Particle Swarm Optimization Technique for Reactive Power Compensation using STATCOM with Voltage Stability Enhancement for Contingency Problem

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Abstract— **This paper presents a particle swarm optimization technique for multi-objective optimal reactive power dispatch problem for contingency problems. The objectives of the optimization problem are minimization of real power loss and enhancement of voltage stability. The proposed method achieves its objectives by determining a control strategy with continuous and discrete variables such as AVR operating values, OLTC tap positions and the amount of reactive power compensation equipment. This paper presents the effective use of STATCOM to achieve above objectives. The proposed method is evaluated in IEEE 14 bus system and the results show the effectiveness of the proposed method.**

Keywords— **Mixed Integer Nonlinear Optimization Problem, Optimal Reactive Power Dispatch (ORPD) Problem, Particle Swarm Optimization (PSO), Reactive Power, STATCOM, Voltage Stability Index (VSI)**

I. Introduction

Optimal reactive power dispatch (ORPD) problem is a mixed integer non-linear optimization problem with many uncertainties. Reactive power could be supplied to the system by generators, synchronous condensers, static compensators, capacitors and tap changing transformers. The problem can be formulated as optimization problem by determining the optimal values of generator bus voltage magnitudes, transformer tap settings and output of reactive sources for minimum real power loss. Recently, voltage stability has been a major concern in power system planning and operation. Voltage magnitudes alone cannot be reliable indicator of how stable a system is. Hence, this paper has formulated the ORPD as multi-objective optimization problem with enhancement of voltage stability index (VSI) as its objective along with minimization of real power loss [1,2]. Voltage stability evaluation using L-index is used as the indicator of voltage stability enhancement [3-5]. This problem is applied to the contingency problem in the power system which here is taken as the disconnection of any transmission line.

Particle swarm optimization (PSO) is one of the evolutionary computation (EC) techniques. PSO can handle both continuous and discrete variables so it is applicable to ORPD problem which is mixed integer problem [6,7]. This technique can generate high quality solutions within shorter calculation time and stable convergence characteristics than other stochastic methods.

STATCOM is one of new generation flexible AC transmission systems (FACTS) devices with a promising future application and is considered to be one of the key advanced technologies of future power system [8]. It is one of the most commonly used shunt compensation FACTS devices whose output can be controlled independent of the system voltage. Its use significantly improves the voltage profile of the system.

This paper presents a PSO technique for ORPD problem formulated as mixed integer non-linear optimization problem considering voltage stability. This paper shows the use of STATCOM for significant improvement of voltage profile. The feasibility of proposed method is demonstrated in IEEE bus systems with promising results.

II. Problem Formulation of ORPD

A. Objective Function

Mathematically, the ORPD problem can be formulated as following objective function [9-11]:

$$Min\ P_{loss} = \sum_{i=1, j\in i}^{N_B} G_{ij}[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \quad (1)$$

where,

P_{loss} is the active power loss in the system

N_B is total number of buses

G_{ij} is the mutual conductance between buses i and j

V_i and V_j are the voltage magnitudes of buses i and j

δ_i and δ_j are the voltage phase angles of buses i and j

B. Constraints

Above mentioned objective function is subject to following constraints:

1) *Equality Constraints*:

$$P_{gi} = P_{di} - V_i \sum_{j\in N_i} V_j(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}), i \in N_0 \quad (2)$$

$$Q_{gi} = Q_{di} - V_i \sum_{j\in N_i} V_j(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}), i \in N_{PQ} \quad (3)$$

where,
P_{gi} and Q_{gi} are the specified active and reactive power supply at bus i
P_{di} and Q_{di} are the specified active and reactive power demand at bus i
B_{ij} is the susceptance between buses i and j
N_0 is total number of buses except slack bus
N_{PQ} is total number of PQ buses

2) Inequality Constraints:

$$V_{i\,min} \le V_i \le V_{i\,max}, i \in N_B \quad (4)$$
$$T_{i\,min} \le T_i \le T_{i\,max}, i \in N_T \quad (5)$$
$$Q_{gi\,min} \le Q_{gi} \le Q_{gi\,max}, i \in N_G \quad (6)$$

where,
T_i is the tap position of transformer i
N_T is total number of transformers
N_G is total number of generator buses

III. Particle Swarm Optimization (PSO)

PSO is a population based stochastic optimization technique developed by Kennedy and Eberhart. It is one of the evolutionary computation techniques. The method has been developed through simulation of simplified social models. The features of the method are as follows [6]:

1. The method is based on researches on swarms such as fish schooling and bird flocking.
2. It is based on a simple concept. Therefore, the computation time is short and it requires little memory.
3. It was originally developed for non-linear optimization problems with continuous variables. However, it is easily expanded to treat problems with discrete variables. Therefore, it is applicable to mixed integer nonlinear optimization problems with both continuous and discrete variables such as ORPD problem.

A population of particles exists in the n-dimensional search space. Each particle has a certain amount of knowledge, and will move about the search space based on this knowledge. The particle has some inertia attributed to it and so it will continue to have a component of motion in the direction it is moving. It knows where in the search space it will encounter with the best solution. The particle will then modify its direction such that it has additional components towards its own best position, pbest and towards the overall best position, gbest [1]. The modification can be represented by the concept of velocity. Velocity of each particle can be modified by the following equation [6]:

$$v_i = v_i + \text{rand} \times (pbest_i - s_i) + \text{rand} \times (gbest_i - s_i) \quad (7)$$

where,
v_i is velocity of particle i
rand is a random number between 0 and 1
$pbest_i$ and $gbest_i$ are the personal best and global best positions of particle i respectively

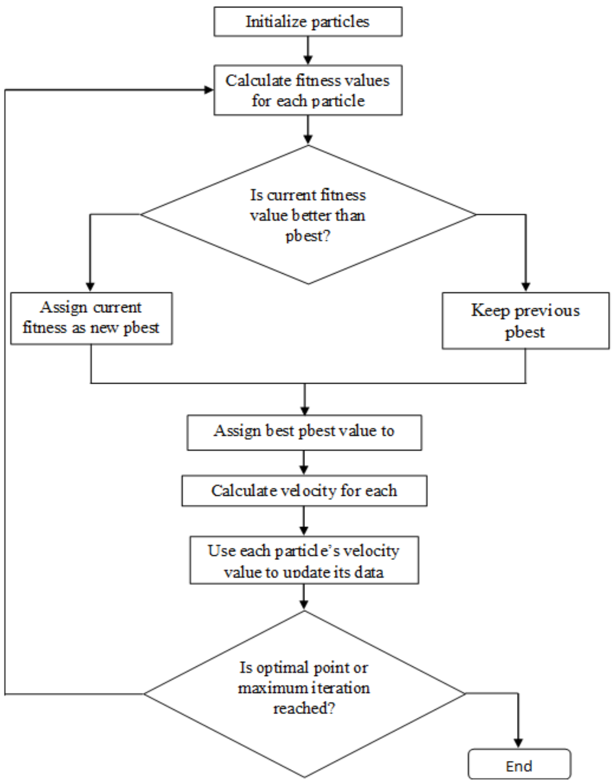

Figure 1 Flowchart for PSO

s_i the current position of particle i

Using (7), a certain velocity that gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$s_i = s_i + v_i \quad (8)$$

PSO utilizes several searching points like Genetic Algorithm (GA) and the searching points gradually get close to the global optimal point using its pbest and gbest. The features of the searching procedure can be summarized as follows [6]:

1. Initial positions of pbest and gbest are different. However, using the different direction of pbest and gbest, all particles gradually get close to the global optimum.
2. The modified value of the particle position is continuous and the method can be applied to continuous problem. However, the method can be applied to the discrete problem using grids for XY position and its velocity.
3. There are no inconsistency in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer non-linear optimization problems with continuous and discrete state variables naturally and easily.
4. The above concept is explained using only XY axis (2-dimensional space). However, the method can be easily applied to n-dimensional problem.

IV. VOLTAGE STABILITY INDEX (L-INDEX)

Consider a system with n number of buses where g is total number of generator buses (including slack bus) and (n-g) is total number of load buses. For a given system, we can write [3]:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (9)$$

where, IG, IL, and VG, VL represent complex current and voltage vectors at the generator nodes and load nodes. [YGG], [YGL], [YLG] and [YLL] are corresponding partitioned portions of network Y-bus matrix.

Rearranging above equation, we get:

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (10)$$

where, $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$ (11)

The elements of $[F_{LG}]$ matrix are complex and its column correspond to the generator bus numbers and rows correspond to the load bus numbers. This matrix gives the relation between load bus voltage and source bus voltages. It also gives information about the location of load nodes with respect to generator nodes that is termed as relative electrical distance between load nodes and generator nodes.

For a given system operating condition, using the operational load flow (state estimation) results, the static voltage stability L-index is computed as follows:

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \quad (12)$$

where, j=g+1,……,n. The L-indices for a given load condition are computed for all load busses.

For stability, the maximum limit for the index Lj is 1 for any of the nodes j. Hence, the voltage stability index of total system is given by L = maximum of Lj for all j (load buses). An L-index value away from one and close to zero indicates an improved system security. When the system is near maximum power transfer condition, the voltage stability index Lj values for load buses gets close to one, indicating that the system is close to voltage collapse. The stability margin is obtained as the distance of L from a unit value, i.e. (1-L).

V. STATCOM

One of many FACTS devices, STATCOM is used to regulate the flow of reactive power in the system. Its characteristics is independent of bus voltage. It can exchange real power with the ac system but since it does not have a continuous source exchange of real power is not practical.

In the transmission systems, STATCOMs primarily handle only the fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances [12].

STATCOM based on current source converter and voltage source converters but voltage source based STATCOM are used more often due to its low cost and easy control. The converter constituting the STATCOM can be composed of GTOs or IGBTs.

VI. LOAD FLOW EQUATION SOLUTION METHODS

Among many methods for solving load flow equations, Newton-Raphson is one of them. This paper uses this method for load flow solution. The reason why this method is chosen in this paper is that this method is found to be more superior and efficient than other methods such as Gauss-Seidel method for large systems, from practical aspects of computational time and convergence characteristics. This method takes less number of iteration to converge and its convergence characteristics is not affected by selection of slack bus.

The linearized equation for this method is [12]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial \delta} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (13)$$

where, ΔP and ΔQ are the real power and reactive power mismatch vectors. ∂P/∂δ and ∂P/∂V are the partial derivative vectors of real power with respect to voltage angles and voltage magnitudes. ∂Q/∂δ and ∂Q/∂V are the partial derivative vectors of reactive power with respect to voltage angles and voltage magnitudes. Δδ and ΔV are voltage angle and voltage magnitude mismatch vectors.

VII. FORMULATION OF ORPD PROBLEM

For ORPD problem, the optimal values of following three quantities have to be determined [6]:

1. AVR operating values
2. Output of reactive power sources
3. Transformer tap settings

In load flow calculations, generator bus voltage magnitudes are treated as voltage specification values. Output of reactive power sources are treated as corresponding susceptance values. Transformer tap settings are treated as tap ratio of each tap position.

In PSO calculation, each initial values of above three quantities are generated randomly between upper and lower bounds. The values are modified in the search procedure between the bounds.

A. ORPD algorithm using PSO

Proposed algorithm for ORPD problem using PSO is as follows:

Step 1. Perform the optimal power flow
Step 2. Initialize particles to random values within their operating limits
Step 3. Initial searching points and velocities are randomly generated within their limits
Step 4. Pbest is set to each initial searching point
Step 5. The best evaluated values among Pbest is set to gbest
Step 6. New velocities and searching points are calculated using (6) and (7)
Step 7. Check if the above values are within the limit
Step 8. Evaluate the fitness values for each particle and obtain the pbest and gbest values
Step 9. Perform load flow
Step 10. Repeat from step 6 until max iteration is reached or optimal point is reached

B. Integration of voltage stability index (VSI) in ORPD

Integration of VSI in ORPD problem is achieved by modifying the objective function by adding L-index to it. The objective function is now changed to:

$$New\ objective\ function = P_{loss} + L\text{-}index \qquad (14)$$

C. Integration of STATCOM in load flow

The power flow constraints of the STATCOM is given by:

$$P_{st} = V_p^{\,2} g_{st} - V_p V_{st}(g_{st}\cos(\theta_p - \theta_{st}) + b_{st}\sin(\theta_p - \theta_{st})) \qquad (15)$$
$$Q_{st} = -V_p^{\,2} b_{st} - V_p V_{st}(g_{st}\sin(\theta_p - \theta_{st}) - b_{st}\cos(\theta_p - \theta_{st}) \qquad (16)$$

where, P_{st} and Q_{st} are active and reactive powers supplied by STATCOM to bus respectively. V_p is the voltage magnitude of the bus P and V_{st} is the voltage across STATCOM. g_{st} and b_{st} are transfer conductance and susceptance between bus and STATCOM respectively. Θ_p and Θ_{st} are the voltage angles of bus and STATCOM respectively.

One operating condition for STATCOM is that the active power exchange should be zero, i.e.

$$PEx = Re(V_{st} I_{st}^{\,*}) = 0 \qquad (17)$$

where, PEx is the active power exchange between STATCOM and specified bus. I_{st} is the current flowing from the STATCOM to bus.

Another control function of STATCOM is that specified bus voltage and STATCOM voltage should be equal, i.e.

$$F = V_p - V_{sp} = 0 \qquad (18)$$

where, F is voltage magnitude mismatch and V_{sp} is the specified voltage for the bus.

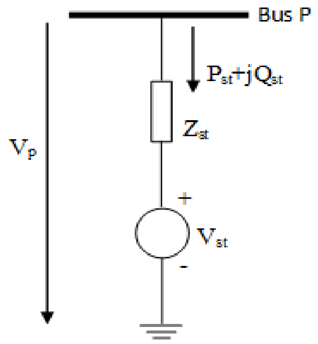

Figure 2 Single line diagram of STATCOM

Considering (13), (17) and (18), the linearized equation for load flow including STATCOM is [8]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta PEx \\ \Delta F \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial V_{st}} & \frac{\partial P}{\partial \delta_{st}} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial V_{st}} & \frac{\partial Q}{\partial \delta_{st}} \\ \frac{\partial PEx}{\partial V} & \frac{\partial PEx}{\partial V} & \frac{\partial PEx}{\partial V_{st}} & \frac{\partial PEx}{\partial \delta_{st}} \\ \frac{\partial F}{\partial V} & \frac{\partial F}{\partial V} & \frac{\partial F}{\partial V_{st}} & \frac{\partial F}{\partial \delta_{st}} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \\ \Delta V_{st} \\ \Delta \delta_{st} \end{bmatrix} \qquad (19)$$

where, ΔPEx and ΔF are active power exchange vector and voltage magnitude mismatch vector respectively. ΔVst and Δδst are the STATCOM voltage magnitude and angle mismatch vectors.

VIII. SIMULATION RESULTS AND DISCUSSION

In order to demonstrate the effectiveness of the proposed method, minimization of real power loss was considered under two conditions; with voltage stability enhancement, and with both voltage stability enhancement and STATCOM. MATLAB code has been developed for this ORPD optimization problem and the validity of the proposed method is demonstrated on IEEE-14 bus systems. The contingencies considered here is the cut off of the transmission line between any two buses. Four different contingencies are taken into consideration: cut off between bus 1 and bus 2, cut off between bus 3 and bus 4, cut off between bus 4 and bus 5, and cut off between bus 12 and bus 13.

The test system used is shown in fig. 3. The control variables considered in the program are:

1. AVR operating values of buses 2, 3, 6 and 8
2. Reactive power generators of buses 2, 3, 6 and 8
3. Tap settings of transformers between buses 4-7, 4-9 and 5-6

Two STATCOMs are used in the test system and the best locations for STATCOMs were obtained using VSI as shown in Table I.

Table II shows the comparison of power loss and voltage stability index with and without STATCOM for different contingencies.

TABLE I
LOWEST VSI FOR BEST LOCATION OF STATCOM IN 14 BUS SYSTEM

Bus	5	13
VSI	0.0353	0.0341

TABLE II
COMPARISON OF POWER LOSS AND VSI WITH AND WITHOUT USING STATCOM FOR DIFFERENT CONTINGENCIES

TABLE II.I
TRANSMISSION LINE BETWEEN BUS 1 AND BUS 2 CUT OFF

Power Loss (MW)		**VSI**	
without STATCOM	**with STATCOM**	**without STATCOM**	**with STATCOM**
63.5007	40.7817	0.0829	0.0332

TABLE II.II
TRANSMISSION LINE BETWEEN BUS 3 AND BUS 4 CUT OFF

Power Loss (MW)		**VSI**	
without STATCOM	**with STATCOM**	**without STATCOM**	**with STATCOM**
32.205	15.1827	0.0753	0.0648

TABLE II.III
TRANSMISSION LINE BETWEEN BUS 4 AND BUS 5 CUT OFF

Power Loss (MW)		**VSI**	
without STATCOM	**with STATCOM**	**without STATCOM**	**with STATCOM**
32.205	15.1827	0.0651	0.035

TABLE IIII.IV
TRANSMISSION LINE BETWEEN BUS 12 AND BUS 13 CUT OFF

Power Loss (MW)		**VSI**	
without STATCOM	**with STATCOM**	**without STATCOM**	**with STATCOM**
17.152	14.9744	0.0813	0.0634

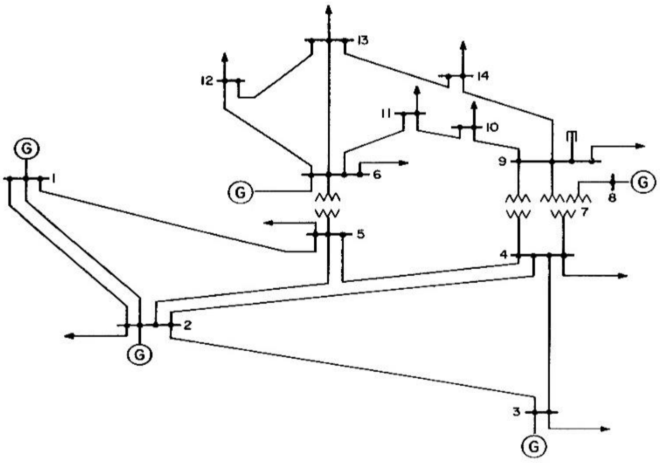

Fig. 3 IEEE 14-bus system

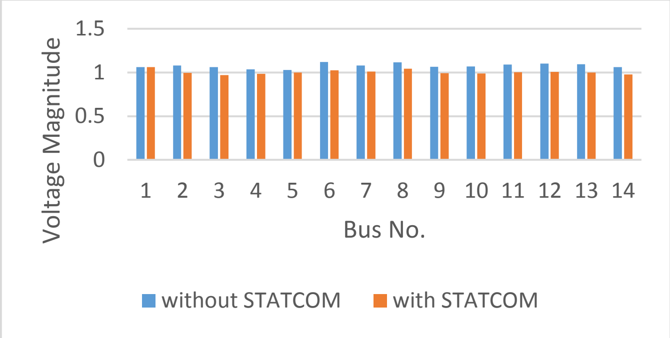

Fig. 4.1Transmission line between Bus 1 and Bus 2 cut off

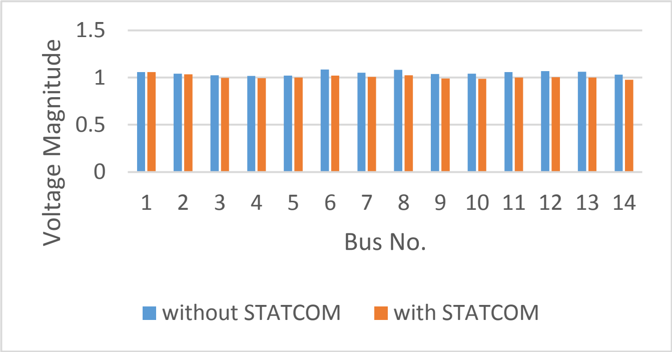

Fig. 4.2 Transmission line between Bus 3 and Bus 4 cut off

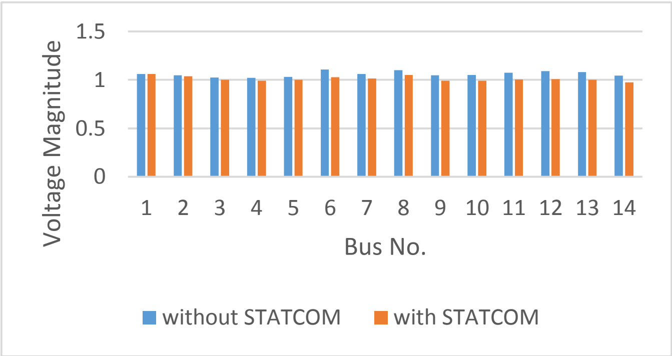

Fig. 4.3 Transmission line between Bus 4 and Bus 5 cut off

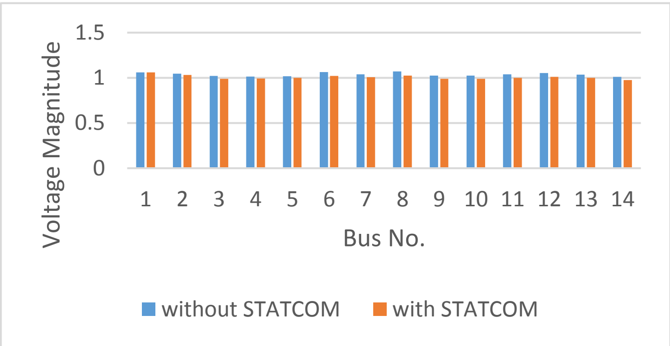

Fig. 4.4 Transmission line between Bus 12 and Bus 13 cut off

Fig. 4 Comparison of Bus voltage magnitudes with and without the use of STATCOM for different contingencies

As seen in Table II, without the use of STATCOM there is certain power loss in the system with certain voltage stability index for all different conditions. These values decreases with the integration of STATCOM in the system i.e. the system's voltage stability is enhanced along with the decrease in transmission loss.

When the transmission line between bus 1 and bus 2 is cut off, the power loss is 63.5007 MW and the voltage stability index is 0.0829. With the introduction of STATCOM in the system power loss is brought down to 40.7817 and the voltage stability index to 0.0332. This show the effectiveness of the use of STATCOM for minimizing power loss and voltage stability enhancement. Similarly, the same works for other contingency problems as shown in Table II.II to Table II.IV.

Fig. 4 shows comparison of bus voltage magnitudes with and without the use of STATCOM for different contingencies. From the graph it can be observed that the voltage magnitudes are deviated more from 1 pu when STATCOM is not present. But the deviation decreases once the STATCOM is introduced in the system. For the first contingency problem i.e. when the transmission line between bus 1 and bus 2 is cut off, the deviation of voltage magnitude from 1 pu is 0.003161 and after the introduction of STACOM the deviation decreases to 0.000284. This definitely proves that the introduction of STATCOM brings improvement in the system.

IX. CONCLUSION

In this paper, particle swarm optimization technique is used for optimal reactive power dispatch problem. The control used for the problem is minimization of real power loss. Voltage stability index is considered in the problem to enhance the voltage stability of the system. STATCOM is used in the system to minimize power loss and make the system more stable. Different contingencies are considered to demonstrate the effectiveness of STATCOM. IEEE-14 bus system are used as test system. The test results reveal that the proposed method is effective for reactive power optimization with voltage stability enhancement.

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