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Reactive Power Optimization and Voltage Stability Limit Improvement with TCSC Device through DE algorithm under Most Credible 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 and economical and/or environmental constraints in construction of new transmission lines. This paper proposes a Differential Evolution (DE) algorithm based optimal reactive power flow control task incorporating only one type of FACTS device under contingency condition. DE is efficient in exploration through the search space of the problem and easy to implement. Optimal settings of control variables of generator voltages, transformer tap settings and location and parameter setting of thyristor controlled series capacitor (TCSC) is considered for optimal solution for reactive power flow control and the resultant reactive power reserves. Coordinated control of TCSC parameter and control parameters of reactive power dispatch is taken. The effectiveness of the proposed work is tested on IEEE-30 Bus test system under most critical line outage contingency condition.

Index Terms— FACTS devices, TCSC, Reactive Power optimization, Differential Evolution, Contingency Condition, Voltage Stability.

1 INTRODUCTION

Present day power system networks 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. Transmission open access in a deregulated environment might result in congestion [2]-[3] and the consequent line outage and voltage instability. Possibility of voltage instability is more in a system under contingencies like line outage than in the system under normal condition. Voltage stability analysis including contingency constraints is necessary for ensuring the security of a power system. Various methods have been reported [4]-[5] to assess voltage stability of power systems to find the possible ways to improve the voltage stability limit.

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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 [6]-[7] are published on reactive power reserve management with the perspective of ensuring voltage stability by providing adequate amount of reactive power reserves.

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]. K.Vaisakh in his work [14] has adopted the easy to implement and most efficient evolutionary algorithm, the DE 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. 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]-[21].

Most of the works [22]-[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]-[25] 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. This work proposes a coordinated control of all parameters of reactive power control and the system is considered under line outage condition to make this work more meaningful with regard to voltage stability limit improvement. 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. 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 disturbances. The reserves of reactive sources can be considered as a measure of the degree of voltage stability.

3. Model of TCSC

TCSC is a series compensation component which consists of a series capacitor bank shunted by thyristor controlled reactor. The basic idea behind 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 variable reactance, where the equivalent reactance of line X_{ij} is defined as:

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

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 (1).

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 [26] and the mathematical expression for SVSI is as follows:

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

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, the no load condition. The value of SVSI should be kept well below 1 to ensure the power system under voltage stability condition.

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

$$X_{ij}^{0} = X_{j}^{\min} + rand \left(X_{j}^{\max} - X_{j}^{\min} \right) \quad 3$$
i=1,2,3…….NP; j=1,2,3…….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 j[th] 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 k[th] iteration as per the following equation:

$$V_i^k = X_a^k + F \left(X_b^k - X_c^k \right) \quad ; i = 1,2,3.....NP \quad 4$$

X_a^k, X_b^k and X_c^k are randomly chosen vectors at the K[th] iteration and a≠b≠c≠i and are selected anew for each parent vector.F is the scaling constant 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:

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

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.

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:

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

THE PSEUDO CODE OF THE DE ALGORITHM:

For i=1 to NP

For j=1 to D

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

End

Calculate $f\left(X_i^0\right)$

End

Repeat until the stopping criterion is not met

For i=1to NP

$$V_i^k = X_a^k + F \left(X_b^k - X_c^k \right) \quad ; i = 1,2,3.....NP$$

For j=1 to D

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

End

Calculate $f\left(U_i^k\right)$

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

End

6. THE STEP BY IMPLEMENTATION OF DE FOR REACTIVE POWER CONTROL

6.1. Representing an individual:

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

Individual is defined as (V_{g1}, V_{g2}…….. V_{gn}, t_1, t_2 …….X_{TCSC})

6.2. 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 5,10 and 20 are chosen as an appropriate population sizes.

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6.3. 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 DE algorithm has to be programmed so that the individual can only move over the feasible region. For instance, the network in Fig. 1 has 4 transmission lines with tap changer transformer. These lines are not considered for locating 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). Finally, in order to limit the sizes of the TCSC units, the restrictions of level of compensation is applied to the individuals.

6.4. Optimal Parameter Values:

Table.1. Optimal values of DE parameters

Parameter	Optimal value
Number of individuals	10
Cross over constant	0.5
Scaling constant	0.2
No of iterations	25

6.5. 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 line with tap setting transformer, then the individual component regarding position is changed to the geographically closest line without a tap setting transformer.

6.6. Fitness function

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

$$F = \min \left(P_{loss} + Q_{loss} + Q_{gen} + \lambda_1 V_{\lim} + \lambda_2 SVSI \right) \quad 7$$

The terms in the objective function are:

$$P_{loss} = \sum_{k=1}^{N_L} G_k \left[V_i^2 + V_j^2 - 2V_iV_j \cos\left(\delta_i - \delta_j\right) \right] \quad 8$$

$$Q_{loss} = \sum_{k=1}^{N_L} Q_{k\,loss} \quad 9$$

$$Q_{gen} = \sum_{k=1}^{N_{PV}} Q_{k\,gen} \quad 10$$

$$V_{\lim} = \frac{\sum_{k=1}^{N_{PQ}} \left(V_k - V_k^{\lim} \right)}{V_k^{\max} - V_k^{\min}} \quad 11$$

$$SVSI = \sum_{k=1}^{N_L} SVSI_k \quad 12$$

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 third term in the objective function is the normalized violation of load bus (also known as 'PQ bus') voltage, V_i; the fourth term is the sum of SVSI of all lines; 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 500.

Subject to

Equality constraints

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij}\left(X_{TCSC}\right) \cos\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad 13$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_iV_jY_{ij}\left(X_{TCSC}\right) \sin\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad 14$$

Inequality constraints

$$X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \quad 15$$

$$V_i^{\min} \le V_i \le V_i^{\max}; \qquad i \in N_{PQ} \quad 16$$

$$S_k \le S_k^{\max}; \qquad k \in N_L \quad 17$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}; \qquad i \in N_{PV} \quad 18$$

7. 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. The effectiveness of proposed approach has been illustrated using the medium size IEEE 30 bus test system [27].

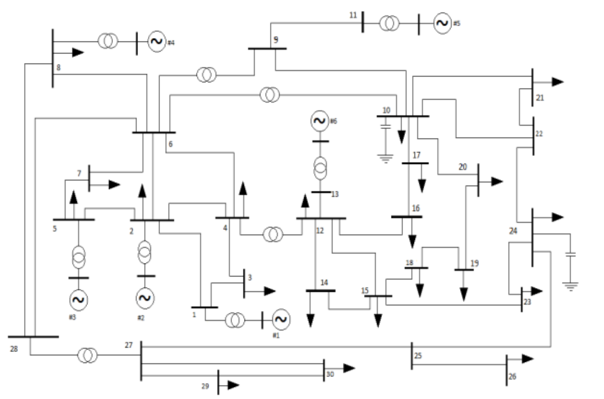

Figure.1. One line diagram of IEEE 30 Bus System

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	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 considered under two different operating conditions of the system. The first case is the most critical line outage contingency condition without FACTS devices and the second case is the same contingency condition with TCSC devices.

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, increased reactive power generation and line loss is identified as the most critical line. The step by step procedure for contingency ranking [28]-[29] is given below.

Step1: Read the system data.
Step2: Run the load flow program considering only one line outage and calculate the total reactive power generation and total line losses.
Step3: The reactive power generation and losses corresponding to all the lines 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 is shown in table 3. 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.

Table. 3. 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 system with 40% increased loading level is considered as a stressed condition for reactive power flow control to improve the voltage stability limit. NR load flow is run several times considering two TCSCs at two different lines and the reduction in real power loss and reactive power generation (objectives) are calculated. The best solution for minimization of the objectives is found by implementing the evolutionary based DE algorithm. 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 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

Control Variables	Buses	Value Without TCSC	Value With TCSC
P_{g1}	1	298.024	250.239
P_{g2}	2	47.8820	45.0646
P_{g5}	5	36.6785	49.4068
P_{g8}	8	25.3832	34.4774
P_{g11}	11	12.4525	16.1434
P_{g13}	13	15.4662	30.6575
V_1	1	1.0600	1.0600
V_2	2	1.0291	1.0893
V_5	5	0.9986	1.0764
V_8	8	1.0839	1.0813
V_{11}	11	1.0543	1.0063
V_{13}	13	1.0150	1.0036
T_1	6-9	0.9276	0.9106
T_2	6-10	0.9488	0.9290
T_3	4-12	1.0562	0.9645
T_4	28-27	1.0009	0.9218

Two TCSCs are located, one in line 12-15 and other one in 9-11 and the line reactances are modified as given in table 5. It is ensured that the locations of TSCSs are lines without tap changer transformers. The TCSCs are helping the control parameters in optimizing the reactive power dispatch.

Table. 5. Global best position of TCSC devices

Device Number	Global BestLoction	Line Reactance Old	Line Reactance New
$TCSC_1$	12-15	0.1304	0.1373
$TCSC_2$	9-11	0.2080	0.1075

Coordinated control of generator bus voltages, tap settings and reactance's of TCSCs reduces the line losses and reactive power generation greatly. The values of reactive power generation, reactive power loss and real power loss before and after TCSCs are compared in table 6. 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 needs it 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.

Table. 6. Reduction in Q_{gen}, Q_{loss}, P_{loss} and SVSI

IEEE 30 Bus System	Total Reactive Power Generation	Total Reactive Power Loss	Total Real Power Loss	Sum of SVSI
Without TCSCs	217.666	135.913	39.126	0.9312
With TCSCs	180.503	100.086	29.228	0.8359

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 2. 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. 2. Voltage profile improvement

Voltage stability improvement is assessed by observing the value of SVSI that is, the reduction in the value of SVSI is an indication that voltage stability limit is improved. SVSI value of all the lines in the system before and after optimization is compared in fig 3. It is obvious from the chart that voltage stability limit is improved considerably in all the lines. The better improvement in voltage stability limit is due to the change in power flow through the lines caused by the insertion of TCSCs.

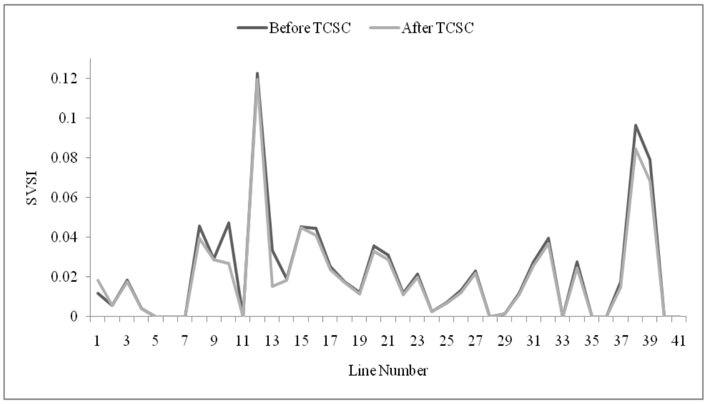

Figure. 3. SVSI of lines before and after insertion of TCSC

For quick understanding of the relief of the system from stressed conditions and increased capability of reactive power reserves, the reduction in the three parameters are compared in fig 4.

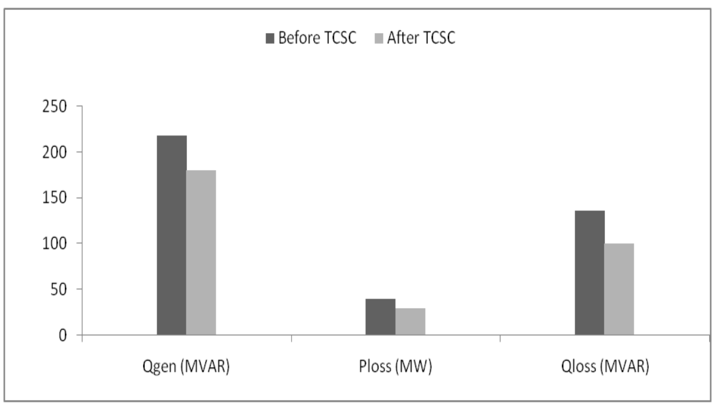

Figure. 4. Reduction in Q_{gen}, P_{loss} and Q_{loss}

8. Conclusions

This work demonstrates the application of the DE algorithm to solve the problem of optimal reactive power control including the placement and sizing of TCSC device in a medium size power network for voltage stability limit improvement by controlling the reactive power flow and reducing the real power loss. This work proves that voltage stability limit improvement is more effective when it is done both by control of reactive power generation and reactive power flow control. 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 by changing their reactance 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 DE algorithm is efficient, easy to implement and gained popularity only during the last one decade. The settings of the DE parameters are shown to be optimal for this type of application. The algorithm is able to find the optimal solutions with a relatively small number of iterations and individuals, therefore with a reasonable computational effort.

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