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Optimal SVC Sizing and Placement for Reducing Real Power Losses and Voltage Security Improvement in the Power System using DE Algorithm

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Abstract: ***The power system across the world operates at highly loaded conditions resulting in voltage instability, high system losses and decreasing voltage profile. The different economic, technical environmental and legal constraints have already provided limitations towards the extension of our existing power system as a result of which with the day to day increase in load demand, the voltage stability can be described as the ability to retain their bus voltages within desirable limits even after following sudden big disturbance in a power system. An increase in loading of the system causes an increased shortage of real and reactive power of the system, which in turn causes a fall in the bus voltages of the system. Also, FACTS devices raises power transfer capability reduces system losses and improves system stability, because of their fast and flexible control characteristics. Owing to their huge capital cost, it is essential to place these devices optimally in a power system. In this paper, Differential Evolution (DE), a population based stochastic meta-heuristic optimization algorithm is applied for optimal placement of static var compensator (SVC) aimed to the voltage security enhancement of a power system. The SVC placement is considered to be a planning problem and is formulated as a multi-criteria problem comprising of minimization of real power loss, voltage security and investment cost of SVC under single line outage contingencies. Effectiveness of the DE algorithm based approach has been demonstrated on IEEE 30-bus test system.***

Keywords: Differential Evolution (DE), Voltage Performance Index (VPI), Loss Reduction, optimal placement, Static Var Compensator (SVC), Flexible AC transmission system (FACTS)

1. Introduction

Because of the restructuring power system, the modern power system is facing new problems like power transmission capacity of the transmission system have increased. And even the new system is reluctantly operated almost near to the operating limits. In that condition there may be voltage collapse as the operating limits change and the security of the system may be disturbed. In the early days some incidents have been taken place and are being informed by the researchers for the prediction of the voltage stability and also for the proximity condition of collapse. Security assessment is an important issue which is considered in the power system for operation, planning and control of the network. This security assessment defines that the system must remain in secure operating state under abnormal conditions. In the power system this security assessment is carried out using an index called as voltage performance index (VPI) following a contingency. The operation of the power system is being more secure and flexible due to development of the device called as flexible alternating current transmission system devices. It is defined as the power electronic based system that controls one or more transmission system parameter to increase the power transfer capability and enhance the system controllability. Static Var Compensator (SVC), STATCOM, Static Synchronous Series Compensator (SSSE), UPFC,TCSC are some of the commonly used FACTS devices which help in improving the voltage stability, reduction of the line losses, improving the voltage profile. It also helps in handling real and reactive power, the magnitude of voltage of the selected bus and phase shift angle. Static synchronous series compensator and thyristor controlled series compensator are the two FACTS devices which are connected in series, while the other two static synchronous compensator and static var compensator are connected in shunt and the unified power flow controller is the one which is connected in combination of shunt and series in the power system. So in this work, the differential evolution algorithm, the population based stochastic meta-heuristic optimization algorithm is used for the optimally placing of SVC aimed to voltage security improvement of the power system. This Flexible AC transmission system (FACTS) device location is always considered as a planning problem and is formulated as a comprising of real power loss minimization, voltage security and SVC investment cost under single line outage contingencies. Here we are considering the IEEE 30bus test system on which the differential evolution algorithm is being demonstrated. MATLAB software is being used for load flow analysis of the IEEE30 bus test system.

2. Facts Device

FACTS devices are static equipments that participate a very important part in managing the power transfer capability of the power transmission system, voltage fluctuation as well as system steadiness of the network.

2.1 Modeling of Static Var Compensator

SVC is the first generation FACTS device. It is the variable impedance FACTS device where current through the reactor is always controlled using back to back connected thyristor valves. The variable reactor is known as thyristor controlled reactor (TCR) which is connected in parallel with the fixed capacitor to form the SVC which is shown in Figure 1.

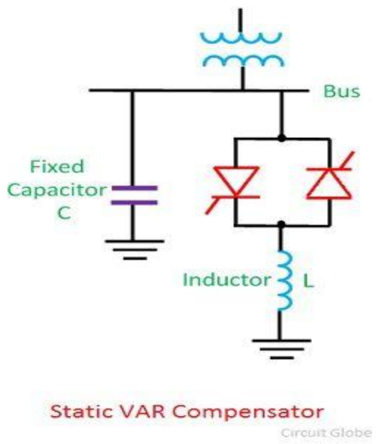

Figure 1: Static VAR Compensator

SVC is a shunt connected FACTS device. The application of SVC was started with the load compensation of fast changing loads like steel mills and arc furnace. Here load compensation includes power factor improvement and load balancing. The objective of the SVC is to balance the current on the receiving end side wherever required. In late seventies SVC was applied in transmission lines. When it is compared to synchronous condenser, it has no inertia and it can be extremely fast in the response. This makes fast control of reactive power in power system.

The injected reactive power and current are as given below:

Isvc = jBsvcVk
Qsvc = -Vk²Bsvc

Where,

Qsvc is the injected reactive power from the SVC
Isvc is the injected current of SVC
Bsvc is the susptance of SVC.

3. Differential Evolution Algorithm

Differential Evolution (DE) algorithm is a sub branch of evolutionary programming for optimization problems over continuous domains is developed by Rainer Storn and Kenneth Price in the year 1997. In DE algorithm, each variable's value is represented by a real number. The advantages of DE algorithm are its simple structure, ease of use, speed and robustness. DE is one of the very best genetic type algorithms for solving problems with the real valued variables. Differential Evolution is a design tool of great utility that is immediately accessible for the practical applications.

3.1 Steps for DE algorithm:

DE algorithm is in brief explained in the subsequent steps:

1) Initialization:

The population vector is randomly selected from the complete population vector j between the upper and lower limits.

$$x_{i,j}(0) = x_i^L + rand(0,1) \times (x_i^U - x_i^L)$$

Here i= 1, 2,3,.....,......,Np;
j=1, 2,3,......,......,D;
rand(0, 1) lies between 0 and 1 is a random number.

2) Mutation:

For creating a population vector $x_{i,G}$, three vectors $x_{r1,G}$, $x_{r2,G}$ and $x_{r3,G}$ are arbitrarily chosen from current population, like it must vary from the indices i, r1, r2 and r3 and they must be specific. From the three selected vectors, the difference of the any two is multiplied with the scalar factor F and this value is added to the third vector. F is a real and constant value between 0 and 2.

For every vector the j^{th} variable can be calculated as:

$$v_{i,j}(t+1) = x_{r1,j}(t) + F \times (x_{r2,j}(t) - x_{r3,j}(t))$$

3) Crossover:

After the mutation processes to increase the diversification of the population vector selected, the crossing over process is performed. In this process, the troubled vector changes its elements with the present vector as follows:

$$u_{i,j}(t) = f(x) = \begin{cases} v_{i,j}(t) & if\ rand(0,1) < CR\ \ or\ j = jrand \\ x_{i,j}(t) & else \end{cases}$$

Where $u_{i,j}(t)$ is the infant vector that will compete with parent vector $x_{i,j}(t)$.

It must be considered that there are two types of crossover schemes in Differential evolution algorithm namely binomial crossover scheme and exponential crossover scheme. In exponential crossover scheme, the crossover operation is basically performed in one loop on the D variables till it is inside the bounds of CR while the crossover process is performed as far as an arbitrarily selected number on all D variables is within the CR bound in binomial crossover scheme.

4) Selection:

The selection process is used with the purpose of maintaining the population size stable higher than the generations. The selection operation is usually performed to know among the parent and the child vector which one will be retained and which one will be replaced in the next generation. The parent vector is replaced by child vector if the fitness value of the child vector is better than the parent vector. And if the fitness value of the child vector is less than the parent vector then in the later generation the parent vector is retained. This algorithm is based on the survival of the fittest in its selection process and is expressed as:

$$\begin{cases} u_{i,j}^{G+1} & if\ f(u_i^{G+1}) \leq f(x_i^G) \\ x_{i,j}^{G} & else \end{cases}$$

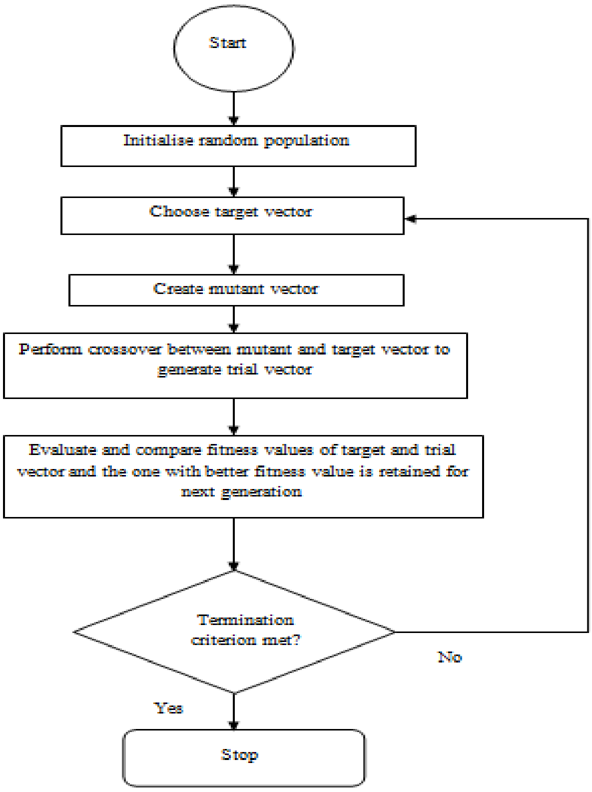

Figure 2: Flowchart of differential evolution algorithm

4. Methodology

4.1 Voltage Security:

The voltage security of the power system can be defined as its ability to hold a set of severe, but credible contingencies, and to survive transition to an acceptable new steady state condition. The problem illustrated in this paper is to find the optimal placement and size of SVC which reduces the voltage performance index (VPI) value, real power losses and the investment cost of SVC after severe contingencies have been occurred in the system. The severity of a contingency occurring in the network is evaluated using Voltage Performance Index (VPI). There are different formulations for VPI calculation proposed by many researches. The voltage performance index formula used in this work is given in below equation.

$$VPI = \sum_{i=1}^{All\ buses} \left(\frac{\Delta|Vi|}{\Delta|Vi^{max}|} \right)^{2m}$$

Where
ΔVi is the difference between the voltage magnitude of base case and line outage condition.
ΔVimax represents the greatest value set to limit the bus voltage from shifting in an outage case.
m is exponential which is taken as 2.

4.2 Objective functions and constraints:

The following objective functions and constraints are considered for the SVC placement problem:

1) Active Power Loss:

The main objective of this objective function is to minimise the active power loss. If the active power losses are minimised in the network, it is responsible for the redistribution of reactive power and this induces the change in real power generated by the slack bus. The minimization of the active power loss can be calculated using the following equation

$$f_1 = \sum_{k=1}^{nl} g_k \left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j) \right]$$

Where
nl is the total number of transmission lines in the network.
g_k is the conductance of k^{th} line

Represent the voltage at the buses i and j of k^{th} line.

2) Voltage Performance Index:

By considering the view point of the violation of bus voltage limits, the VPI index should be minimum for the power system network to remain in the secured condition. So the second objective is to reduce VPI value which is calculated using the following equation

$$f_2 = VPI$$

3) Investment Cost of SVC:

According to the Siemens AG Database, the objective function which is related to the investment cost of SVC in terms of (US$/kVar) is given by the following equation

$$f_3 = Cost$$

Where

$Cost = 0.0003S^2 - 0.3051S + 127.38$
S gives the kVar size of SVC.

The optimization is subjected to the following constraints:

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i. Equality constraints:

The objective of using the SVC is to control the system variables like real and reactive line flows and bus voltages of the power system. The equality constraints consist of active and reactive power flow equations and must satisfy at each bus of the power system network. The general form of the equality constraint is given as follows:

For bus i:

$$P_{gi} - P_{di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\emptyset_{ij} + \delta_i - \delta_j) = 0$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\emptyset_{ij} + \delta_i - \delta_j) = 0$$

$$P_{rs}^{spec} - P_{rs} = 0$$

ii. Inequality constraints:

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \; \forall i \; \varepsilon \; NG$$
$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \; \forall i \; \varepsilon \; NG$$
$$V_i^{min} \leq V_i \leq V_i^{max} \; \forall i \; \varepsilon \; N$$
$$\delta_{ij}^{min} \leq \delta_{ij} \leq \delta_{ij}^{max} \; \forall i \; \varepsilon \; N$$

The problem mentioned above in section 1, 2 and 3 forms a nonlinear constrained optimization problem, which is computed using equations given above and they can be devised as an objective function with multi criterion

$$F = min[f_1 + f_2 + f_3]$$

Subjected to above mentioned equality and inequality constraints.

4.3 Implementation:

The implementation of the above method is carried out using MATLAB software and is described below in the following steps:

Step 1: The data of the required power system network is assembled and tabulated, studied and the system is constructed.
Step 2: For the system, Newton Raphson load flow analysis is done by using MATLAB software.
Step 3: By considering different line outages in the system VPI calculation is carried out for identification of critical contingency.
Step 4: Under single line outage contingencies, proper size SVC were penetrated at the identified weak bus by using differential evolution algorithm to minimize the real power loss, improve the voltage security and reduce the investment cost of SVC.
Step 5: Load flow study was done again in Newton Raphson method using MATLAB software separately with SVC.
Step 6: Calculate the voltage performance indices with SVC.
Step 7: The VPI was compared with the base case values and the new solution was stored.
Step 8: End

5. Results and Discussions

The proposed methodology is applied on IEEE 30 bus system to test the methodology. Based on the proposed methodology, a Newton-Raphson method is developed in MATLAB 2010 software to run the load flow.

The proposed methodology has been tested, whose results are as shown below.

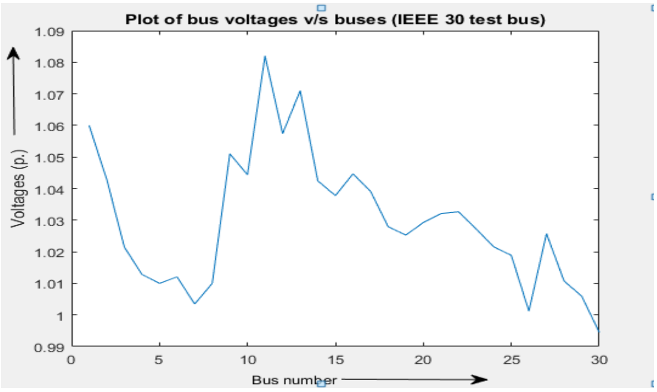

Figure 3: Plot of bus voltages v/s buses (IEEE 30 bus system -Base case)

Table I: Total generation, demand and losses of base case

Total Generation (in MW)	300.998
Total Demand (in MW)	283.4
Total Losses (in PU)	0.175

By calculating the VPI value for various single line outages, the severity of an outage in a network is determined. This VPI calculation is done using VPI formula.

The most critical contingencies were seen when there is outage in the line numbers 36, 37 and 38. This is observed from the VPI values obtained.

Table II: VPI and loss values without SVC of critical line outages

Line number	VPI	Real power losses PU
36	0.1581	0.199
37	0.000038197	0.180
38	0.000031951	0.181

By considering the most severe three line outages, the optimally placing of SVC of appropriate size is done using DE algorithm.

5.1 For line outage 36:

When SVC is not inserted at any of the buses, the value of VPI was 0.1581 and the real power loss was observed as 0.199p.u for line outage 36. To place SVC optimally 20 trials were carried out using DE algorithm in this case. During these trials 30, 29, 27 and 25 are the bus numbers which are obtained as weak buses, out of these locations one location at a time was considered as the optimal location for the placing of SVC. Graph below shows that after line outage 36 the voltage magnitude at each bus verses the bus number. The results obtained are shown in Table III using Differential Evolution algorithm. Simultaneously minimization of real power losses, VPI and the cost of SVC is considered. As can be observed from Table III, among these 4 bus solutions, bus number 30, 29 and 27 gives better solutions. It is also clear from Table III that when SVC is connected at bus 25, the real power losses and investment cost of SVC are at minimum but the VPI value is greater compared to other results. And on the other hand, when SVC is connected at bus 30, the value of VPI at bus 30 is smaller than SVC at bus 29 but gives real power losses slightly more than that when SVC is at bus 29. With SVC connected at bus number 27, losses are reduced; minimum VPI and cost were obtained. As the placement of SVC involves huge amount, so depending on the requirement of our preference, its placement is decided. Effect of SVC placement on voltage profile, real power losses, voltage security and investment cost are considered simultaneously for choosing optimal location of SVC. Therefore the optimal location for the placement of SVC is bus number 27 as far as the most critical line outage 36 is considered.

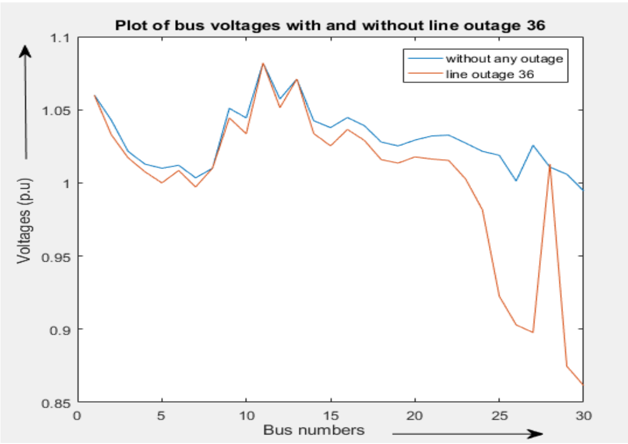

Figure 4: Plot of bus voltage verses bus number for line outage 36

Table III: Impact of placing SVC for line outage 36

	Without SVC	With SVC			
Bus number		At bus 30	At bus 29	At bus 27	At bus 25
Ploss	0.199	0.19381	0.19831	0.19281	0.19274
VPI	0.1581	0.00028984	0.0003214	0.00068695	0.0021534
Cost		124.46	124.65	124.46	124.5

5.2 For line outage 37:

For outage in the line number 37, without any SVC placed at any bus of the system, the value of real power losses and VPI were 0.18006 p.u. and 0.0010909 respectively. 20 trials were carried out using differential evolution algorithm in this case to place SVC optimally. Among the three locations namely bus number 30, 29 and 26 one was obtained as optimal location for placement of SVC. Graph below shows that after line outage 37 the voltage magnitude at each bus verses the bus number. Table IV shows the results obtained using algorithm for the three weak buses. From Table IV, the impact of SVC connected at bus 30, 29 and 26 is being analyzed. When SVC is connected at bus 30, the real power losses were observed to be 0.17878 which is less as compared to the other two bus results and the cost is also slightly minimum than SVC connected at the other two buses namely bus 29 and 26 but VPI value is observed slightly more than SVC connected at bus 29. Also, when the good investment cost is considered it was found that the cost was at minimum when SVC is connected at bus 29 also. the optimal location is location at bus 30 for the placement of SVC as the VPI value is slightly more compared to SVC at bus number 29 but from view point of voltage security, real power losses and SVC investment cost, SVC at bus number 30 is the optimal location.

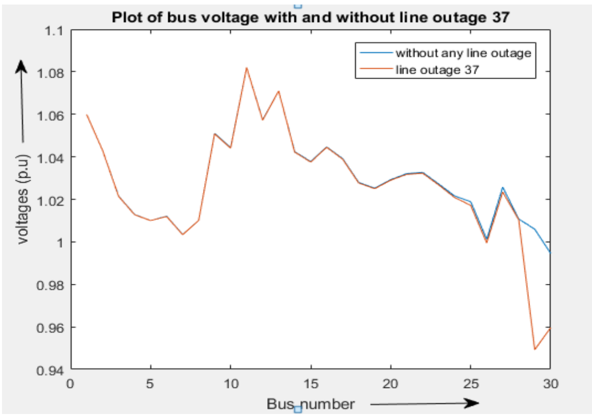

Figure 5: Plot of bus voltage verses bus number for line outage 37

Table IV: Impact of placing SVC for line outage 37

	Without SVC	With SVC		
Bus number		At bus 30	At bus 29	At bus 26
Ploss	0.18006	0.17869	0.17927	0.17986
VPI	0.0010909	0.00033367	0.0010637	0.00088253
Cost		124.44	124.5	124.46

5.3 For line outage 38:

For the line outage 38, it is clear from Table V that when SVC was not included at any bus, the losses were 0.18139 p.u, whereas the VPI value was 0.00091255. After completing 20 trials using differential evolution algorithm, three locations among all buses namely bus number 30, 29 and 26 were obtained as the optimal placement for connecting SVC device. Among these buses 30 and 29 gives better solutions for placement of SVC compared to bus number 26. Graph below shows that after line outage 38 the voltage magnitude at each bus verses the bus number. In Table 3 the real power losses, the value of VPI and the investment cost of SVC is tabulated for bus number 30, 29 and 26. As can be observed from Table V, when SVC is placed at bus 30, the real power losses, voltage performance index and the investment cost of SVC was at minimum as compared to that of bus 29 and bus 26. Hence, the optimal location for the placement of SVC may be bus 30.

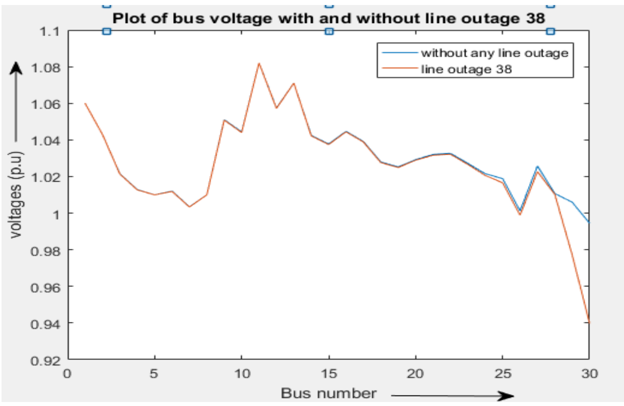

Figure 6: Plot of bus voltage verses bus number for line outage 38

Table V: Impact of placing SVC for line outage 38

	Without SVC	With SVC		
Bus number		At bus 30	At bus 29	At bus 26
Ploss	0.18139	0.17878	0.18043	0.18061
VPI	0.00091255	0.00033367	0.00034319	0.0000959
Cost		124.37	124.49	124.46

6. Conclusion

In this project, the Differential evolution algorithm is been implemented for searching the optimal size and location of SVC for minimization of real power loss and voltage security improvement by taking into consideration the investment cost of SVC following a single line outage contingencies. This multi-criteria optimization issue is transformed to a single objective problem solution by giving equal importance to each of the objective function simultaneously. For optimal placement of SVC device under various critical outage contingencies, different optimal locations were considered and the best location is obtained by analyzing the objective functions.

For the system considered here only one SVC is placed, for enhancement or improvement of voltage security in the power system we can place more than one SVC devices which have to be optimally located. The load assumed in the project is assumed to be constant but in practical it is varying, so proposed algorithm can be extended for varying loads. This methodology can be implemented on higher bus distribution system.

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