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ATC Enhancement Through Optimal Location And Sizing Of FACTS Devices Using BB-BC Algorithm

S. Sakthivel
Associate Professor
Department of Electrical and Electronics Engineering
V.R.S. College of Engineering and Technology
Villupuram, Tamil Nadu, India.

P. Mathiazhagi
UG Scholar
Department of Electrical and Electronics Engineering
V.R.S. College of Engineering and Technology
Villupuram, Tamil Nadu, India.

T. K. Archana
UG Scholar
Department of Electrical and Electronics Engineering
V.R.S. College of Engineering and Technology
Villupuram, Tamil Nadu, India.

ABSTRACT

In an open power market, sufficient transmission capability should be made available for satisfying the demand of increasing power transactions. Certain methodologies are to be developed to enhance the power handling capacity of existing transmission lines. In this work, power flow pattern is changed by transformer tap settings and reactance of TCSCs to enhance ATC of a system. Flexible AC transmission System (FACTS) devices are inserted in electrical systems to enhance power transfer capability. Thyristor controlled series compensator (TCSC) is highly helpful in enhancing the power carrying capacity of a line by adjusting its reactance. The location and sizing of TCSC is the major issue in optimizing the benefits. The recently developed metaheuristic algorithm of Big Bang-Big Crunch (BB-BC) algorithm is proposed for optimizing the location and size of TCSC devices. The algorithm is with less number of parameters and can be easily implemented for practical applications. The proposed algorithm is tested on the standard IEEE 30 bus system and results obtained are really satisfactory.

1. INTRODUCTION

Power system networks across the world are undergoing tremendous changes to meet the growing power demand and to improve the quality of power supply. Deregulation of electric power system networks is one such changes and it ensures cheap power to the consumers. Deregulation poses several challenges that are to be solved. Insufficient transmission capability is the major challenge to be addressed [1]. Usually, there is mismatch between construction of power plants and transmission systems [2]. This is due to several socioeconomic reasons. Sufficient transmission capability may be provided by enhancing the capability of existing transmission lines.

One of the possible ways to improve the capability of a transmission line is to use FACTS devices [3]-[4]. The insertion of FACTS devices extends the possibility that current through a line can be controlled at a reasonable cost, enabling large potential of increasing the capacity of existing lines, and use of one of the FACTS devices to enable corresponding power to flow through such lines under normal and contingency conditions. Several studies [5] have found that FACTS technology not only provides solutions for efficiently increasing transmission system capacity but also increases ATC, relieve congestion, improve reliability and enhances operation and control.

The benefits of FACTS devices are maximized by optimizing their location and parameters [6]. However, it is hard to determine the optimal location and sizing of FACTS devices. Therefore a suitable optimizing technique is necessary. Recently several optimization algorithms are proposed and exploited for many power system operation optimization [7]-[8].

A method based on continuation power flow [9] incorporating limits of reactive power flows, voltage limits as well as voltage collapse and line flow limits is described. However, with this method the computational effort and time requirement are large. For very large systems, the method may be quite cumbersome. The localized linearity of the system is assumed and additional load required to hit the different limits are separately calculated and the minimum of all these is taken as ATC.

The task of calculating ATC is one of the main concerns in power system operation and planning. ATC is determined as a function of increase in power transfers between different systems through prescribed interfaces. Methods available for ATC calculations include Repeated Power Flow (RPF) and Continuation Power Flow (CPF) based methods [10]-[11], Sensitivity based methods [12] and Optimal Power Flow (OPF) based methods [13].

ATC can also be calculated by using the power flow distribution factors. The distribution factors may be calculated using AC power flow or DC power flow solutions. The DC power transfer distribution factors (DCPTDFs) are derived based on DC load flow assumptions and hence are provide less accurate results [14]. The AC power transfer distribution factors [15]-[16] (ACPTDFs) are more accurate and provides acceptable ATC values.

FACTS devices are highly useful in enhancing ATC of a power system. Series connected FACTS devices are more suitable than shunt connected FACTS devices for ATC enhancement. TCSC is a series connected FACTS device which is used in this work ATC enhancement. Insertion of TCSC can increase ATC when it is located in any line. But the benefits of TCSC can be maximized by optimizing its location and size [17]-[18]. The BB-BC algorithm is exploited in this work for the optimization of TCSC parameters.

2. MODELLING OF TCSC DEVICE

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

$$X_{ij} = X_L + X_{TCSC} \tag{1}$$

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

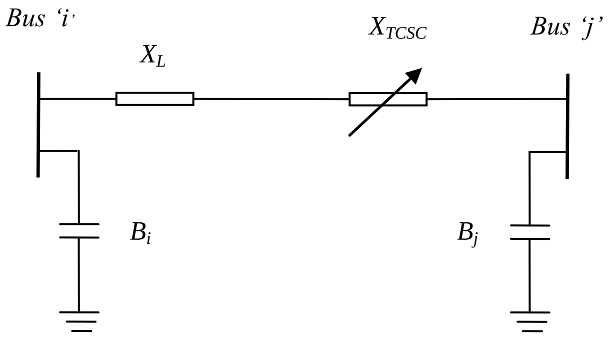

Fig 1. Model of TCSC

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

3. ATC ENHANCEMENT PROBLEM STATEMENT

3.1 ATC

ATC is the transmission capability available for further transactions in a deregulated power market. ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above the already committed uses. It can be expressed as follows:

$$\text{ATC} = \text{TTC} - \text{Existing Transmission Commitments} \tag{2}$$

Where, Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network or particular path or interface in a reliable manner while meeting all of a specific set of defined pre and post contingency conditions. ATC at the base case, between bus *m* and bus *n* using line flow limit (thermal limit) criterion is mathematically formulated using ACPTDF as given in the below equation:

$$ATC_{mn} = \min\{T_{ij,mn}\}, ij \epsilon N_L \tag{3}$$

Where T_{ij}, *mn* denotes the transfer limit values for each line in the system. It is given by the following equation:

$$T_{ij,mn} = \begin{cases} \dfrac{\left(P_{ij}^{max} - P_{ij}^{0}\right)}{ACPTDF_{ij,mn}}; & ACPTDF_{ij,mn}. > 0 \\ \alpha(infinite); & ACPTDF_{ij,mn} = 0 \\ \dfrac{\left(P_{ij}^{max} - P_{ij}^{0}\right)}{ACPTDF_{ij,mn}}; & ACPTDF_{ij,mn} < 0 \end{cases} \qquad (4)$$

Where the following holds true:Pij^{max} is the MW power limit of a line between bus *i* and *j*. Pij^{o} is the base case power flow in line between bus *i* and *j*.*NL* is the total number of lines. *ACPTDFij,mn* is the power transfer distribution factor for the line between bus *i* and *j* when a transaction is taking place between bus *m* and *n*. ACPTDF as given in equation (3) is operating point dependent and was computed using Jacobian inverse. ACPTDFs remain fairly constant for reasonable variations in power injections.

3.2 ACPTDF Formulation

ACPTDF is based on the results of AC power flow solutions. ACPTDF values provide a linearized approximation of how the flow on the transmission lines and interfaces change in response to transaction between the seller and the buyer. Considering a bilateral transaction t_k between a seller bus *m* and buyer bus *n*, line *l* connected between bus *i* bus j carries a part of the transacted power. For a change in real power in the transaction between the above buyer and seller by Δtk MW, if the change in a transmission line quantity q_l is Δq_1 , power transfer distribution factors can be defined as follows:

$$ACPTDF_{ij,mn} = \frac{\Delta q_l}{\Delta t_k} \qquad (5)$$

3.3 Objective function

The objective of this work is to increase the total transfer capability a power system for realizing more number of power transactions by changing the power flow pattern.

Equality constraints

Power balance equations

$$P_{gi} - P_{di} - \sum_{j=1}^{NB} |V_i|\,|V_j|\,|Y_{ji}|\cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \qquad (6)$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{NB} |V_i|\,|V_j|\,|Y_{ji}|\sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \qquad (7)$$

Where, P_{gi} and P_{di} are the real power generation and load at bus '*i*'; Q_{gi} and Q_{di} are the reactive power generation and load at bus '*i*'.

Inequality constraints

Line real power flow limit

$$MW_{ij}(\delta, V) \leq MW_{ij}^{max} \qquad (8)$$

TCSC reactance limit

$$x_c^{min} \leq x_c \leq x_c^{\max} \tag{9}$$

Bus voltage magnitude limit

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{10}$$

4. BB –BC ALGORITHM

4.1 Overview

A new nature inspired optimization technique which has low computational time and high convergence speed called BB-BC is introduced recently [17]-[18]. It has two phases,

1. Big bang phase and 2. Big crunch phase.

In Big Bang phase, candidate solutions are randomly distributed over the search space and in the Big Crunch phase, randomly distributed particles are drawn into an orderly fashion.

The Big Bang-Big Crunch optimization method generates random points in the Big Bang phase and shrinks these points to a single point in the Big Crunch phase after a number sequential Big Bangs and Big Crunches.

The Big Crunch phase has a convergence operator that has many inputs but only one output, which is named as the ‘‘centre of mass”, since the only output has been derived by calculating the centre of mass. The point representing the centre of mass is denoted by X_c and is calculated according to the following equation.

$$X_C = \frac{\sum_{i=1}^{NP} \frac{1}{f(X_i)} X_i}{\sum_{i=1}^{NP} \frac{1}{f(X_i)}} \tag{11}$$

Where X_i is the i^{th} candidate in an D-dimensional search space, $f(X_i)$ is a fitness function value of this point, NP is the population size in Big Bang phase.

After the Big Crunch phase, the algorithm creates new candidates to be used as the Big Bang phase of the next iteration step. This can be done in various ways, the simplest one being identifying the best candidate in the population. In this work, the new candidates are generated around the centre of mass and knowledge of centre of mass of previous iteration is used for better convergence. The parameters to be supplied to normal random point generator are the centre of mass of the previous step and the standard deviation. The deviation term can be fixed, but decreasing its value along with the elapsed iterations produces better results.

$$X^{new} = X_c + \frac{r\alpha\left(X^{max} - X^{min}\right)}{t} \tag{12}$$

Where r is a normal random number, α is a parameter limiting the size of the search space, X^{max} and X^{min} are the upper and lower limits, and t is the iteration step. Since normally distributed numbers can be exceeding ±1, it is necessary to limit the population to the prescribed search space boundaries. This narrowing down restricts the candidate solutions into the search space boundaries.

4.2 BB-BC applied to ATC maximization:

Big Bang Big Crunch algorithm involves the steps shown below in reactive power flow control

Step 1: Form an initial generation of NP candidates in a random manner respecting the limits of search space. Each candidate is a vector of all control variables, i.e. [T_k, X_{TCSC}]. There are 4 T_k’s and 2 X_{TCSC} in the IEEE-30 system and hence a candidate is a vector of size 1x6.

Step 2: Calculate the fitness function values of all candidate solution by running the NR load flow. The control variable values taken by different candidates are incorporated in the system data and load flow is run. The total line loss corresponding to different candidates are calculated.
Step 3: Determine the centre of mass which has global best fitness using equation (11). The candidates are arranged in the ascending order their fitness (fitness) and the first candidate will be the candidate with best fitness (minimum loss).
Step 4: Generate new candidates around the centre of mass by adding/subtracting a normal random number according to equation (12). It should be ensured that the control variables are within their limits otherwise adjust the values of 'r' and 'α'.
Step 5: Repeat steps 2-4 until stopping criteria has not been achieved.

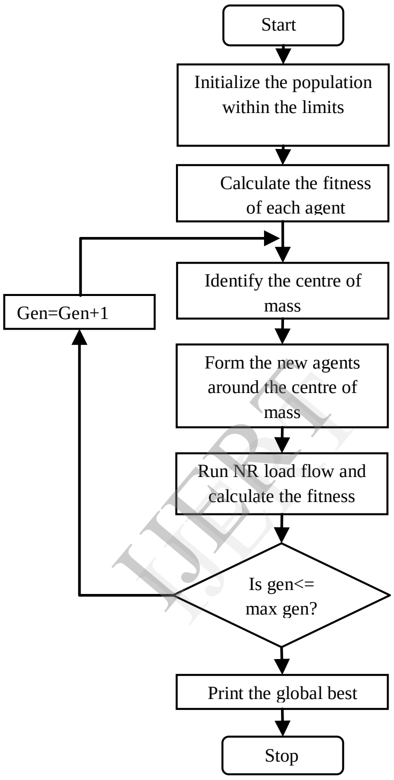

Figure 2. Flow chart for BB-BC algorithm

5. RESULTS AND DISCUSSIONS

The proposed BB-BC algorithm based ATC enhancement problem is tested on the standard IEEE-30 bus test system [19]. System data are on 100MVA base. Bus 1 is taken as the reference bus. The base load condition is considered. The algorithm is coded in MATLAB 7.6 language tool. The test system has the following parameters.

Table 1. System parameters

Sl.No	Variables	Quantity
1	Buses	30
2	Branches	41
3	Generators	6
4	Shunt capacitors	2
5	Tap-Changing transformers	4

The system has 4 transmission lines with tap changer transformers. For insertion of TCSC only the lines without tap changer transformer are taken as candidate locations. ATC enhancement is done by adjusting tap positions of the 4 transformers and reactmce of 2 TCSCs.

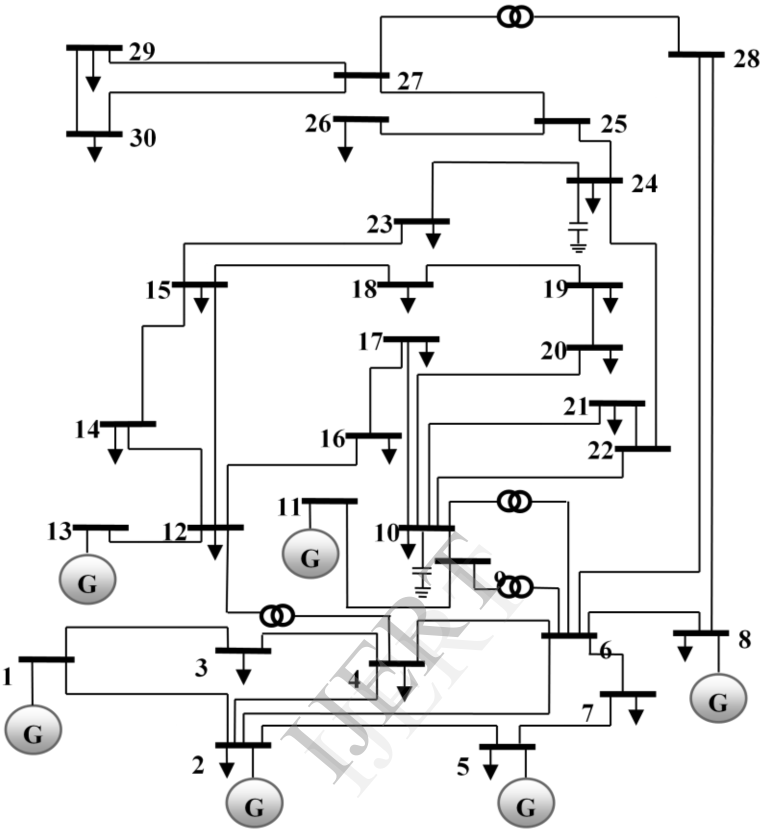

Figure 3. Single line diagram of the test system

Two bilateral transactions are considered for proving the efficiency the proposed BB-BC based algorithm for ATC enhancement. The first transaction is from generator bus 2 to load bus 29 and the second transaction is from generator bus 5 to load bus 24. The results obtained in these two transactions are discussed below.

Transaction-1: Bus 2-Bus 29

Bus 2 is the GENCO and bus 29 is the DISCO in this transaction. 10 MW power transaction is considered. ATC available before optimization was only 1.1239 MW. This is a low value of ATC of the system and needs to be enhanced. ATC is enhanced by adjusting the transformer tap positions and properly setting the values for TCSC parameters.

The BB-BC algorithm is run with 50 individuals and for 200 iterations. The algorithm takes line 22-24 and line 4-6 as suitable locations for ATC enhancement. Table 2 compares the ATC values before and after insertion of TCSCs. ATC of the system is improved from 1.1239 MW to 1.74 MW.

Table 2. Optimal values of transformer tap settings (Bus 2-Bus 29)

Sl no	Transformer tap	Before	After
1	$T_{6\text{-}9}$	1.078	1.0306
2	$T_{6\text{-}10}$	1.069	1.0567
3	$T_{4\text{-}12}$	1.032	1.1000
4	$T_{28\text{-}27}$	1.068	0.9000

Table 3 indicates the size and location of the two TCSCs used. In this case both TCSCs are operated in capacitive mode.

Table 3. Optimal settings of FACTS devices (Bus 2-Bus 29)

Sl. No	Transaction Between buses	ATC without TCSC	ATC with TCSC	Location of TCSCs		Degree of compensation	
				$TCSC_1$	$TCSC_2$	$TCSC_1$	$TCSC_2$
1	2-29	1.1239	1.7400	21-23	1-3	-0.4829	-0.7176

ATC enhancement results in changed power flows through the lines. Table 4 compares the power flow before and after optimization. Line 1 is relieved much from nearly overloaded condition and the underutilized lines are forced to carry increased power. Line flow limits of all the lines are respected.

Table 4. Line power flows (Bus 2-Bus 29)

Line number	Flow (before)	Flow (after)	MVA limit	Line number	Flow (before)	Flow (after)	MVA limit
1	**121.130**	**97.524**	130	22	7.105	6.205	16
2	60.881	83.129	130	23	3.827	2.958	16
3	29.841	14.670	65	24	5.689	-6.549	32
4	56.957	77.797	130	25	7.974	8.870	32
5	46.125	40.743	130	26	3.459	5.149	32
6	40.853	28.732	65	27	19.733	18.229	32
7	48.207	60.256	90	28	9.797	5.187	32
8	0.977	-4.206	70	29	2.041	0.563	32
9	21.967	27.235	130	30	7.592	4.098	16
10	14.403	14.160	32	31	9.705	5.164	16
11	14.569	12.513	65	32	6.311	1.441	16
12	12.193	10.723	32	33	7.094	-2.155	16
13	20.000	-20.000	65	34	3.559	3.547	16
14	34.569	32.513	65	35	3.416	-6.011	16
15	30.098	23.662	65	36	29.013	27.470	65
16	20.000	-20.000	65	37	19.826	11.842	16
17	8.854	7.585	32	38	12.573	9.334	16
18	20.797	17.429	32	39	1.298	1.544	16
19	9.247	7.448	32	40	4.379	4.136	32
20	2.534	1.305	16	41	24.751	23.466	32
21	5.603	3.889	16	----	-----	------	---

The optimization is carefully achieved that the change in power flow pattern does not result in much increased line losses.

Transaction 2: Bus 5-Bus 24

This bilateral transaction is between GENCO 5 and DISCO 24. ATC before insertion of TCSC was 2.2251 MW. Optimization of control parameter values (table 5) maximized the ATC to 3.5287 MW.

Table 5. Optimal values of transformer tap settings (Bus 5-Bus 24)

Sl no	Transformer tap	Before	After
1	T_{6-9}	1.078	1.0730
2	T_{6-10}	1.069	1.0923
3	T_{4-12}	1.032	0.9592
4	T_{28-27}	1.068	1.0986

In this case one TCSC is in capacitive mode and the other one is in inductive mode. Table 6 shows the optimal location and size of TCSCs.

Table 6. Optimal settings of FACTS devices (Bus 5-Bus 24)

Sl. No	Transaction Between buses	ATC without TCSC	ATC with TCSC	Location of TCSC		Degree of compensation	
				$TCSC_1$	$TCSC_2$	$TCSC_1$	$TCSC_2$
1	5-24	2.2251	3.5287	3-4	1-3	0.1927	-0.4823

Line MVA flows are compared in table 7. Line 1 carries only 77.076 MVA against 121.130 MVA after optimization. This is a much relief for the line from congestion and it is left with sufficient capability. This relief ensures adequate transmission corridor and still more transaction are also possible.

Table 7. Line power flows (Bus 5-Bus 24)

Line number	Flow (before)	Flow (after)	MVA limit	Line number	Flow (before)	Flow (after)	MVA limit
1	**121.130**	**77.076**	130	22	7.105	7.570	16
2	60.881	67.615	130	23	3.827	4.270	16
3	29.841	27.650	65	24	5.689	-5.256	32
4	56.957	63.338	130	25	7.974	7.527	32
5	46.125	67.315	130	26	3.459	2.983	32
6	40.853	39.371	65	27	19.733	17.496	32
7	48.207	50.832	90	28	9.797	7.618	32
8	0.977	-18.869	70	29	2.041	-0.144	32
9	21.967	2.368	130	30	7.592	7.930	16
10	14.403	11.586	32	31	9.705	7.554	16
11	14.569	11.341	65	32	6.311	4.382	16
12	12.193	10.083	32	33	7.094	1.769	16
13	20.000	-20.000	65	34	3.559	3.558	16
14	34.569	31.341	65	35	3.416	-1.807	16
15	30.098	31.611	65	36	29.013	15.180	65
16	20.000	-20.000	65	37	19.826	6.228	16
17	8.854	9.220	32	38	12.573	7.141	16
18	20.797	21.347	32	39	1.298	3.715	16
19	9.247	9.843	32	40	4.379	1.566	32
20	2.534	2.886	16	41	24.751	13.649	32
21	5.603	6.130	16	----	-----	------	---

6. CONCLUSIONS

This work proves the effectiveness of the BB-BC algorithm in ATC enhancement incorporating TCSC devices. ATC of the system is enhanced by changing the power flow pattern by inserting TCSCs and adjusting tap positions of transformers. It is obvious from the numerical results that the ATC improvement is very much encouraging. The system operator can use this method to facilitate more power transfer agreements for the future power markets. Further, all the lines in the system are left with sufficient ATC and therefore the

system becomes capable of transmitting increased amount of power flows and with sufficient security.
In a deregulated environment, the very purpose of supplying power to consumers at competitive price can be ensured. Moreover, the BB-BC algorithm is simple, has less number of parameters and it can be implemented easily.

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Author Biographies

S. Sakthivel received the Degree in Electrical and Electronics Engineering in 1999 from Madras University and Master Degree in Power Systems Engineering in 2002 from Annamalai University. He is pursuing the Ph.D., Degree in Electrical Engineering faculty from Anna University of Technology, Coimbatore, India. He is presently working as an Associate Professor in Electrical and Electronics Engineering at V.R.S.College of Engineering and Technology, Villupuram, Tamil Nadu, India. His research areas of interest are Power System control, Optimization techniques, FACTS, Economic load dispatch, Power system deregulation and Voltage stability improvement.

P. Mathiazhagi is an undergraduate student with the Department of Electrical and Electronics Engineering at VRS College of Engineering and Technology, Villupuram, Tamil Nadu, India. Optimal power flow using evolutionary algorithms is her important area of interest.

T. K. Archana is an undergraduate student in the Department of Electrical and Electronics Engineering at VRS College of Engineering and Technology, Villupuram, Tamil Nadu, India. She is interested in power system operation optimization by using intelligent techniques.