SVC Location for TTC Enhancement Using Differential Evolution: Making the Algorithm Faster

Malihe M. Farsangi , Hossein Nezamabadi-pour, Majid Hesari and Jalal Razavi
Department of Electrical Engineering,
Shahid Bahonar University of Kerman, Kerman,
IRAN

Abstract: - In this paper, a new Differential Evolution (DE) with small population (DESP) comparing to standard DE (SDE) is proposed for maximizing the Total Transfer Capability (TTC) between source and sink area by considering voltage limits and thermal limits in a power system by placing Static Var Compensator (SVC). Different strategies are considered to solve the problem. A comparison is made between the obtained results by SDE and DESP in terms of their success rate. Furthermore, simulation studies on a multi-machine network (IEEE 30-bus system) are presented to illustrate the capability of SDE and DESP algorithms with different strategies to solve the problem.

Key-Words: - Total Transfer Capability, Differential Evolution, genetic algorithm, FACTS devices, SVC, and heuristic approach**.**

1 Introduction

Total Transfer Capability (TTC) is the largest value of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of specified constraints. Flexible AC Transmission System (FACTS) devices such as TCSC and SVC could help system to increase power transfer capacity. TCSC provides a series compensation which consists of a series capacitor bank shunted by thyristors that can change its apparent reactance smoothly and rapidly. SVC is a shunt compensation component whose output is adjusted to exchange capacitive or inductive current. Different mathematical methods and algorithms have been developed for calculating TTC where can be found in [1]-[4].

Over the last decades there has been a growing interest in algorithms inspired by observing natural phenomenon. It has been shown that these algorithms are good alternatives as tools in solving complex computational problems. Various heuristic approaches have been adopted in research including genetic algorithm, tabu search , simulated annealing, etc. In view of this, to help the power system engineering, the IEEE power engineering society, IFAC symposium and ISAP organized tutorial courses on heuristic approaches [5]-[7]. Recently, different heuristic approaches are paid attention by researches around the world in power system, where the capabilities of different heuristic approaches are investigated.

Since it is found that flexible AC transmission system (FACTS) devices are good choices to improve TTC in power systems, various heuristic approaches have been adopted by researches including genetic algorithm, tabu search and evolutionary programming [8]-[10] to enhance TTC by placing the FACTS devices.

Among heuristic algorithms, Differential Evolution (DE) is a stochastic algorithm whose performs a multi-directional search by maintaining a population of potential solutions and encourages information exchanges between these directions. Thus this population can move over hills and across valleys to discover a globally optimal point. DE has been quite successfully applied to a few areas of power system such as network reconfiguration [11], generation expansion planning problem [12], Designing controller for power system stabilizers [13] and capacitor placement problems [14]. In view of this the authors applied DE algorithm in [15] to determine the optimal allocation of SVC for maximizing the TTC of power transmission between source and sink areas in power system. Now in this paper a new DE with small population is proposed. Since in [15] GA is applied to validate the obtained results by SDE and it was shown that both algorithm converging to the same solution, therefore in this paper SDE and DESP will be compared.

A comparison is made between the obtained results by SDE and DESP in terms of their success rate.

2 DESP Algorithm

To make a proper background, first the SDE algorithm is briefly described and followed by explanations of DESP.

2.1 SDE algorithm

DE is similar to genetic algorithm but differs from GA with respect to the mechanics of mutation, crossover and selections are performed. DE algorithm is briefly described below.

Step 1: *Initialization*. The initial vector population is chosen by randomly selection as follows:

$$x_{j,i}^{G=0} = x_{j,\min} + rand_j[0,1] \times (x_{j,\max} - x_{j,\min}) \qquad (1)$$

$$i = 1,2,\ldots,N_p;\; j = 1,2,\ldots,D$$

The initial process can produce N_p D-dimensional individuals of $x_{j,i}^{G=0}$ randomly.

Step 2: *Mutation*. A mutant vector is generated in the mutation process at the G^{th} generation according to different strategies.

In this paper, 5 different mutation strategies are used as follows [12],[17]:

i. Rand/ rand

$$u_{j,i}^{G+1} = x_{j,r3}^{G} + F \times (x_{j,r1}^{G} - x_{j,r2}^{G}) \qquad (2)$$

ii. Best/rand

$$u_{j,i}^{G+1} = x_{best} + F \times (x_{j,r1}^{G} - x_{j,r2}^{G}) \qquad (3)$$

iii. Old/best/rand

$$u_{j,i}^{G+1} = x_{j,i}^{G} + F \times (x_{best} - x_{j,i}^{G}) + F \times (x_{j,r1}^{G} - x_{j,r2}^{G}) \qquad (4)$$

iv. Best/rand-rand

$$u_{j,i}^{G+1} = x_{best} + F \times (x_{j,r1}^{G} - x_{j,r2}^{G} + x_{j,r3}^{G} - x_{j,r4}^{G}) \qquad (5)$$

v. Rand/rand-rand

$$u_{j,i}^{G+1} = x_{j,r5}^{G} + F \times (x_{j,r1}^{G} - x_{j,r2}^{G} + x_{j,r3}^{G} - x_{j,r4}^{G}) \qquad (6)$$

where x is set of population; $u_{j,i}^{G+1}$ is mutated i^{th} individual for the next generation; $x_{j,i}^{G}$ is the i^{th} individual among the population x ; x_{best} is the best individuals among the population x; F is the scaling factor which is real and constant $\in [0 \;\; 2]$; $x_{j,r1}^{G}; x_{j,r2}^{G}; x_{j,r3}^{G}; x_{j,r4}^{G}$ and $x_{j,r5}^{G}$ are the randomly chosen populations in the current generation .

Step 3: *Crossover*. In order to increase the diversity of the vectors, the parameters of the mutant vector and the target vector are mixed to yield a vector based on the following equation:

$$\hat{u}_{j,i}^{G+1} = \begin{cases} u_{j,i}^{G+1} & if\,(rand_j[0,1) < CR \;or\; j = jrand \\ x_{j,i}^{G} & otherwise \end{cases} \qquad (7)$$

$$i = 1,2,\ldots,N_p;\; j = 1,2,\ldots,D$$

In equation (7), CR is crossover factor which is a constant value $\in [0 \;\; 1]$ and assigned by the user. $rand_j$ is the j^{th} evaluation of a uniform random number generator ranging over $[0 \;\; 1]$ and $jrand$ is an index randomly chosen from $\{1,2,\ldots,D\}$.

Step 4: *Selection*. The parent is replaced by its offspring if the fitness of the offspring is better than that of its parent. Contrarily, the parent is retained in the next generation if the fitness of the offspring is worse than that of its parent. The parents for the next generation are selected as follows:

$$\bar{x}_i^{G+1} = \begin{cases} \bar{u}_{j,i}^{G+1} & if \quad f(\bar{u}_i^{G+1}) \le f(\bar{x}_i^{G}) \\ \bar{x}_i^{G} & otherwise \end{cases} \qquad (8)$$

2.2 Standard Differential Evolution

As mentioned already, F in Equations (2)-(6) is real and constant parameter and is a user specified control variable that typically belongs to the interval [0,2]. In this paper as another try to solve the problem of improvement of TTC by placing SVC, a variable scaling factor is used where alleviate the problem of selection of mutation operator in algorithm. The rule of the updating a scaling factor based on the 1/5 success rule of the evolution strategies [16] is used to adjust the scaling factor. The rule of updating scaling factor is as follows:

$$F^{t+1} = \begin{cases} c_d \times F^t & if\ p_s^t < \frac{1}{5} \\ c_i \times F^t & if\ p_s^t > \frac{1}{5} \\ F^t & if\ p_s^t = \frac{1}{5} \end{cases} \quad (12)$$

where p_s^t is the frequency of successful mutations measured. The successful mutation defining the fitness value of the best individual in the next generation is better than the best individual in the current generation. c_d and c_i are constant values.

3. TTC Calculation

The ability of interconnected transmission networks to reliably transfer electric power may be limited by voltage level limits, transmission line thermal limit, generation limit, voltage stability limit and transient stability limit. For the TTC calculations, one area is considered as the source area and the other considered as the sink area where TTC is a directional quantity from the source to the sink.

The scenario that is used for TTC calculation is Load / Generation method (LG) so that the loads in the sink area are increased and the source area will compensate for this increase by increasing its generation. The mathematical formulation of TTC can be expressed as follows:

Maximize λ

Subject to :

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |Vi||Vj|(GijCos\delta ij + BijSin\delta ij) = 0 \quad (9)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |Vi||Vj|(GijSin\delta ij + BijCos\delta ij) = 0 \quad (10)$$

$$|Vi|_{\min} \le |Vi| \le |Vi|_{\max} \quad (11)$$

$$S_{ij} \le S_{ij\max} \quad (12)$$

where λ is scalar parameter representing the increase in bus load or generation, $\lambda = 0$ corresponds to no transfer (base case) and $\lambda = \lambda_{\max}$ corresponds to the maximal transfer. P_{Gi}, Q_{Gi} are real and reactive power generation at bus i, P_{Di}, Q_{Di} are real and reactive power demand at bus i, n is the bus number, $|V_i|, |V_j|$ are voltage magnitude at bus i and j, δij is voltage angle difference between bus i and bus j, $|V_i|_{\min}, |V_i|_{\max}$ are lower and upper limits of voltage magnitude at bus i, S_{ij} is apparent power flow in line i and j and $S_{ij\max}$ is thermal limit of line i and j.

P_{Gi} and P_{Di}, Q_{Di} in the equations (9) and (10) are reformulated as follows:

$$P_{Gi} = P_{Gi}^0 (1 + \lambda k_{Gi}) \quad (13)$$

$$P_{Di} = P_{Di}^0 (1 + \lambda k_{Di}) \quad (14)$$

$$Q_{Di} = Q_{Di}^0 (1 + \lambda k_{Qi}) \quad (15)$$

where P_{Gi}^0 is original real power generation at bus i which is in source area, P_{Di}^0, Q_{Di}^0 are original real and reactive load demand at bus i which is in sink area and k_{Gi}, k_{Di} are constants used to specify the change rate in generation and load as λ varies.

TTC level in each case (normal or contingency case) is calculated as follows:

$$TTC = \sum_{i \in Sink} P_{Di}(\lambda_{\max}) - \sum_{i \in Sink} P_{Di}^0 \quad (16)$$

where $P_{Di}(\lambda_{\max})$ is the sum of loads in sink area when $\lambda = \lambda_{\max}$ and P_{Di}^0 is the sum of loads in sink area when $\lambda = 0$.

Also, the limitation of voltage angle differing from the reference node voltage angle, 45 degrees, is used in this paper to limit the transmission due to transient stability:

$$\delta_k = \delta_{\lim it} \qquad 45^\circ\ or -45^\circ \quad (17)$$

Voltage stability will be checked by increasing loads at the sink-bus near to the point of collapse.

4. The study system and results

A modified IEEE 30-bus system, shown in Fig. 1, is used as a test system. The system has three areas with two generators in each area. In this paper area 1 is known as source and area 2 and area 3 are known as sink1 and sink2 respectively.

Improving TTC by placing SVC using DESP and SDE is implemented as follows:

4.1 The use of SDE algorithm

In the SDE algorithm, N_p individuals are generated randomly where N_p is selected to be 30. Since optimizations are made on two parameters: the location and size, therefore, each individual is a D-dimensional vector in which $D = 2$. In this paper, the crossover probability is chosen to be $CR = 0.9$, the number of iteration is considered to be 30, which is the stopping criterion and the scaling factor is set to be $F = 0.5$.

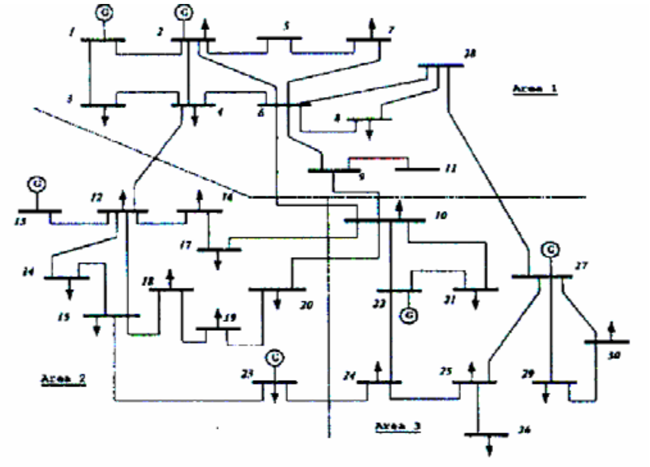

Fig. 1. Single line diagram of IEEE 30-bus system.

Different strategies addressed in Subsection 2.1, are applied to solve the problem. To locate SVC by SDE, suitable buses are selected based on 10 independent runs under different random seeds for each different strategy. The obtained results by applying different strategies are as follows: 10% of the results obtained by SDE with the Best/rand, Old/best/rand and Rand/rand/rand strategies show that to improve TTC, SVC should be placed at bus 12 and 90% of the results obtained reveal that to improve TTC; SVC should be located at bus 8. Furthermore, 100% of the results obtained by the Best/rand/rand and Rand/rand strategies show that to improve TTC, a 50 Mvar SVC should be placed at bus 8. The effects of SVC on TTC are given in Table 1.

Table1. The effects of SVC on TTC by using DE

Transfer		TTC without SVC	TTC with SVC
From Area	To Area		
1	2	23.345	74.837
1	3	26.833	35.344
Total TTC		50.1788	110.181

The results obtained by SDE with different strategies are averaged over independent runs. The average best-so-far and average cost function of each run are recorded and averaged over 10 independent runs. To have a better clarity, the convergence characteristics for different strategies are given in Figs. 3-4. These figures show that for the current problem, the strategy; Best/ rand/rand; has better features to find optimal solution comparing to other strategies.

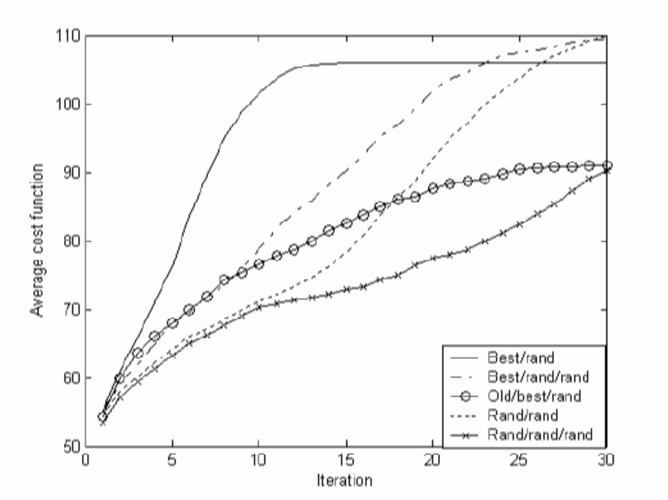

Fig. 3. Convergence characteristics of DE on the average cost function in finding the solution, 50 Mvar SVC at bus 8.

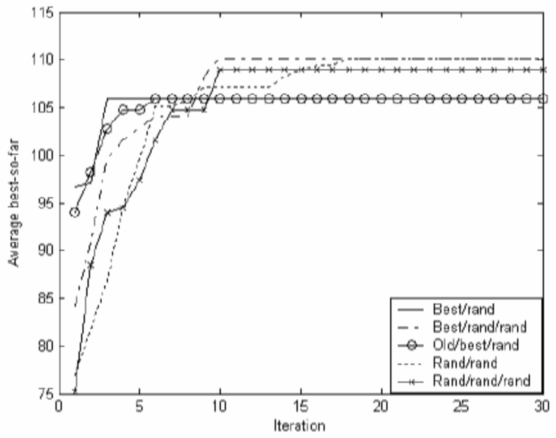

Fig. 4. Convergence characteristics of SDE on the average best-so- far in finding the solution, 50 Mvar SVC at bus 8.

4.2 The use of DESP algorithm

The main difference between the SDE algorithm and the DESP algorithm is in the population size (N_p). In SDE algorithm, N_p is set to be 30 but in DESP algorithm, N_p is set to be 10. This is due to (12) that the algorithm can converge to the optimal solution even by small number of population.

As mentioned before, the N_p is considered to be 10. The initial value of the scaling factor is set to 1.2, c_d is set to be 0.82 and c_i is chosen to be 1/0.82 [16]. To locate SVC by DESP, suitable buses are selected based on 10 independent runs, under different random seeds for each different strategy.

The results obtained by DESP with different strategies are averaged over independent runs. The average best-so-far and average fitness function of each run are recorded and averaged over 10 independent runs. To have a better clarity, the convergence characteristics in finding the location and size of a SVC for different strategies are given in Figs. 5-6. Once again, these figures show that for the current problem, the strategy Best/rand/rand has better features to find optimal solution comparing to other strategies. The results obtained show that the SVC should be placed at bus 8.

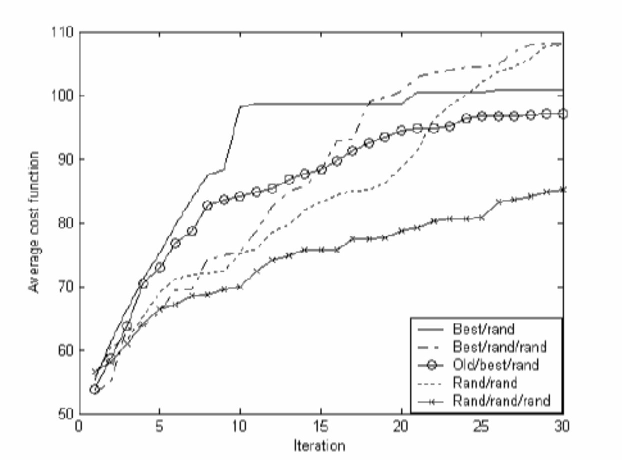

Fig. 5. Convergence characteristics of DESP on the average cost function in finding the solution, 50 Mvar SVC at bus 8.

Figs. 3 - 6 show that the convergence characteristic of strategy Best/rand/rand is better than the other strategies. Now the convergence characteristic of strategy Best/rand/rand by considering SDE and DESP are compared in Fig. 7. This figure shows that in SDE when F is constant, the convergence characteristics of strategy Best/rand/rand on the average fitness function in finding the solution is slightly better than when it is considered as a variable in DESP. But the point is that with the small population size of DESP when F is variable, the algorithm leads us to the optimal solution. Also, considering small population resulted in less execution time. Generally speaking, we can say that the DESP is performing better than the SDE.

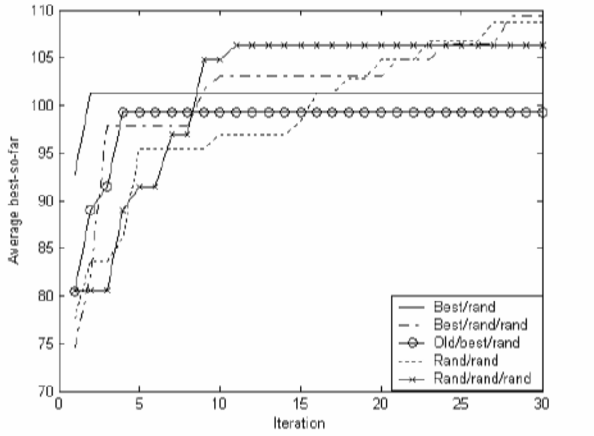

Fig. 6. Convergence characteristics of DESP on the average best-so- far in finding the solution, 50 Mvar SVC at bus 8.

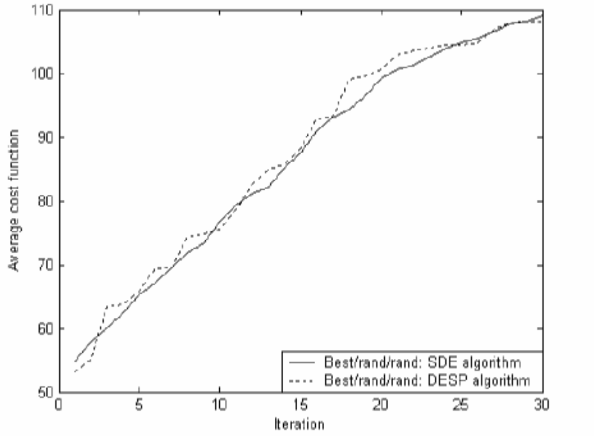

Fig. 7. Convergence characteristics of SDE and DESP with Best_rand_rand on the average fitness function in finding the solution, placement of SVC at bus 8.

5. Conclusion

In this paper, the capability of DESP with different strategies in placement of SVC to maximize TTC between different control areas is investigated. TTC is calculated based on voltage level limit, transmission line thermal limit, generation limit, voltage stability limit and transient stability limit. To validate the results, SDE is applied. The results obtained show that between different strategies of

SDE, Best/ rand/rand has better characteristics to find optimal solution. Both algorithms (SDE and DESP with the strategy Best/ rand/rand), find the same solution with almost the same convergence characteristics. For solving complex problem with higher dimensions by heuristic methods for example GA or SDE with high number of population, the execution time is high and the DESP algorithm could be a good replacement.

It should be noted that among different types of FACTS devices, the series types such as TCSC have more effects than shunt types such as SVC on TTC improvement. Since in this paper, the placement of SVC by DESP to improve TTC is done successfully, the placement of TCSC by DESP and then the coordination of SVC and TCSC by DESP to improve TTC are the future work by the authors.

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