k \ ; i = 1,2,3.....NP \\ X_i^k, & otherwise \end{cases} \qquad 6$$

6. Particle Swarm Optimization (PSO)

The concept of PSO was first suggested by Kennedy and Eberhart [9] in 1995. Since its development, PSO has become one of the most promising optimizing techniques for solving global optimization problems. Its mechanism is inspired by the social and cooperative behavior displayed by various species like birds, fish, termites, ants and even human beings. The PSO system consists of a population (swarm) of potential solutions called particles. These particles move through the search domain with a specified velocity in search of optimal solution. Each particle maintains a memory which helps it in keeping the track of its previous best position.

The positions of the particles are distinguished as personal best and global best. In the past several years, PSO has been successfully applied in many research and application areas. It has been demonstrated that PSO gets better results in a faster and cheaper way in comparison to other methods like GA, simulated annealing (SA) etc.The particles or members of the swarm fly through a multidimensional search space looking for a potential solution. Each particle adjusts its position in the search space from time to time according to the flying experience of its own and of its neighbors (or colleagues).

For a D-dimensional search space, the position of the i_{th} particle is represented as:

$$X_i = \ x_{i1}, x_{i2}.............x_{id}..............x_{iD} \qquad 7$$

Each particle maintains a memory of its previous best position which is represented as:

$$P_i = \ p_{i1}, p_{i2}.............p_{id}.............p_{iD} \qquad 8$$

The best one among all the particles in the population is represented as:

$$P_g = \ p_{g1}, p_{g2}.............p_{gd}.............p_{gD} \qquad 9$$

The velocity of each particle is represented as:

$$V_i = \ v_{i1}, v_{i2}.............v_{id}.............v_{iD} \qquad 10$$

The maximum velocity is represented as:

$$V_{max} = \ v_{max1}, v_{max2}.............v_{maxd}.............v_{maxD} \qquad 11$$

The velocity V_i of each particle is clamped to a maximum velocity V_{max} which is specified by the user. V_{max} determines the resolution with which regions between the present position and the target position are searched. Large values of V_{max} facilitate global exploration, while smaller values encourage local exploitation. If V_{max} is too small, the swarm may not explore sufficiently beyond locally good regions. On the other hand, too large values of V_{max} risk the possibility of missing a good region.At each iteration a new velocity value for each particle is evaluated according to its current velocity, the distance from the global best position. The new velocity value is then used to calculate the next position of the particle in the search space. This process is then iterated a number of times or until a minimum error is achieved. The two basic equations which govern the working of PSO are that of velocity vector and position vector given by:

$$v_{id} = wv_{id} + c_1r_1\ p_{id} - x_{id}\ + c_2r_2\ p_{gd} - x_{id} \qquad 12$$

$$x_{id} = x_{id} + v_{id} \qquad 13$$

Here w is the inertia constant, c_1 and c_2 are acceleration constants. They represent the weighting of the stochastic acceleration terms that pull each particle towards personal best and global best positions. Therefore, adjustment of these constants changes the amount of tension in the system. Small values of these constants allow particles to roam far from the target regions before tugged back, while high values result in abrupt movement toward, or past, target regions. The constants r_1, r_2 are the uniformly generated random numbers in the range of (0, 1).

The first part of Eq. (12), wv_{id}, represents particle's previous velocity, which serves as a memory of the previous flight direction. This memory term can be visualized as a momentum, which prevents the particle from drastically changing its direction and biases it towards the current direction. The second part, $c_1r_1(p_{id} - x_{id})$, is called the cognition part and it indicates

the personal experience of the particle. We can say that, this cognition part resembles individual memory of the position that was best for the particle. The effect of this term is that particles are drawn back to their own best positions, resembling the tendency of individuals to return to situations or places that were most satisfying in the past. The third part, $c_2r_2(p_{gd} - x_{id})$, represents the cooperation among particles and is therefore named as the social component . This term resembles a group norm or standard which individuals seek to attain. The effect of this term is that each particle is also drawn towards the best position found by its neighbor.

7. The Hybrid DE/PSO Algorithm

DE and PSO are hybridized [26]-[28] to combine the exploration strength of DE and exploitation feature of PSO. The proposed DE/PSO is highly efficient in finding global best solution. DE/PSO starts like the usual DE algorithm up to the point where the trial vector is generated. If the trial vector satisfies the conditions given by equation (6), then it is included in the population otherwise the algorithm enters the PSO phase and generates a new candidate solution. The method is repeated iteratively till the optimum value is reached. The inclusion of PSO phase creates a perturbation in the population, which in turn helps in maintaining diversity of the population and producing a good optimal solution.

7.1. The pseudo code of the Hybrid DE/PSO Algorithm:

Initialize the particle position and velocities

Do

For $i = 1$ to NP

Select a, b, c ∈ NP randomly

// a, b, c are selected such that a≠ b≠ c≠ i //

For j = 1 to D do

Select j_{rand} ∈ D

$$if \quad rand() < CR \quad or \quad j = j_{rand}$$

//rand () denotes a uniformly distributed random number between 0 and 1//

$$U_{ij,g+1} = x_{a,g} + F \quad x_{b,g} - x_{c,g}$$

End if
End for

$$if \quad f \quad U_{i,g+1} \quad < f \quad X_{i,g} \quad then$$

$$X_{i,g+1} = U_{i,g+1}$$

Else

PSO activated

Find a new particle using equations (12) and (13).(Let this particle be *TX*)

For *j=1* to D do

$$v_{ij,g+1} = wv_{ij,g} + c_1r_1 \quad p_{ij,g} - x_{ij,g}$$
$$+ c_2r_2 \quad p_{gj,g} - x_{ij,g}$$

$$tx_{ij} = x_{ij,g} + v_{ij,g+1}$$

End for

$$if \quad f \quad TX_i \quad < f \quad X_{i,g} \quad then$$

$$X_{i,g+1} = TX_i$$

Else

$$X_{i,g+1} = X_{i,g}$$

End if

End if

End for

Until stopping criterion is not reached.

7.2. The step by algorithm of DE/PSO for reactive power control

7.2.1. Representing an individual:

Each individual in the population (particle) is defined as a vector containing the values of control parameters including the size of TCSCs.

Individual = (V_{g1}, V_{g2}........ V_{gn} ,T_1, T_2 ....T_4, X_{TCSC1}, X_{TCSC2})

7.2.2. DE/PSO Parameters:

The performance of the DE/PSO is greatly affected by its parameter values. Therefore, a way to find a suitable set of parameters has to be chosen. In this case, the selection of the DE/PSO parameters follows the strategy of considering different values for each particular parameter and evaluating its effect on the DE/PSO performance. The optimal values for the DE/PSO parameters are as in table 1.

7.2.3. Number of particles:

There is a trade-off between the number of particles and the number of iterations of the swarm and each particle fitness value has to be evaluated using a power flow solution at each iteration, thus the number of particles should not be large because computational effort could increase dramatically. Swarms of 25 and 50 particles are chosen as an appropriate population sizes.

7.2.4. Inertia weight:

The inertia weight is linearly decreased. The purpose is to improve the speed of convergence of the results by reducing the inertia weight from an initial

value of 0.9 to 0.1 in even steps over the maximum number of iterations as shown in (14).

$$w_{iter} = 0.9 - 0.8 \left(\frac{iter - 1}{\max iter - 1} \right) \qquad 14$$

Where W_{iter} is the inertia weight at current iteration. $Iter$ is the current iteration number.
$maxiter$ is the maximum number of iterations.

7.2.5 Acceleration and constants:

A set of three values for the individual acceleration constants are evaluated to study the effect of giving more importance to the individual's best or the swarm's best: $c_1 = \{1.5, 2, 2.5\}$. The value for the social acceleration constant is defined as: $c_2 = 4 - c_1$.

7.2.6 Number of Iterations:

Different numbers of iterations {100, 250, 500} are considered in order to evaluate the effect of this parameter on the PSO performance.

7.2.7 Values for maximum/minimum velocity:

In this case, for each particle component, values for the maximum velocity have to be selected. Based on previous results, a value of 7 is considered as the maximum velocity and -3 as minimum velocity for the locating line number.

7.2.8 Feasible region Definition:

There are several constraints in this problem regarding the characteristics of the power system and the desired level of reactive power control. Each of these constraints represents a limit in the search space; therefore the DE/PSO algorithm has to be programmed so that the particles can only move over the feasible region. For instance, the network in fig. 2 has 4 transmission lines with tap changer transformer. These lines are not considered for locating TCSC, leaving 37 other possible locations for the TCSC.

7.2.9 Optimal Parameter Values:

Table 1. Optimal values of DE/PSO parameters

Parameter	Optimal values
Number of particles	50
Inertia weight	Linearly decreased
Individual acceleration constant	2.5
Social acceleration constant	2.0
No of iterations	500
Velocity bounds	{-3,7}
r_1	0.3
r_2	0.2

7.2.10 Integer DE/PSO:

For this particular application, the position of the particle is determined by an integer number (line number). Therefore the particles' movement given by (13) is approximated to the nearest integer numbers. Additionally, the location number must not be a line with tap setting transformer. If the location is line with tap setting transformer, then the particle component regarding position is changed to the geographically closest line without transformer.

7.2.11 Fitness function

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

$$F = \min \quad P_{loss} + Q_{loss} + Q_{gen} + \lambda_1 VD + \lambda_2 SVSI \qquad 15$$

The terms in the objective function are:

$$P_{loss} = \sum_{k=1}^{N_L} G_k \left[V_i^2 + V_j^2 - 2V_i V_j \cos \ \delta_i - \delta_j \ \right] \qquad 16$$

$$Q_{loss} = \sum_{k=1}^{N_L} Q_{k\,loss} \qquad 17$$

$$Q_{gen} = \sum_{k=1}^{N_{PV}} Q_{k\,gen} \qquad 18$$

$$VD = \sum_{k=1}^{N_{PQ}} V_k - V_{ref}^{\,2} \qquad 19$$

$$SVSI = \sum_{k=1}^{N_L} \qquad 20$$

where P_{loss} is the total system real power loss; Q_{loss} is the total reactive power loss; Q_{gen} is the total reactive power generated by generators; the fourth term in the objective function is the normalized violation of load bus (also known as 'PQ bus') voltage, V_i; N_L is the number of transmission lines; N_{PQ} and N_{PV} are the number of load buses and generator buses respectively; λ_1 and λ_2 are the penalty coefficient and are set to 10.

Subject to:

Equality constraints

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij\,x_{TCSC}} \cos \ \delta_{ij} + \gamma_j - \gamma_i = 0 \qquad 21$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij\,x_{TCSC}} \sin \ \delta_{ij} + \gamma_j - \gamma_i = 0 \qquad 22$$

Inequality constraints

$$X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \qquad\qquad 23$$

$$V_i^{\min} \le V_i \le V_i^{\max} \; ; \; i \in N_{PQ} \qquad 24$$

$$S_k \le S_k^{\max} \; ; k \in N_L \qquad\qquad 25$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \; ; \; i \in N_{PV} \qquad 26$$

8. Simulation Results and Discussions

The optimal reactive power flow control is formulated with the primary objective of minimization of reactive power generation and secondary objective of minimization of real power loss subject to voltage limit and reactive power limit constraints (15). The effectiveness of proposed approach has been illustrated using the IEEE 30 bus test system [29].
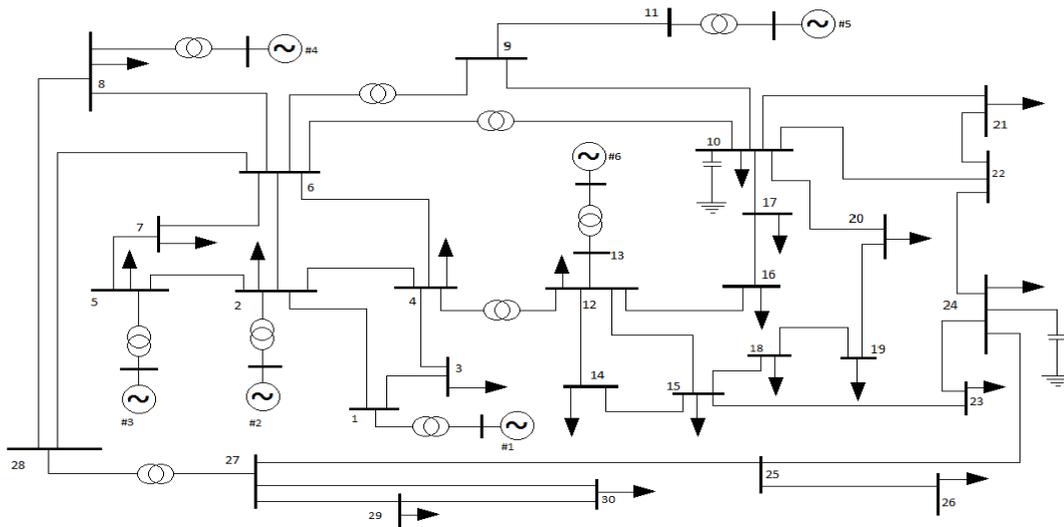
Figure 2. One line diagram of IEEE 30 Bus System

The system has 6 generator buses, 24 load buses and 41 transmission lines. Transmission lines 6-9, 6-10, 4-12, and 28-27 are with tap changer transformers and therefore are not suitable for positioning of TCSC. Only the remaining 37 lines are considered as candidate locations for positioning of TCSC.

Reactive power flow in the system is optimized by controlling the parameters of generator bus voltages, tap settings of transformers and reactance of TCSCs. These control parameters are varied within their respective limits and the limits are given in table 2.

Table 2. Limits of control parameters

Sl No	Parameter	Range
1	Generator voltage magnitude (V_g)	0.9-1.1
2	Transformer tap setting (T_p)	0.9-1.1
3	TCSC reactance (X_{TCSC})	(-0.8X_L)-(0.2X_L)

Case 1: System under normal condition

Normal system (No Outage) with 100% loading condition is considered for reactive power flow control to improve the voltage stability limit.

The real power settings are taken from [29]. 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 optimization work is repeated by considering different number of TCSC devices and the results obtained with two TCSCs are acceptable. Use of more number of TCSCs increases the benefits but to keep the cost minimum only two devices are taken.

The values of reactive power generation, reactive power loss and real power loss obtained by using the basic PSO and the hybrid DE/PSO are compared in table 3. Reduction in 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 reactive power reserve and it may be used when the system enters into a highly stressed condition again in future. The voltage stability limit improvement is obvious from the reduction in the value of sum of SVSI after the TCSCs are located. Though the sum of SVSI appears to be increased when PSO is applied, it is ensured that SVSI values of different lines of the

system are below 0.5. The benefits of the optimization work are clear from the table 3. The results show that DE/PSO outperforms PSO.

Table 3. Reduction in Q_{gen}, Q_{loss}, P_{loss} and SVSI (case 1)

IEEE 30 Bus System	Total Reactive Power Generation	Total Reactive Power Loss	Total Real Power Loss	Sum of SVSI
Initial	146.924	68.691	17.514	0.8179
PSO	143.827	68.019	17.163	0.8287
DE/PSO	142.552	65.208	16.778	0.7597

The values of generator terminal voltages and tap settings are allowed to vary within their limits during the optimization process and the values shown in table 4 are the most suitable ones for the objectives considered.

Table 4. Optimal Values of Control Parameters (case 1)

Control Variables	Buses	Value		
		Initial	PSO	DE/PSO
V_{g1}	1	1.060	1.0840	1.0886
V_{g2}	2	1.043	1.0663	1.0836
V_{g3}	5	1.010	1.0358	1.0335
V_{g4}	8	1.010	1.0387	1.0251
V_{g5}	11	1.082	1.0501	1.0117
V_{g6}	13	1.071	1.0204	1.0876
T_1	6-9	0.978	0.9866	0.9742
T_2	6-10	0.969	0.9884	0.9256
T_3	4-12	0.932	1.0237	0.9255
T_4	28-27	0.968	1.0871	0.9779

Positions of the two TCSCs suggested by PSO and DE/PSO and the modification of the line reactance are given in table 5. These TCSCs are helping the control parameters in optimizing the reactive power dispatch.

Table 5. Global best position of TCSC devices (case 1)

Device Number	Global best position		Degree of compensation		Line reactance			
	PSO	DE/PSO	PSO	DE/PSO	X_{old}		X_{new}	
					PSO	DE/PSO	PSO	DE/PSO
TCSC1	22-24	12-13	-0.3534	0.5107	0.1790	0.1400	0.1157	0.0911
TCSC2	15-18	18-19	0.3248	-0.6595	0.2185	0.1292	0.2895	0.1019

Reactive power optimization accompanies with voltage profile improvement and all the load buses are at about nominal voltage levels. The voltage profile improvement is encouraging one and is depicted in figure 3. It may noted that the profile is good in the load bus area.
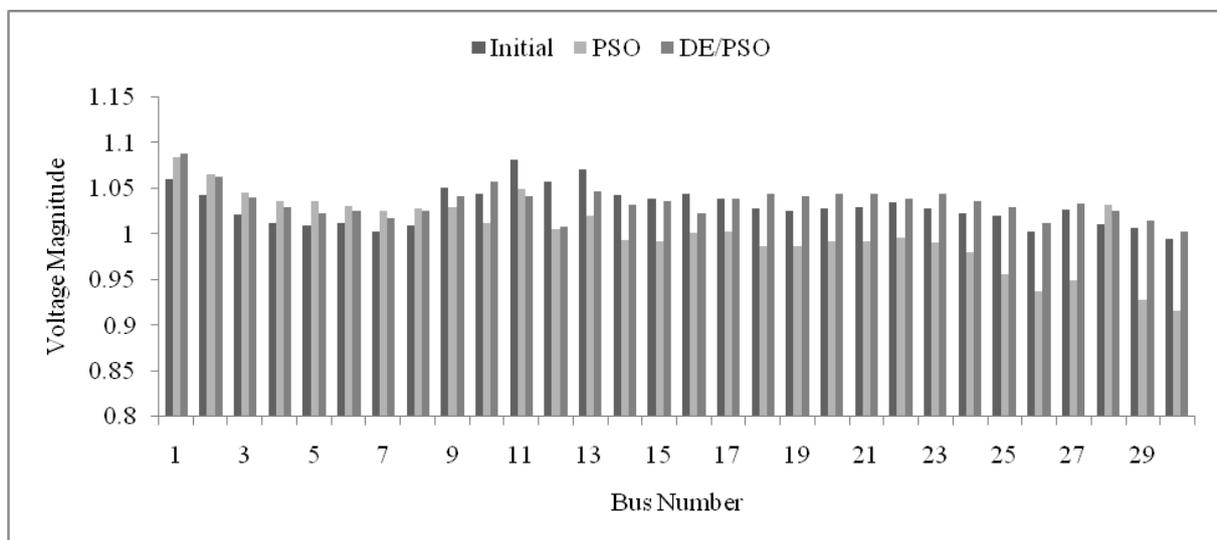
Figure 3. Voltage profile improvement (case 1)

Case 2: System under line outage contingency condition

Voltage instability is usually initiated by faults like line outages. As such, voltage stability improvement under contingency condition is more meaningful rather under normal condition of a power system. Line outage contingency screening and ranking is carried out first to identify the critical line outages for consideration of voltage stability improvement. All the

possible line outages of the system are considered one each at a time. The line, whose outage leaves the system with decreased voltage level and increased reactive power generation, is identified as the most critical line. The step by step procedure for contingency ranking [30]-[31] 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 all the line outages of the system 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).

Line outage contingency screening and ranking, carried out on the test system are shown in table 6. The line outage is ranked according to the severity and severity is taken on the basis of increased reactive power generation and real power losses. It is clear from the table that outage of line 2-5 is the most critical line outage and this condition is considered for voltage stability improvement. Operating the system under more than one line outage condition is not recommended and also will not be economical due to increased losses. Hence, only the critical line outage condition is considered.

Table 6. Contingency Ranking in 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

The operating condition of the system considered is 40% increase in total load with line 2-5 outaged. Simultaneous control of generator bus voltages, tap settings and reactance's of TCSCs reduces the line losses and reactive power generation greatly. The reduction in reactive power generation, reactive power loss and real power loss by PSO and DE/PSO are compared in table 7. The reduction in reactive power generation and losses obtained by DE/PSO is much and it shows the efficiency of the proposed algorithm.

Table 7. Reduction in Q_{gen}, Q_{loss}, P_{loss} and SVSI (case 2)

IEEE 30 Bus System	Total Reactive Power Generation	Total Reactive Power Loss	Total Real Power Loss	Sum of SVSI
Initial	352.866	270.259	80.554	1.0155
PSO	334.082	251.856	76.813	0.9308
DE/PSO	325.212	245.610	75.455	0.9737

PSO and the proposed DE/PSO algorithm is run separately until the minimum possible line loss and reactive power reduction are achieved. For different values the control parameters the Newton – Raphson load flow is carried and the fitness is calculated. The line losses and reactive power generation are minimum when the control parameters take values as shown in table 8.

Table 8. Optimal Values of Control Parameters (case 2)

Control Variables	Buses	Value		
		Initial	PSO	DE/PSO
V_{g1}	1	1.060	1.0601	1.0856
V_{g2}	2	1.043	1.0493	1.0376
V_{g3}	5	1.010	1.0608	1.0621
V_{g4}	8	1.010	1.0755	1.0500
V_{g5}	11	1.082	0.9922	1.0142
V_{g6}	13	1.071	1.0129	1.0636
T_1	6-9	0.978	1.0063	0.9942
T_2	6-10	0.969	0.9630	1.0561
T_3	4-12	0.932	1.0032	0.9855
T_4	28-27	0.968	0.9409	1.0590

It can be observed that the locations of the TCSCs are different from the locations taken by the devices when the system is under normal condition and the global best positions are as shown in table 9.

Table 9. Global best position of TCSC devices (case 2)

Device Number	Global best position		Degree of compensation		Line reactance			
					X_{old}		X_{new}	
	PSO	DE/PSO	PSO	DE/PSO	PSO	DE/PSO	PSO	DE/PSO
TCSC1	2-4	16-17	-0.1571	-0.3768	0.1737	0.1923	0.1464	0.11984
TCSC2	29-30	4-6	0.0268	-0.5320	0.4533	0.0414	0.4654	0.01940

The bus voltage deviation is also minimized considerably after the installation of TCSC device and the resultant improvement in voltage profile is illustrated in figure 4. It is clear from the figure that the voltage profile is improved considerably. 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 condition).The much reduction in real power loss and increase in voltage magnitudes after the insertion of TCSC proves that FACTS devices are highly efficient in relieving a power network from stressed condition and improving voltage stability improvement.
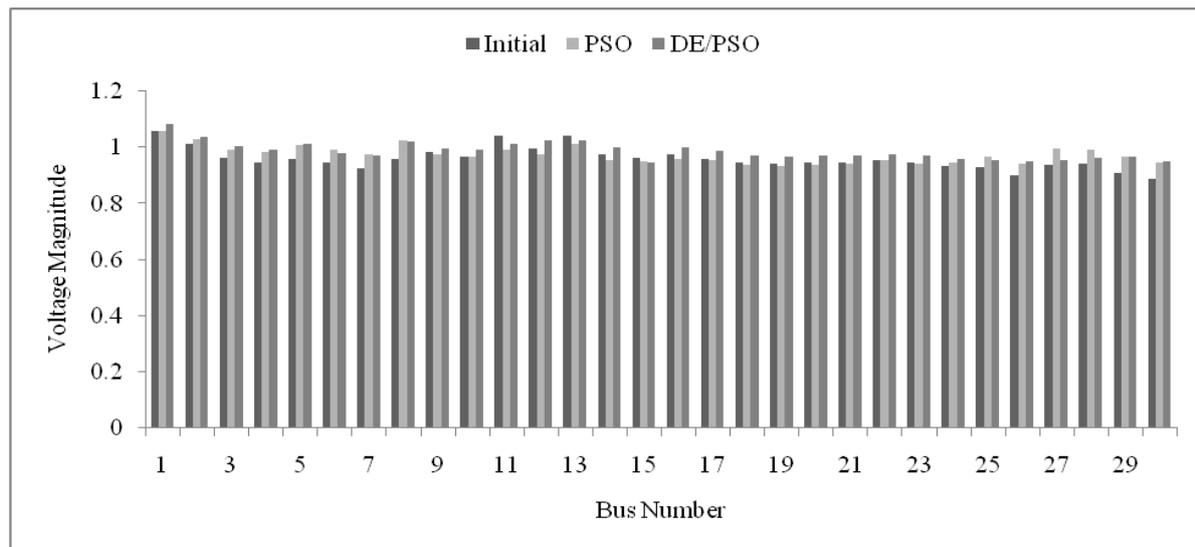
Figure 4. Voltage profile improvement (case 2)

9. Conclusions

This work demonstrates the performance of the hybrid DE/PSO algorithm to solve the problem of optimal reactive power control including the placement and sizing of TCSC devices in a medium size power network for voltage stability limit improvement by controlling the reactive power flow and reducing the real power loss. This algorithm combines the exploration strength of DE algorithm and exploitation property of PSO and hence the hybrid algorithm is better in both exploration and exploitation of the search space. The effectiveness of the hybrid algorithm is proved in the reactive power optimization task. This work shows that voltage stability limit improvement is more effective when it is done both by reactive power generation and reactive power

flow controls. Reactive power generation control is indicated by the control of generator bus voltages and reactive power flow by the control of tap setter positions and reactance of TCSCs. It is clear from the simulation results that 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. The reduction in reactive power generation can be used as reactive power reserve when the system needs it again. That is the system is left with reactive capability and thereby under voltage secured condition. The settings of the DE/PSO parameters are shown to be optimal for this type of application. From the numerical results,it is clear that the hybrid DE/PSO performs better than the basic PSO.

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