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Big Bang-Big Crunch Algorithm for Voltage Stability Limit Improvement by Coordinated Control of SVC Settings

[1]S. Sakthivel and [2]D. Mary
[1]Department of Electrical and Electronics Engineering, V.R.S. College of Engineering and Technology, Villupuram, TN, India
[2]Department of Electrical and Electronics Engineering, Government College of Engineering, Bargur, TN, India

Abstract: Modern power system networks are operated under highly stressed conditions and there is a risk of voltage instability problems owing to increased load demand. A power system needs to be with sufficient voltage stability margin for secured operation. In this study, SVC parameters of location and size along with generator bus voltages, transformer tap settings are considered as control parameters for voltage stability limit improvement by minimizing loss and voltage deviation. The control parameters are varied in a coordinated manner for better results. The line based LQP voltage stability indicator is used for voltage stability assessment. The nature inspired meta heuristic Big Bang-Big Crunch (BB-BC) algorithm is exploited for optimization of the control variables and the performance is compared with that of PSO algorithm. The effectiveness of the proposed algorithm is tested on the standard IEEE 30 bus system under normal and N-1 line outage contingency conditions. The results obtained from the simulation encourage the performances of the new algorithm.

Keywords: BB-BC algorithm, FACTS devices, LQP index, PSO algorithm, SVC, voltage stability improvement

INTRODUCTION

Increasing demand for electricity and unmatched expansion in generation and transmission system leads a power system to a stressed operating condition and the possible voltage instability problems (Devaraj and Preetha, 2010). Erection of new transmission systems to cope with the increasing load demand has certain technical and economical difficulties. Better utilization of existing transmission system is the alternative solution, at least to delay the investment for transmission lines. Voltage instability is a major threat to power system operation and it resulted in many block outs across the world (Kazemi and Badrzadeh, 2004). Voltage instability can occur in a power system during disturbance like line outage or under highly stressed operating conditions (Shin *et al*., 2007). Voltage instability is primarily because of insufficient reactive capability of systems.

In the emerging scenario of deregulation of power system networks, the optimum generation bidders are chosen based on real power cost characteristics and may result 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 (Elango and Paranjothi, 2011; Charles *et al*., 2011) 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 (Kessel, 1986; Wan *et al*., 2000) to assess voltage stability of power systems to find the possible ways to improve the voltage stability limit.

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 (Hingorani and Gyugyi, 2004) are useful in taking fast control actions to ensure security of power systems. FACTS devices are capable of controlling the voltage angle, voltage magnitude (Yorino *et al*., 2003) at selected buses and/or line impedance of transmission lines. Static VAR compensator is a shunt connected FACTS device, capable of supplying reactive power to improve voltage stability. However, the benefits of FACTS devices depend on their location and size (Gerbex *et al*., 2001). FACTS devices can be coordinated along with system parameters for reactive power optimization (Benabid *et al*., 2009; Chien-Feng *et al*., 2012; Shanmukha and Ravikumar, 2012; Reza *et al*., 2012).

Corresponding Author: S. Sakthivel, Department of Electrical and Electronics Engineering, V.R.S. College of Engineering and Technology, Villupuram, TN, India

Most of the works (Claudio and Zeno, 1999; Kowsalya *et al*., 2009) 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 (Venkataramu and Ananthapadmanabha, 2006; Abdullah *et al*., 2010) have been done on voltage stability improvement under contingency condition.

Voltage stability is strongly influenced by reactive power and reactive power optimization is necessary for voltage stability limit improvement. Reactive power optimization, a special case of Optimal Power Flow (OPF), is done through minimization of real power loss and voltage deviation of load buses (Varadarajan and Swarup, 2008a; Roy *et al*., 2012). Several classic optimization methods are attempted to solve the voltage stability improvement problem (Kirschen and Van Meeteren, 1988; Grudinin, 1998; Aoki *et al*., 1988). Those methods have certain drawbacks like easily converging to local minima and need for derivative of the objective function. Evolutionary Algorithms (EAs) like Genetic Algorithm (GA), Differential (DE) and Particle Swarm Optimization (PSO) (Bhagwan and Patvardhan, 2003; Liang *et al*., 2006, 2007; Yoshida *et al*., 2000; Varadarajan and Swarup, 2008b; Subbaraj and Rajnaryanan, 2009; Khorsandi *et al*., 2011; Bhattacharya and Chattopadhyay, 2011; Kürsat and Ulas, 2012) are widely exploited during last two decades in the field of engineering optimization.

The proposed algorithm for optimal reactive power flow control achieves the goal by setting suitable values for generator terminal voltages, transformer tap settings and parameters of FACTS devices. This study proposes a coordinated control of all parameters of reactive power control and the system is considered under line outage condition to make this study more meaningful with regard to voltage stability limit improvement. The optimal location and size of FACTS are done based on different factors such as loss reduction, voltage stability enhancement and sum of voltage deviation. 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 SVC device alone is considered but the results obtained are encouraging one.

MODELLING OF FACTS DEVICES

Static model of SVC: SVC is a shunt connected FACTS device capable of exchanging reactive power with the power system through the bus at which it is connected. Amount of reactive power injected by the device is varied by varying the susceptance (Gerbex *et al*., 2001). A variable susceptance B_{SVC} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. This model is an improved version of SVC models. Figure 1 shows the variable susceptance model of SVC which is used to derive its nonlinear power equations and the linearised equations required by Newton's load flow method.

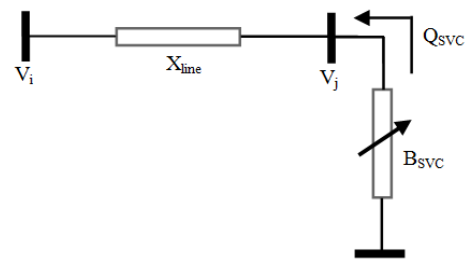

Fig. 1: Variable susceptance model of SVC

In general, the transfer admittance equation for the variable shunt compensator is:

$$I_{SVC} = jB_{SVC} V_j \quad (1)$$

The reactive power exchanged is:

$$Q_{SVC} = -V_j^2 B_{SVC} \quad (2)$$

In SVC susceptance model the total susceptance B_{SVC} is taken to be the state variable, therefore the linearised equation of the SVC is given by:

$$\begin{bmatrix} \Delta Pj \\ \Delta Qj \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \theta_j \end{bmatrix} \begin{bmatrix} \Delta\theta j \\ \Delta Bsvc/Bsvc \end{bmatrix} \quad (3)$$

At the end of iteration *i* the variable shunt susceptance B_{SVC} is updated according to:

$$B_{SVC}^{(i)} = B_{svc}^{(i-1)} + (\Delta B_{SVC} / B_{SVC})^{(i)} B_{SVC}^{(i-1)} \quad (4)$$

This changing susceptance value represents the total SVC susceptance which is necessary to maintain the nodal voltage magnitude at the specified value (1.0 p.u. in this study).

LINE VOLTAGE STABILITY INDEX

The Line stability index (LQP) based on a power transmission concept (Mohamed and Jasmon, 1989) is used in this study. The value of line index shows the voltage stability of the system. The value close to unity indicates that the respective line is close to its stability limit and value much close to zero indicates light load in the line. The formulation begins with the power equation in a power system. Figure 2 illustrates a single line of a power transmission concept.

The power equation can be derived as:

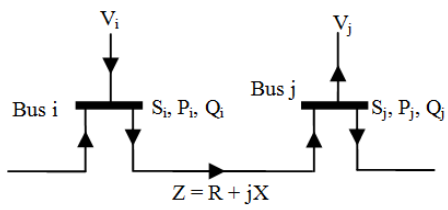

Fig. 2: Single line concept of power transmission

$$\frac{X}{V_i^2}Q_i^2 - Q_i + \left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \quad (5)$$

The line stability factor is obtained by setting the discriminant of the reactive power roots at bus 1 to be greater than or equal to zero thus defining the line stability factor, LQP as:

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \quad (6)$$

This indicator is highly sensitive to change in reactive power flow through the line. In this study, reactive power flow is adjusted for voltage stability improvement. Change in reactive power flow affects the voltage stability limit and it can be assessed suitably by using LQP index.

PROBLEM FORMULATION

The objective of this study is to improve the voltage stability limit by minimizing real power loss, sum of load bus voltages and sum of line voltage stability index. An augmented objective function is formed with the three objective components and weights.

Objective function: The objective function of this study is to find the optimal rating and location of SVC and optimal values of system control variables which minimizes the real power loss, minimization of voltage deviation and maximizes the voltage stability limit. Hence, the objective function can be expressed as:

$$F = \mathrm{Min}\{P_L + wVD + (1 - w)LQP\} \quad (7)$$

where, w is the weighing factor for voltage deviation and LQP index and is set to 0.3.

Real power loss minimization (P_L): The total real power loss of the system can be calculated as follows:

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

where

N_L = The total number of lines in the system

G_k = The conductance of the line 'k'

V_i, V_j = The magnitudes of the sending end and receiving end voltages of the line

δ_i, δ_j = Angles of the end voltages

Load bus Voltage Deviation minimization (VD): Bus voltage magnitude should be maintained within the allowable range to ensure quality service. Voltage profile is improved by minimizing the deviation of the load bus voltage from the reference value (it is taken as 1.0 p.u. in this study):

$$VD = \sum_{k=1}^{N_{PQ}} |(V_i - V_{ref})| \quad (9)$$

Line voltage stability index minimization (LQP): Voltage stability limit of a power system is increased by minimizing voltage stability index value. The indicator takes values between 0 (no-load) and 1 (full load). The Line based stability index (LPQ) is given as:

$$LQP = \sum_{j=1}^{N_L} LQP_j \quad (10)$$

Constraints: The minimization problem is subject to the following equality and inequality constraints:

- **Equality constraints:**
  Load flow constraints:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_iV_{ij}Y_{ij}\cos\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad (11)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_iV_{ij}Y_{ij}\sin\left(\delta_{ij} + \gamma_j - \gamma_i\right) = 0 \quad (12)$$

- **Inequality constraints:**
  Reactive power generation limit of SVCs:

$$Q_{ci}^{min} \le Q_{ci} \le Q_{ci}^{max}; i \in N_{SVC} \quad (13)$$

Voltage constraints:

$$V_i^{min} \le V_i \le V_i^{max}; i \in N_B \quad (14)$$

Transmission line flow limit:

$$S_i \le S_i^{max}; i \in N_l \quad (15)$$

BIG BANG-BIG CRUNCH (BB-BC) OPTIMIZATION ALGORITHM

Overview:

- **Big bang phase:** The BB-BC is a meta heuristic global optimization method and is developed by Erol-Osman and Ibrahim (2006). It involves two phases: The Big Bang phase and the Big Crunch phase. In the Big Bang phase, candidate solutions are randomly distributed over the search space. Randomness can be seen as equivalent to the

energy dissipation in nature while convergence to a local or global optimum point can be viewed as gravitational attraction. Since energy dissipation creates disorder from ordered particles, we will use randomness as a transformation from a converged solution to the birth of totally new solution candidates. The creation of the initial population randomly is called the Big Bang phase. In this phase, the candidate solutions are spread all over the search space in a uniform manner.

- **Big crunch phase:** The Big Bang phase is followed by the Big Crunch phase. The Big Crunch is 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 (Erol-Osman and Ibrahim, 2006). The point representing the centre of mass that is denoted by X_c is calculated according to the following equation:

$$X_C = \frac{\sum_{i=1}^{NP} \frac{1}{f(X_i)} X_i}{\sum_{i=1}^{NP} \frac{1}{f(X_i)}} \quad (16)$$

where,
X_i = A point within an D-dimensional search space generated
$f(X_i)$ = A fitness function value of this point
NP = The population size in Big Bang phase

The convergence operator in the Big Crunch phase is different from 'exaggerated' selection since the output term may contain additional information (new candidate or member having different parameters than others) than the participating ones, hence differing from the population members. This one step convergence is superior compared to selecting two members and finding their centre of gravity. This method takes the population members as a whole in the Big Crunch phase that acts as a squeezing or contraction operator; and it, therefore, eliminates the necessity for two-by-two combination calculations.

After the Big Crunch phase, the algorithm must create new members to be used as the Big Bang of the next iteration step. This can be done in various ways, the simplest one being jumping to the first step and creating an initial population. The algorithm will have no difference than random search method by so doing since latter iterations will not use the knowledge gained from the previous ones; hence, the convergence of such an algorithm will most probably be very low. In this study, 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:

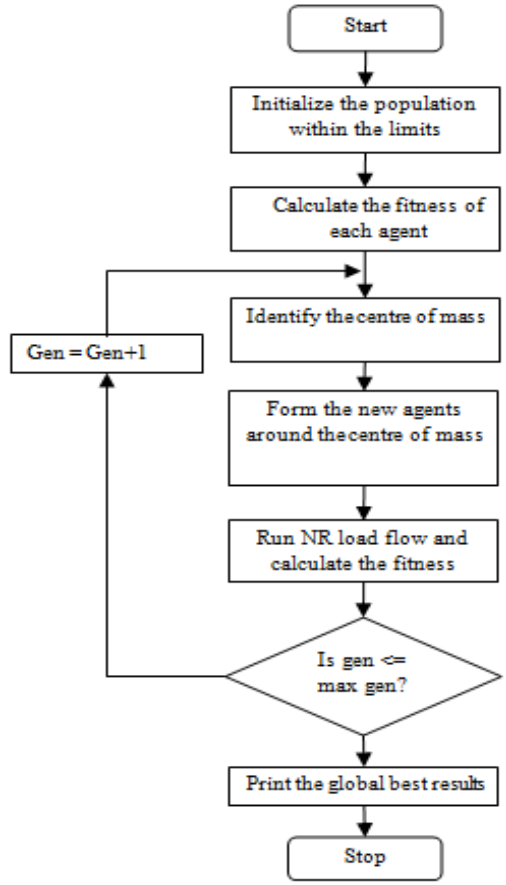

Fig. 3: Flow chart for BB-BC algorithm

$$X^{new} = X_c + \frac{r\alpha(X^{max} - X^{min})}{t} \quad (17)$$

where,
r = A normal random number
α = A parameter limiting the size of the search space
X^{max}, X^{min} = The upper and lower limits
t = 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. This BB-BC algorithm is similar to PSO in searching behavior (Kennedy and Eberhart, 1995).

Implementation BB-BC algorithm for voltage stability improvement (Fig. 3): The BB-BC algorithm is implemented for identifying the most suitable location and size of SVC and optimal values of system parameters that gives the minimum objective function value. The algorithm runs the NR load flow with one

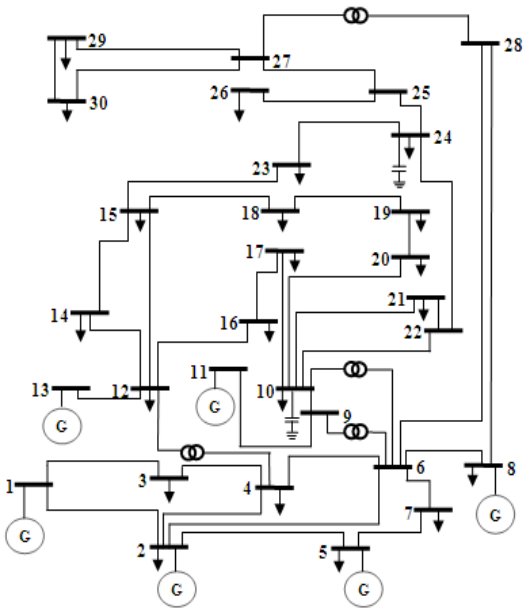

Fig. 4: One line diagram of IEEE 30 bus test system

TCSC located in a line and two SVCs located in two load buses and calculate the fitness. This is repeated for all the candidates in the population and the global best solution is obtained. The BB-BC approach takes the following steps:

Step 1: Initialize the number of individuals (NP), upper and lower bounds (X^{max} and X^{min}) of each variable and maximum iterations.

Step 2: Form an initial generation of NP agents with each agent as a vector of V_G, T_P, Q_{SVC} in a random manner respecting the upper and lower limits of the each control variable.

Step 3: Calculate the objective function values of all the agents by running NR load flow.

Step 4: Find the centre of mass using Eq. (16). Global best fitness individual can be also taken as the centre of mass.

Step 5: Create new agents around the centre of mass by adding or subtracting a normal random number whose value decreases as the iterations elapse of using (17).

Step 6: Repeat Step 3 to 5 until stopping criteria is not met.

RESULTS AND DISCUSSION

The proposed algorithm is coded in MATLAB 7.6 platform using 2.8 GHz Intel Core 2 Duo processor based PC. The algorithm is tested in the IEEE 30 bus test system shown in Fig. 4. The line data and bus data are taken from Abou *et al*. (2010). The system has 6 generator buses, 24 load buses and 41 transmission lines. System data and results are based on 100 MVA and bus no 1 is the reference bus.

Table 1: Control variable limits

Sl no.	Control variable	Range
1	Generator Voltage (V_G)	(0.9-1.1) p.u.
2	Tap setting (T_P)	(0.9) - (1.1) p.u.
3	MVAR by static compensators (Q_{svc})	(0-20)

There are certain constraints in locating FACTS devices in the system. Generator buses are capable of generating var and therefore no need to have SVCs that is, SVC should not be located in those buses. In order to validate the presented algorithm two different operating conditions are considered on the test system as mentioned below:

Case 1: The system with normal load in all the load buses is considered as base load condition and the Newton-Raphson load flow is carried out with loading factor value equal to 1.0.

Case 2: Contingency is imposed by considering the most critical line outage in the system. This is the most suitable condition for voltage stability analysis of a power system as voltage stability is usually triggered by line outages. The loading factor is taken as 1.2 for this case.

Generator bus voltages, transformer tap settings and size and locations of SVC devices are taken as control variables for voltage stability improvement. During optimization process these variables are varied within the limits for optimizing the voltage stability. The set of variables that gives the maximum voltage stability limit is the global best control parameters. The limits of the control variables are given in Table 1.

Case 1: Base load condition: Newton-Raphson program is repeatedly run with the presence of SVC devices. The voltage stability limit improvement is assessed by the value of sum of LQP index, loss minimization and sum of voltage deviation. The optimal values of control variables obtained by BB-BC algorithm is given in Table 2.

The strength of BB-BC can be realized by the total MVAR requirement indicated. For improved performance, BB-BC requires only small amount of MVAR. The total var requirement of PSO is 28.9271 MVAR whereas it is only 9.4662 MVAR by BB-BC.

The proposed algorithm is run for several times and best results are obtained in second run. Table 3 gives the optimal values of parameters for voltage stability improvement. SVC locations are fixed as bus numbers 10 and 24 only the sizes are varied.

Table 2: Optimal parameter values (normal case)

			With SVC	
Sl no.	Parameter	Initial value	Optimal value [PSO]	Optimal value [BBBC]
1	V_{G1}	1.050	1.0626	1.0681
2	V_{G2}	1.040	1.0488	1.0535
3	V_{G5}	1.010	1.0166	1.0253
4	V_{G8}	1.010	1.0196	1.0323
5	V_{G11}	1.050	0.9710	1.0346
6	V_{G13}	1.050	1.0252	1.0281
7	T_{6-9}	1.078	1.0095	0.9525
8	T_{6-10}	1.069	0.9920	1.0019
9	T_{4-12}	1.032	0.9901	0.9594
10	T_{27-28}	1.068	0.9806	0.9731

Table 3: Optimal parameters of FACTS devices (normal case)

Facts device	Algorithm	Location	Size
SVC10	PSO	10	14.4510
	BB-BC	10	1.9148
SVC24	PSO	24	13.4761
	BB-BC	24	7.5514

Table 4: Minimization of objective terms (normal case)

Sl no.	Parameter	Initial value	PSO	BB-BC
1	P_{loss}	5.7440	5.2210	5.2530
2	VD	1.4753	0.2595	0.2985
3	LPQ	1.3948	1.2322	0.7111

Table 5: Contingency ranking

Rank	Line outage	LQP-value	P_{loss}
1	12-15	0.2931	12.0024
2	2-5	0.2907	18.3783
3	1-3	0.2902	15.4456
4	3-4	0.2901	15.0421
5	2-6	0.2866	12.6630

The objective function terms are tabulated in Table 4 after optimization by BB-BC algorithm. The total real power loss by the algorithm is less than that reported by PSO. All the three components are minimized considerably after insertion of FACTS devices. Table 4 compares the value of real power loss, sum of voltage deviation and sum of line stability index by both the algorithms.

Convergence characteristics of BB-BC algorithm in reactive power optimization is depicted in Fig. 5. The value of objective function to which the algorithm converged is very small as compared to the value obtained by PSO. LQP value corresponding to converged results is 0.7111 this was 1.3948. This indicates commendable improvement in voltage stability limit.

Voltage profile improvement at load buses is an important requirement and is part of reactive power optimization. When loss minimization alone is taken as the objective function for reactive power minimization it results in unacceptably low voltages at load buses. Therefore loss reduction should be achieved along with voltage profile improvement. It is clear from the Fig. 6 that voltage profile is at about 1.0 p.u. at all the load buses after optimization. The initial voltage magnitudes were even lower than 0.9 p.u. at most of the load buses. In this case also BB-BC performs better than PSO (Fig. 6):

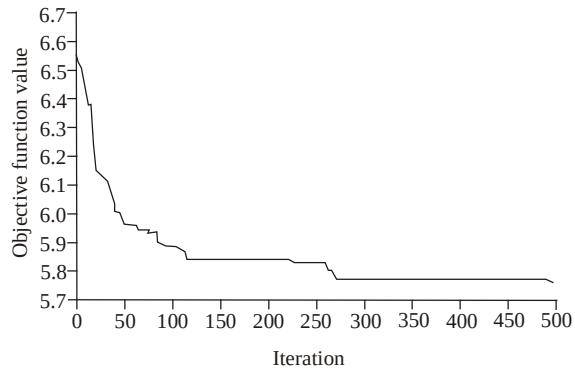

Fig. 5: Convergence of BB-BC (normal case)

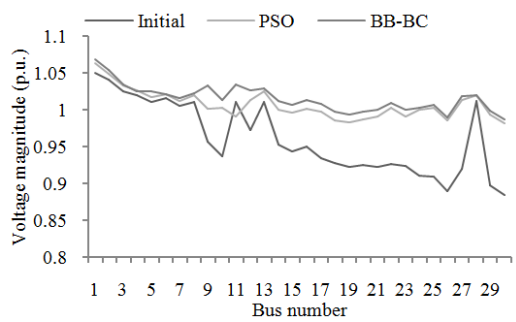

Fig. 6: Voltage profile improvement (normal case)

Case 2: N-1 critical contingency condition: Voltage instability is usually triggered by disturbance like line outage and the outage may be due to stressed condition or forced outage in deregulated environment for congestion management. It is necessary to keep the system under voltage secured condition even in contingency conditions. In this case, contingency screening and ranking is carried out using the LQP index. The line outage is ranked according to the severity and the severity is taken on the basis of the Line stability index values (LQP) and those values are arranged in descending order (Sakthivel *et al*., 2011; Sakthivel and Mary, 2011). The maximum value of index indicates the most critical line outage. Contingency ranking is carried out on the test system and the results are shown in Table 5. It is clear from the results that outage of line number 12-15 is the most

Table 6: Optimal parameter values (contingency case)

			With SVC	
Sl no.	Parameter	Initial value	Optimal value [PSO]	Optimal value [BB-BC]
1	V_{G1}	1.050	1.0454	1.1000
2	V_{G2}	1.040	1.0312	1.0827
3	V_{G5}	1.010	0.9955	1.0418
4	V_{G8}	1.010	1.0047	1.0482
5	V_{G11}	1.050	1.0349	1.0551
6	V_{G13}	1.050	1.0158	1.0394
7	T_{6-9}	1.078	0.9681	0.9401
8	T_{6-10}	1.069	1.0244	0.9506
9	T_{4-12}	1.032	1.0265	0.9783
10	T_{27-28}	1.068	1.0278	0.9458

Table 7: Optimal parameters of facts devices (contingency case)

FACTS device	Algorithm	Location	Size
SVC10	PSO	10	18.8848
	BBBC	24	2.8145
SVC24	PSO	10	21.9010
	BBBC	24	9.1900

Table 8: Minimization of objective terms (contingency case)

Sl no.	Parameter	Initial value	PSO	BB-BC
1	P_{loss}	12.0020	11.1750	10.4580
2	VD	2.0974	0.7049	0.5122
3	LQP	1.7600	0.8504	0.9141

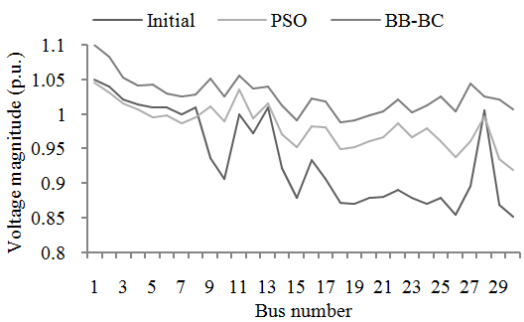

Fig. 7: Voltage profile improvement (contingency condition)

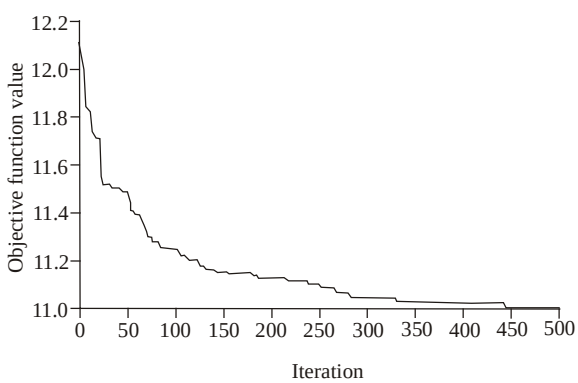

Fig. 8: Convergence of BB-BC (contingency case)

critical line outage and this condition is considered for voltage stability improvement. Outage of other lines has no much impact on the system and therefore they are not given importance and will not be economical also.

The BB-BC algorithm is run for optimizing the control variables to relieve the system much from stressed conditions. The control parameters so obtained are shown in Table 6. Relief from stressed conditions improves the voltage stability limit of a power system.

The SVC parameters after optimization by PSO and BB-BC as shown in Table 7 are totally different. In this case also BB-BC suggests small sized SVCs and this ensures economical operation of the power system.

Load flow is run on the system with line 12-15 outaged. Outage of this line results in large value of LQP index or very closeness to voltage stability limit. The system is under stressed conditions and needs to be relieved by some means. Installation of SVC devices at suitable locations relives the system much from stressed conditions (reduced line index value).

LQP values of the lines before and after insertion of SVC devices are compared but not shown due to large space requirement. The sum of voltage stability index of lines after optimization is smaller than the value before optimization. It is clear from Table 8 that real power loss reduction is from 12.002 to 10.458 MW it is 12.865% savings in real power and it will increase the economy of the system and optimize the reactive power. Sum of voltage is reduced to 0.9141from 1.7600 this is highly encouraging.

The contingency is imposed by outage of line number 12-15 and load is increased by 20% at all load buses and hence the voltage profile was worst. Voltage profile improvement is absolutely necessary in such a stressed condition. It can be observed from Fig. 7 that the voltage profile is improved highly and voltage level of most of the buses is within the limit.

The excellent convergence characteristic of BB-BC (Fig. 8) is proved in contingency condition also. The minimization of objective function is better with the presence of FACTS devices. The proposed BB-BC algorithm is found to be good in better convergence when coordinating both system parameters and FACTS device parameters inn reactive power optimization.

CONCLUSION

In this study, optimal sizing of FACTS for voltage stability limit improvement, voltage profile improvement and loss minimization are demonstrated. The voltage stability limit improvement and real power

loss minimization are done under normal and line outage contingency conditions. The reactive power flow change sensitive LQP index is used for voltage stability assessment. The susceptance model of SVC is considered to improve the voltage stability limit by controlling power flows and maintaining voltage profile. This model is more accurate and gives better results. The coordinated control of FACTS device parameters and system parameters in optimal power flow control for voltage stability limit improvement is proved in the numerical results by comparing the system real power loss, voltage deviation and voltage stability limit with and without the FACTS devices. The voltage stability improvement is more effective when it is done by coordinating the system and FACTS parameters. It is clear from the numerical results that voltage stability limit improvement and real power loss minimization are highly encouraging by the proposed BB-BC algorithm. The BB-BC algorithm has less number of operators like PSO and hence simple to implement for power system optimization. When compared to the performance of PSO, BB-BC performance better and has good convergence characteristics. Therefore, this BB-BC algorithm can be used for optimizing power system operation and control.

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