

# Performance Comparison of GA, DE, PSO and SA Approaches in Enhancement of Total Transfer Capability using FACTS Devices

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**Abstract** – In this paper the performance of meta-heuristics algorithms such as GA (Genetic Algorithm), DE (Differential Evolution), PSO (Particle Swarm Optimization) and SA (Simulated Annealing) for the problem of TTC enhancement using FACTS devices are compared. In addition to that in the assessment procedure of TTC two novel techniques are proposed. First the optimization algorithm which is used for TTC enhancement is simultaneously used for assessment of TTC. Second the power flow is done using Broyden – Shamanski method with Sherman – Morrison formula (BSS). The proposed approach is tested on WSCC 9 bus, IEEE 118 bus test systems and the results are compared with the conventional Repeated Power Flow (RPF) using Newton Raphson (NR) method which indicates that the proposed method provides better TTC enhancement and computational efficacy than the conventional procedure.

**Keywords:** Differential evolution, Genetic algorithm, Particle swarm optimization, Simulated annealing and total transfer capability.

## 1. Introduction

According to NERC report [1], Total Transfer Capability (TTC) is defined as the amount of Electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all defined pre and post contingencies. Available Transfer Capacity (ATC) is a measure of transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Hence in the competitive electricity market ample amount of TTC should be provided to ease congestion. One way of doing it is by installing FACTS devices.

FACTS devices are capable of controlling voltage magnitude, phase angle and circuit reactance, by controlling these we can redistribute the load flow and regulate bus voltage. Therefore this method provides a promising one to improve TTC [2-7]. Since the cost of FACTS devices are very high, location and settings of these devices for enhancement of TTC need a detail analysis. This analysis involves two sub problems, the problem of assessment of TTC and the problem of enhancement of TTC. The problem of assessment of TTC is done using either DC or AC power transfer distribution factors [8-10] or Repeated Power Flow (RPF) [11] or CPF (Continuation Power Flow) [12, 13] or OPF (Optimal Power Flow) [14] based methods.

The problem of enhancement of TTC is a combinatorial analysis. Many researchers have tested different optimization algorithms in the recent past. The best suited approach to such type of problems is to use Meta – heuristics optimization algorithms such as Differential Evolution (DE) [15, 16], Particle Swarm Optimization (PSO) [17, 18], Genetic Algorithm (GA) [19-24], Evolutionary programming [25, 26], Simulated Annealing (SA) and Tabu Search [27].

According to western interconnection report [28] a typical TTC calculation is

- Hourly TTC for the next 168 Hours : Once per day
- Daily TTC for the next 30 days : Once per week
- Monthly TTC for months 2 through 13: Once per month.

From [28, 29], it can be understood that the problem of assessment of TTC with 15000 buses considering 7000 contingencies for 500 different transactions will take up to 24 hrs even when using linear methods. Along with the assessment of TTC, if the problem of enhancement of TTC is considered then this demands the use of optimization algorithms, which adds up the computational burden further. This means a significant reduction in computational time is needed in the problem of assessment and enhancement of TTC.

Hence to improve the computational efficacy, for the first time in enhancement of TTC using FACTS device two techniques are introduced in this paper. First, the optimization algorithm which is used to enhance TTC is simultaneously used for assessment of TTC also. This avoids the use of separate assessment methods such as RPF, CPF or OPF based methods which reduce the computational time significantly. Second, the power flow is

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performed using Broyden – Shamanski with Sherman – Morrison formula (BSS) method instead of a conventional Newton Raphson (NR) method. Even with the implementation of sparsity technique in NR method, BSS method proves to be superior since it reduces the number of functional evaluations and eliminates the computation of repeated Jacobian inverse thus improving the computational efficiency further. These two modifications are implemented in the well known meta-heuristics optimization algorithms GA, DE, PSO and SA for a comparative study.

The remaining paper is organized as follows: Section 2 deals with overview of GA, DE, PSO and SA methods. Section 3 deals with the problem formulation for TTC enhancement. Results and discussions are given in Section 4. Finally conclusions are drawn in section 5.

## 2. Overview of GA, DE, PSO and SA methods

All modern stochastic algorithms fall under the category of meta-heuristics. From the recent literatures [30-32] it is understood that these algorithms are the only practical solution to obtain global optimal for real world problems which are non linear, non differentiable, continuous and real valued. Of all these algorithms the most powerful ones are GA, DE, PSO and SA. Hence in this paper these algorithms are tested and compared for the problem of enhancement of TTC using FACTS devices.

### 2.1 Genetic Algorithm (GA)

GA [33] is a search algorithm that depends on conjecture of natural selection and genetics. The general procedure of GA is to evaluate fitness (or objective function value) for a randomly generated initial population. Then based on fitness, selection is done on the individuals for reproduction. Upon selected individuals crossover and mutation is performed to create offspring which forms the population of next generation. This process is repeated until maximum number of generations or convergence is reached.

### 2.2 Differential Evolution (DE)

DE [34] uses the difference of randomly sampled pairs of object vectors to guide the mutation process which makes it relatively new when compared to other algorithms. Similar to GA a randomly generated initial population is created. For each individual three other individuals are selected in random. A new vector is created by adding a weighted (mutation factor) difference of two individual to the other. Cross over or recombination is one of the main operators for GA but it is complementary in DE. When the entire individuals are processed by this way then fitness is evaluated. If the fitness value of the new individual is

better than that of old individual then replace the old individual with the new one. This process is repeated until maximum number of generations or convergence is reached.

### 2.3 Particle Swarm Optimization (PSO)

PSO [35] algorithm is based on the social behavior of birds. In this algorithm, initially a random population is created. Every individual known as particle is assigned a velocity and a small social network. For all particles, fitness or objective function values are evaluated. Based on fitness unlike GA, PSO doesn't have crossover/mutation, but the personal optimal for each individual, global optimal in the complete population and neighborhood optimal found by the neighbors of each individual are saved to update velocity and position for each individual. This process is repeated until either maximum generations or convergence is reached.

### 2.4 Simulated Annealing (SA)

SA [36] is based on thermodynamics theory of the liquids that solidify into crystalline upon cooling. As in other heuristic methods populations are initialized and an initial temperature is associated with it. Fitness is evaluated for the complete individuals in the population. Now a new population is generated which is close to the older one based on the temperature and a random number and their fitness is evaluated. The ratio of difference in fitness of old and new population to the existing temperature is compared with a random number and the best individual is placed in the existing population. Then a cooling schedule is applied to update the temperature. This process is repeated until maximum generations or convergence is reached.

## 3. Problem formulation

The TTC level in normal or contingency state is given by:

$$TTC = \sum_{i \in \text{sink}} P_{D_i}(\lambda_{\max}) \quad (1)$$

and ATC neglecting TRM, ETC is given by

$$ATC = \sum_{i \in \text{sink}} P_{D_i}(\lambda_{\max}) - \sum_{i \in \text{sink}} P_{D_i}^0 \quad (2)$$

where

$$\sum_{i \in \text{sink}} P_{D_i}(\lambda_{\max}) \text{ is the sum of load in sink area when } \lambda = \lambda_{\max} .$$

$\sum_{i \in \text{sink}} P_{D_i}^0$  is the sum of load in sink area when  $\lambda = 0$ .

Therefore the objective function is

$$\text{maximize TTC} = \sum_{i \in \text{sink}} P_{D_i}(\lambda_{\text{max}}) \quad (3)$$

Subject to

$$P_{G_i} - P_{D_i} - \sum_{j=1}^n P_{\text{loss}j} = 0 \quad (4)$$

$$Q_{G_i} - Q_{D_i} - \sum_{j=1}^n Q_{\text{loss}j} = 0 \quad (5)$$

$$V_{i \text{ min}} \leq V_i \leq V_{i \text{ max}} \quad (6)$$

$$S_j = S_{j \text{ max}} \quad (7)$$

$$P_{G_i} \leq P_{G_i \text{ max}} \quad (9)$$

Hence in assessment of TTC the objective is to find the maximum value of  $\lambda$  such that Eqs. (4) to (9) is not violated. On the other hand enhancement of TTC is to maximize the difference of Eq. (3) before and after the placement of FACTS device using heuristic optimization method explained in section 2 without violating Eqs. (4) to (9).

In this paper FACTS device, TCSC and SVC with Power flow model from [27] is considered for enhancement of TTC.

### 3.1 TTC assessment using the optimization algorithm

In the conventional approach, RPF or CPF or OPF based methods are used to find  $\lambda_{\text{max}}$  for assessment of TTC and the optimization algorithms are used for placement of FACTS device to enhance TTC [21-24]. In this approach the generalized representation of an individual in the population of the optimization algorithm is as shown in Fig. 1.

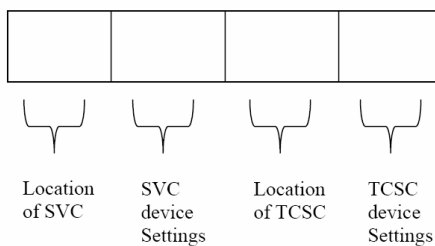


Fig. 1. Representation of an individual

If assessment of TTC alone is considered, then conventional assessment procedure is preferred since it is faster than optimization based method, but enhancement of TTC using FACTS device demands optimization procedure to be combined with the conventional assessment procedures which takes much computational time. To minimize to computational time, in this paper the optimization algorithm is simultaneously used to asses

TTC. This is achieved by modifying the representation of the individual in the population as shown in Fig. 2. In this approach every individual of the population, has the information of FACTS device location and settings and also a value of  $\lambda_{\text{ttc}}$ . The  $\lambda_{\text{ttc}}$  can take a value between 0 and 2 (for an increase of loading factor up to 200%), since no power system even under the worst case will be under utilized for more than 200%. Therefore this approach directly searches  $\lambda_{\text{ttc}}$  (a real number with an accuracy up to four decimal places) using the optimization algorithm in the search space instead of increasing it in steps of 0.1p.u or 0.01p.u as in the case of conventional approach. Hence the proposed method has higher accuracy and requires lesser computational time when compared to that of conventional approach. Power flow Eqs. (4) to (7) are solved for every individual and if any equations got violated then a very low fitness value is assigned for that individual as penalization else fitness is evaluated as per the difference of Eq. (3) before and after the placement of FACTS device.

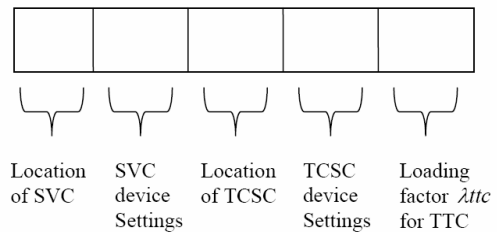


Fig. 2. Modified representation of an individual

### 3.2 Power flow using BSS method

In general, an NR method finds the value of 'x' iteratively such that

$$F(x) = 0 \quad (10)$$

In the iterative process, say in  $m^{\text{th}}$  iteration 'x' is updated as given below

$$x^{m+1} = x^m - \Delta x \quad (11)$$

and 
$$\Delta x = -(J^m)^{-1} F(x^m) \quad (12)$$

where  $J^m$  is the Jacobian matrix.

In the assessment of TTC the power flow equations are solved repeatedly, for every step increment of  $\lambda_{\text{ttc}}$  there are more than one iteration and for every iteration a Jacobian matrix of size  $n \times n$  is computed and then inverted. For 'n' non linear equations, computation of Jacobian matrix elements includes computation of  $n^2$  partial derivatives and 'n' number of component functions. Therefore  $n^2 + n$  functional evaluations need to be done. Again inversion of an  $n \times n$  Jacobian matrix using Gauss Jordan elimination method requires  $n^3$  arithmetic

operations or if sparsity technique is used to compute Jacobian inverse with some form of Gauss elimination technique then the total time taken for the inversion is  $k \times n$ , where ‘k’ is the average non zero entries in a row or column of the sparse LU factors and ‘n’ is the size of the Jacobian matrix. This procedure takes more computational time.

The Quasi-Newton BSS method [37-39] belongs to the class of two step iteration which differentiates it from the conventional Broyden’s method. Let us consider the expression (10) which has to be solved iteratively using BSS method. In the first iteration  $x^0$  is chosen as in the case of NR method, then  $w^0$  is calculated as given below

$$w^0 = -(J^0)^{-1} F(x^0) \tag{13}$$

Using (13)  $v^0$  is updated as

$$v^0 = x^0 + w^0 \tag{14}$$

this is the first step iteration. Using (14)  $s^0$  is computed as

$$s^0 = -(J^0)^{-1} F(v^0) \tag{15}$$

Then with the value of  $s^0$  and  $v^0$ ,  $x^1$  is updated using

$$x^1 = v^0 + (M - C \cdot \|s^0\|^\alpha) s^0 \tag{16}$$

which is the second step iteration. Here  $M$ ,  $C$  and  $\alpha$  are the real variables defined in [37], where the role of  $M$  is to increase the rate of convergence,  $C$  and  $\alpha$  keeps the new iteration in the convergence region.

From the second iteration the above procedure is repeated by replacing the Jacobian matrix ‘ $J$ ’ with an equivalent matrix ‘ $A$ ’ which is defined at the  $m^{\text{th}}$  iteration as given below

$$A^m = A^{(m-1)} + [\Delta F(x) - A^{m-1}(\Delta x)] \tag{17}$$

where

$$\Delta F(x) = F(x^m) - F(x^{m-1}) \tag{18}$$

$$\Delta x = x^m - x^{m-1} \tag{19}$$

This reduces the number of functional evaluations to ‘n’ from ‘ $n^2 + n$ ’ when compared to the case of NR method but makes the convergence of BSS as super linear when compared to quadratic convergence of NR method.

Further the  $n^3$  arithmetic operation for computing the inverse of  $A^m$  matrix can be reduced to  $n^2$  operations using the Sherman Morrison formula as

$$(A^m)^{-1} = \frac{[A^{(m-1)}]^{-1} + U}{\Delta x^T [A^{m-1}]^{-1} \Delta F(x)} \tag{20}$$

where

$$U = \{\Delta x - [A^{m-1}]^{-1} \Delta F(x)\} * \{\Delta x^T [A^{m-1}]^{-1}\} \tag{21}$$

Unlike NR method, here the Jacobian inverse is computed only once during the first iteration and for the remaining iterations a rank one update is done to compute the inverse.

In a normal power flow, the quadratic convergence and the implementation of sparsity technique in NR method proves to be superior to BSS method which has super linear convergence and Sherman Morrison formula for Jacobian inverse. When it comes to the problem of TTC assessment where power flow is solved repeatedly, which involves multiple Jacobian computations and inverses, in this process computation using BSS method is faster when compared to NR method.

#### 4. Results and Discussion

Comparison of the optimization methods GA, DE, PSO and SA to enhance TTC in presence of FACTS device is presented in this section. The control parameter values [31] for all the optimization algorithms are given below

- GA: real coded, population=30, generations=300, crossover probability=0.5, mutation probability=0.1.
- DE: population=30, generations=300, differentiation factor randomly between=-1.5 to 1.5, crossover probability=0.95.
- PSO: population=30, generations=300, cognitive learning factor=2, cooperative factor=2, social learning factor=0.5, inertial constant=0.5 and number of neighbors=5.
- SA: population=30, generations=300, initial cooling temperature =100 and cooling constant=0.9.

Two different assessment procedures for TTC are used, the conventional method i.e. RPF with power flow using NR [2] method with sparsity technique (RPFNR) and the proposed method i.e. Optimization Algorithm with power flow using BSS method (OABSS). The effectiveness of the proposed methodology is illustrated using the WSCC 9 bus and IEEE 118 bus test system. In RPFNR, 0.1 p.u. and 0.01 p.u. in  $\lambda$  respectively is considered as incremental step for WSCC 9 bus and IEEE 118 bus test system. Only one TCSC and one SVC are considered for placement at a time. The limits  $X_{\text{TCSC}}$  of TCSC device is considered as  $-0.5X_L$  to  $+0.5X_L$  and  $Q_{\text{SVC}}$  of SVC device is  $-100$  Mvar to  $+100$  Mvar, where  $X_L$  is the reactance of the transmission line in which TCSC is installed. The base MVA for the load flow

**Table 1.** WSCC 9 bus test system: TTC enhancement comparative results

Parameters		TTC without FACTS device	TTC with FACTS device (RPFNR method)				TTC with FACTS device (OABSS method)			
			GA	DE	PSO	SA	GA	DE	PSO	SA
TCSC	Location	-	Line 7-8	Line 4-5	Line 5-6	Line 7-8	Line 1-4	Line 1-4	Line 8-2	Line 7-8
	$X_{TCSC(p.u)}$	-	-0.4514	-0.4881	0.3817	0.1182	-0.4258	-0.5	-0.5	-0.2264
SVC	Location	-	Bus 5	Bus 9	Bus 5	Bus 5	Bus 5	Bus 4	Bus 4	Bus 5
	$Q_{svc}$ (Mvar)	-	89.31	90.04	72.17	70.71	97.79	100	100	76.34
<b>TTC (MW)</b>		<b>399.00</b>	<b>475.00</b>	<b>475.00</b>	<b>475.00</b>	<b>475.00</b>	<b>492.10</b>	<b>493.45</b>	<b>492.32</b>	<b>481.65</b>
Limiting condition		$V_{min}$ (Bus 5)	line 1 - 4	line 1 - 4	line 1 - 4	line 1 - 4	Line 1 - 4	Line 1 - 4	Line 1 - 4	Line 1 - 4
<b>CPU time (sec)</b>		-	<b>1280.84</b>	<b>1130.77</b>	<b>1282.86</b>	<b>1195.31</b>	<b>91.43</b>	<b>84.94</b>	<b>96.22</b>	<b>90.19</b>

is assumed to be 100. The values of  $M$ ,  $C$  and  $\alpha$  for BSS method [37] is taken as 2, 1 and 0.1 respectively for all the test system. Transfer of power from Area 1 to Area 2 alone is considered for both test systems. The power flow data for the test system are considered from [40-42]. Load flow programs are executed in MATLAB using modified MATPOWER [42] coding in INTEL core 2 Duo CPU T5500@ 1.66 GHz processor under Windows XP professional operating system.

#### 4.1 WSCC 9 bus test system

WSCC 9 bus test system consists of 3 generators and 9 transmission lines. This system has been divided into two areas. Area 1 includes buses 3,6,8 and 9 and Area 2 includes buses 1,2,4,5 and 7. The base load in Area 2 is 190 MW. For a transfer of power from Area 1 to Area 2 without FACTS device, the TTC value is 399.0 MW. With placement of FACTS and using RPFNR method as shown in Table 1 the TTC value is 475 MW which is 19.04 % higher when compared to TTC without FACTS and this value remains same for all the optimization methods. With placement of FACTS using OABSS method the TTC value obtained using GA, DE, PSO and SA methods are higher when compared to RPFNR method as shown in Table 1. In RPFNR method loading factor  $\lambda_{tc}$  is increased in discrete steps. This limits the search space for the optimization algorithms, hence results in local optimal points that has same TTC value for different location and settings of FACTS devices. In OABSS method,  $\lambda_{tc}$  (a real number with accuracy up to four decimal places) is directly searched using the optimization algorithm. This approach provides wider search space for the optimization algorithms which results in better TTC value with different location and settings of FACTS devices when compared to RPFNR method. From Table 1 it is also evident that the DE algorithm being the most promising one, with a TTC value of 493.45 MW which is 23.67 % high when compared to TTC without FACTS. The percentage rise in TTC value using GA, PSO and SA methods are 23.33%, 23.38% and 20.71% respectively. The CPU time for computing TTC with RPFNR method is very high when compared to

OABSS method as shown in Table 1. Among the optimization algorithms used either with RPFNR method or with OABSS method DE proves to be superior. The computational time for DE with OABSS method is 92.48% less when compared to that of DE with RPFNR method. Out of the four algorithms compared SA, GA and PSO are ranked second, third and fourth respectively in computational time as shown in Table 1.

#### 4.1 IEEE 118 bus test system

This system has 54 generators and 186 transmission lines.

This system has been divided into three areas as shown in Table 2.

**Table 2.** Area classification of IEEE 118 bus test system

Area	Area 1	Area 2	Area 3
Bus Numbers	1-23, 25-32, 113-115, 117	24, 38, 65-112, 116, 118	33-37, 39-64,

For a transfer of power form Area 1 to Area 2 without FACTS device the TTC value is 2169.4 MW. Table 3 shows the placement of TCSC and SVC device with device settings and the limiting condition for TTC using various optimization algorithms with RPFNR and OABSS methods. As in the case of WSCC 9 bus test system, in RPFNR method the TTC value remains same for all the optimization methods as 2188.8 MW which is 0.89 % higher when compared to TTC without FACTS, but with OABSS method the value of TTC is still higher as shown in Table 3. In OABSS method, DE outperforms other optimization algorithm with a TTC value of 2205.0 MW which is 1.64 % more when compared to TTC without FACTS device. Using GA, PSO and SA methods with OABSS the corresponding rise in TTC value is 1.42%, 1.59% and 1.05% respectively when compared to that of TTC without FACTS device. From the computational point of view, Table 3 shows that the optimization algorithm with RPFNR method takes more time when compared to that of OABSS method as expected and DE being the best in it. The time taken by DE algorithm using OABSS method is

**Table 3.** IEEE 118 bus test system: TTC enhancement comparative results

Parameters		TTC without FACTS device	TTC with FACTS device (RPFNR method)				TTC with FACTS device (OABSS method)			
			GA	DE	PSO	SA	GA	DE	PSO	SA
TC	Location	-	Line 49-54	Line 75-118	Line 31-32	Line 5-11	Line 38-65	Line 49-66	Line 49-66	Line 49-66
	$X_{TCSC(p.u)}$	-	0.0822	-0.3469	-0.4460	-0.1125	-0.4451	-0.4827	-0.5	-0.1828
SCSV	Location	-	Bus 96	Bus 94	Bus 57	Bus 35	Bus 14	Bus 43	Bus 14	Bus 44
	$Q_{svc}$ (Mvar)	-	-69.94	9.89	-93.63	41.70	80.28	99.68	100.0	14.21
<b>TTC (MW)</b>		<b>2169.4</b>	<b>2188.8</b>	<b>2188.8</b>	<b>2188.8</b>	<b>2188.8</b>	<b>2200.4</b>	<b>2205.0</b>	<b>2204.1</b>	<b>2192.3</b>
Limiting condition		line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68	line 65 – 68
<b>CPU time (sec)</b>		<b>-</b>	<b>8204.86</b>	<b>7463.53</b>	<b>7948.53</b>	<b>8117.23</b>	<b>295.42</b>	<b>273.21</b>	<b>290.56</b>	<b>292.61</b>

96.33% less when compared to that of DE with RPFNR. Here PSO, SA and GA are ranked second, third and fourth respectively as shown in Table 3.

### 5. Conclusion

Comparison of the performance of GA, DE, PSO and SA algorithms in enhancement of TTC with FACTS device are presented. These algorithms are tested with WSCC 9 bus and IEEE 118 bus test system using the conventional RPFNR and the proposed OABSS methods. Results indicate that there is a considerable improvement in TTC value as well as a huge reduction in computational time when OABSS method is used when compared to RPFNR since the later is more conservative. Though all the optimization algorithms produce better results when it is combined with OABSS when compared to RPFNR method, DE outperforms GA, PSO and SA methods both in enhancement of TTC and in computational efficacy. It is also evident from the results that the percentage reduction in CPU time using OABSS method increases with the increase in size of the system when compared to that of RPFNR method.

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