

Voltage Stability Enhancement Using Cat Swarm Optimization Algorithm

P. Suryakumari, P. Kantarao

Abstract—Optimal Power Flow (OPF) problem in electrical power system is considered as a static, non-linear, multi-objective or a single objective optimization problem. This paper presents an algorithm for solving the voltage stability objective reactive power dispatch problem in a power system. The proposed approach employs cat swarm optimization algorithm for optimal settings of RPD control variables. Generator terminal voltages, reactive power generation of the capacitor banks and tap changing transformer setting are taken as the optimization variables. CSO algorithm is tested on standard IEEE 30 bus system and the results are compared with other methods to prove the effectiveness of the new algorithm. As a result, the proposed method is the best for solving optimal reactive power dispatch problem.

Keywords—RPD problem, voltage stability enhancement, CSO algorithm.

I. INTRODUCTION

REACTIVE power dispatch (RPD) is one of the important tasks in the operation and control of power system. Efficient distribution of reactive power in an electric network leads to minimization of the system losses and improvement of the system voltage profile. One of the important operating requirements of a reliable power system is to maintain the voltage within the permissible ranges to ensure a high quality of customer service. The optimal power flow (OPF) has been widely used for both the operation and planning of a power system. Therefore, a typical OPF solution adjusting the appropriate control variables, so that a specific objective in operating a power system network is optimized (maximizing or minimizing) with respect to the power system constraints, detected by electrical network.

The problem that has to be solved in a reactive power optimization is to determine the required reactive generation at various locations so as to determine the required reactive generation at various locations so as to optimize the objective function. Here the reactive power dispatch problem [1]-[3] involves best utilization of the existing generator bus voltage magnitude, transformer tap setting and the output of reactive power sources so as to minimize the loss and to enhance the voltage stability of the system.

To solve the RPD problem, a number of conventional optimization techniques have been proposed. These include the Gradient method, Non-linear Programming (NLP), Quadratic Programming (QP), Linear programming (LP) and

Interior point method. Though these techniques have been successfully applied for solving the reactive power dispatch problem, still some difficulties are associated with them. One of the difficulties is the multimodal characteristic of the problems to be handled. Also, due to the non-differential, non-linearity and non-convex nature of the RPD problem, majority of the techniques converge to a local optimum. Recently, Swarm Intelligence techniques like Particle Swarm Optimization [4]-[6], Cat Swarm Optimization techniques [7]-[12], have been applied to solve the optimal dispatch problem.

In this paper, CSO approach has been proposed to solve the RPD problem. Nowadays voltage instability has become a new challenge to power system planning and operation. Insufficient reactive power availability or non-optimized reactive power flow may lead a power system to insecure operation under heavily loaded conditions. By reallocating reactive power generations in the system by adjusting transformer taps, generator voltages and switchable VAR sources, the problem can be solved to a far extent. In this paper, CSO algorithm is used to solve the voltage constrained reactive power dispatch problem. The proposed algorithm identifies the optimal values of generation bus voltage magnitudes, transformer tap setting and the output of the reactive power sources so as to minimize the transmission loss and to improve the voltage stability [13], [14]. The effectiveness of the proposed approach is demonstrated through IEEE-30 bus system.

II. VOLTAGE STABILITY ENHANCEMENT

Consider a system where, n total number of busses, with 1, 2... g generator busses (g), $g+1$, $g+2$... $g+s$ SVC busses (s), $g+s+1$... n the remaining busses ($r=n-g-s$) and t number of OLTC transformers. The transmission system can be represented using a hybrid representation, by the following set of equations. A load flow result is obtained for a given system operating condition which is otherwise available from the output of an on-line state estimator. The load flow algorithm incorporates load characteristics and generator control characteristics. Using the load flow results, the L -index is computed as

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

where $j=g+1$... n and all the terms within the sigma on the RHS of (1) are complex quantities. The values F_{ji} are obtained from the Y bus matrix as follows:

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$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} z_{LL} F_{LG} \\ K_{GL} Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (2)$$

where, I_L , V_L are the currents and voltages vectors at the load nodes. V_G , I_G are the currents and voltages vector at the generator nodes. Z_{LL} , F_{LL} , K_{GL} , Y_{GG} are the sub-matrices of the hybrid matrix H . The H matrix can be evaluated from the Y bus matrix by a partial inversion, where the voltages at the load buses are exchanged against their currents. This representation can then be used to define a voltage stability indicator at the load bus, namely L_j which is given by,

$$L_j = \left| 1 + \frac{V_{0j}}{V_j} \right| \quad (3)$$

where

$$V_{0j} = - \sum_{i \in G} F_{ji} V_i \quad (4)$$

The term V_{0j} is representative of an equivalent generator comprising the contribution from all generators. The index L_j can also be derived and expressed in terms of the power terms as the following:

$$L_j = \left| \frac{S_{j+}^*}{Y_{jj} + V_j^2} \right| \quad (5)$$

$$S_{j+} = S_j + S_{jcorr} \quad (6)$$

* indicates the complex conjugate of the vector

$$S_{jcorr} = \left(\sum_{\substack{i \in \text{loads} \\ i \neq j}} \frac{Z_{ji}^* S_i}{Z_{ji}^* V_i} \right) V_j \quad (7)$$

$$Y_{jj+} = \frac{1}{z_{jj}} \quad (8)$$

The complex power term component S_{jcorr} represents the contributions of the other loads in the system to the index evaluated at the node j . It can be seen that when a load bus approaches a steady state voltage collapse situation, the index L approaches the numerical value 1.0. Hence for an overall system voltage stability condition, the index evaluated at any of the buses must be less than unity. Thus the index value L gives an indication of how far the system is from voltage collapse. This feature of this indicator has been exploited in our proposed algorithm to evolve a voltage collapse margin incorporated RPD routine. The L -indices for a given load condition are computed for all load buses. The equation for the L -index for j -th node can be written as

$$L_j = \left| 1.0 - \sum_{i=1}^{i=g} F_{ji} \left| \frac{V_i}{V_j} \right| \cos(\theta_{ji} + \delta_i - \delta_j) \right| \quad (9)$$

$$L_j = \left| 1.0 - \sum_{i=1}^{i=g} \left| \frac{V_i}{V_j} \right| (F_{ji}^r + j F_{ji}^m) \right| \quad (10)$$

$$\begin{aligned} F_{ji} &= |F_{ji}| \cos(\theta_{ji}) \\ F_{ji}^r &= |F_{ji}| \cos(\theta_{ji} + \delta_i - \delta_j) \\ F_{ji}^m &= |F_{ji}| \sin(\theta_{ji} + \delta_i - \delta_j) \end{aligned} \quad (11)$$

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III. PROBLEM FORMULATION

A. Nomenclature:

P_{loss}	Network real power loss
P_i, Q_i	Real and reactive powers injected into network at bus i
G_{ij}, B_{ij}	Mutual conductance and susceptance between bus i and bus j
G_{ii}, B_{ii}	Self-conductance and susceptance of bus i
Q_{gi}	Reactive power generation at bus i
Q_{ci}	Reactive power generated by i^{th} capacitor bank
t_k	Tap setting of transformer at branch k
V_i	Voltage magnitude at bus i
V_j	Voltage magnitude at bus j
θ_{ij}	Voltage angle difference between bus i and bus j
S_l	Apparent power flow through the l^{th} branch
g_k	Conductance of branch k
N_B	Total number of buses
N_{B-1}	Total number of buses excluding slack bus
N_{PQ}	Number of PQ buses
N_g	Number of generator buses

N_C	Number of capacitor banks
N_T	Number of tap-setting transformer branches
N_l	Number of branches in the system
δ_i	Voltage phase angle of i^{th} generator bus

The optimal power flow problem is a nonlinear optimization problem. It consists of a nonlinear objective function defined with nonlinear constraints. The optimal power flow problem requires the solution of nonlinear equations, describing optimal and/or secure operation of power systems. The general optimal power flow problem can be expressed as a constrained optimization problem as follows.

$$\begin{array}{ll} \text{Minimize} & f(x) \\ \text{Subject to} & g(x) = 0, \text{ equality constraints} \\ & h(x) \leq 0, \text{ inequality constraints} \end{array}$$

The objective of ORPD is to identify the reactive power control variables, which minimizes of L-index value. This is mathematically stated as follows

$$\text{Minimize } F = \max(L_j; j=1,2,\dots,n)$$

where n : number of buses. The reactive power optimization problem is subject to the following constraints

B. Equality Constraints

These constraints represent load flow equation such as

$$P_i - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0, i \in N_B - 1 \quad (12)$$

$$Q_i - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0, i \in N_{PQ} \quad (13)$$

C. Inequality Constraints

These constraints represent the system operating constraints. Generator bus voltages (V_{gi}), reactive power generated by the capacitor (Q_{ci}), transformer tap setting (t_k), are control variables and they are self restricted. Load bus voltages (V_{load}) reactive power generation of generator (Q_{gi}) and line flow limit (SI) are state variables, whose limits are Satisfied by adding a penalty terms in the objective function. These constraints are formulated as

1. Generator bus voltage limits

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max}; i \in N_B \quad (14)$$

2. Load bus voltage limits

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}; i \in N_B \quad (15)$$

3. Generator reactive power capability limit

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max}; i \in N_g \quad (16)$$

4. Capacitor reactive power generation limit

$$Q_{ci}^{\min} \leq Q_{ci} \leq Q_{ci}^{\max}; i \in N_c \quad (17)$$

5. Transformer tap setting limit

$$t_k^{\min} \leq t_k \leq t_k^{\max}; k \in N_T \quad (18)$$

IV. CAT SWARM OPTIMIZATION

A. Overview

CSO algorithm is divided into two sub models based on two of major behavioral traits of cats. These are termed as "Seeking mode" and "Tracing mode".

Seeking mode has four essential factors. Such as SMP, SRD, CDC, SPC which are designed as follows.

- Seeking Memory pool (SMP):- It is used to define the size of seeking memory of each cat, indication any points sort by cat.
- Seeking Rang of Selected Dimensions (SRD):- It is used to declare mutative ration for selected dimensions. While in seeking mode; if a dimension is selected for mutation, the difference between old and new ones may not be out of range, the range defines by SRD.
- Counts of Dimensions to Change (CDC):- It is used tell how many dimensions to will be varied. All these factors play important roles in seeking mode.
- Self Position Consideration (SPC):- It is a Boolean valued variable, and indicates whether the point at which the cat is already standing will be one of the candidate point to move to. SPC cannot influence SMP.

B. Seeking Mode: Resting and Observing

The seeking mode of the CSO algorithm models the behavior of the cats during the period of resting but staying alert-observing its environment for its next move.

The seeking mode of the CSO algorithm can be described as follows

- Step 1. Make j copies of the present position of each cat_k , where $j=SMP$. if the value of SPC is true. Let $j=(SMP-1)$, then retain present position as one of the candidates.
- Step 2. For each copy according to CDC add or subtract SRD percent values and replace the old ones.
- Step 3. Calculate the fitness values (FS) of all candidate points.
- Step 4. If all the FS are not exactly equal calculate the selecting probability (19) of each candidate point. Otherwise set all the selecting probability of each candidate point to 1.

$$P_i = \frac{|FS_i - FS_b|}{FS_{\max} - FS_{\min}}, \text{ where } 0 < i < j \quad (19)$$

If the global of the fitness is to find the minimum solution; $FS_b = FS_{\max}$, otherwise $FS_b = FS_{\min}$.

- Step 5. Randomly pick the point to move to form the candidate points, and replace the position of cat_k .

C. Tracing Mode:- Running After a Target

- Step 1. Update the velocities for every dimension (V_{id}) according to (20).
 Step 2. Check if the velocities are in the range of maximum velocity is over-range, it is set equal to the limit.
 Step 3. Update the position of cat_k according to (21).

$$V_{id} = W * V_{id} + C * r * (P_{gd} - X_{id}) \quad (20)$$

where, W is inertia weight, P_{gd} is position of cat, who has the best fitness value. X_{id} is the position of cat_k , C is constant r is a random value in the range of $[0,1]$.

$$X_{id} = X_{id} + V_{id} \quad (21)$$

D. CSO Movement = Seeking Mode + Tracing Mode

When applying the CSO algorithm to solve optimization problems, the initial step is to make a decision on the number of individuals or cats to use. Each cat in the population has the following attributes:

1. a position made up of M dimensions;
2. velocities for each dimension in the position;
3. a fitness value of the cat according to the fitness function; and
4. a flag to indicate whether the cat is in seeking mode or tracing mode.

The CSO algorithm keeps the best solution after each cycle and when the termination condition is satisfied, the final solution is the best position of one of the cats in the population. CSO has two sub-modes, namely seeking mode and tracing mode and the mixture ratio MR dictates the joining of seeking mode with tracing mode. To ensure that the cats spend most of their time resting and observing their environment, the MR is initialized with a small value. The CSO algorithm can be described in 6 steps as presented in [7]-[9].

Step 1. Create N cats in the process.

Step 2. Randomly sprinkle the cats into the M -dimensional solution space and randomly give values, which are in-range of the maximum velocity, to the velocities of every cat. Then haphazardly pick number of cats and set them into tracing mode according to MR , and the others set into seeking mode.

Step 3. Evaluate the fitness value of each cat by applying the positions of cats into the fitness function, which represents the criteria of our goal, and keep the best cat into memory. Note that we only need to remember the position of the best cat (x_{best}) because it represents the best solution so far.

Step 4. Move the cats according to their *flags*, if cat_k is in seeking mode, apply the cat to the seeking mode process, otherwise apply it to the tracing mode process.

Step 5. Re-pick number of cats and set them into tracing mode according to MR , then set the other cats into seeking mode.

Step 6. Check the termination condition, if satisfied, terminate the program, and otherwise repeat Step 3 to Step 5.

E. CSO Flow Chart

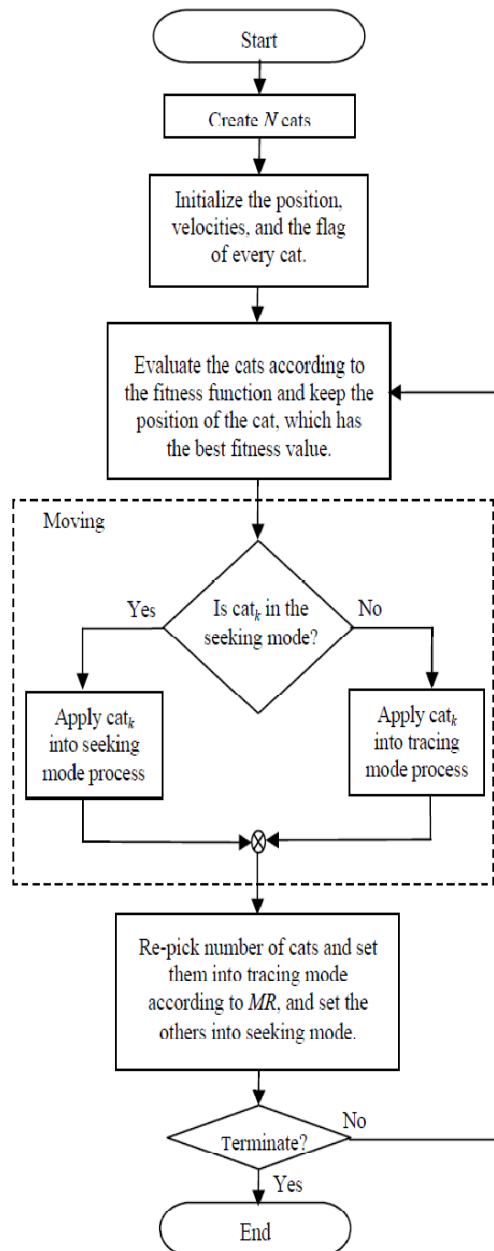


Fig. 1 CSO flow chart

V. RESULTS

The OPF using CSO has been carried out on the IEEE 30 bus system. The network consists of 41 branches, six generator buses and 24 load buses. Four branches 6–9, 6–10, 4–12 and 27–28 have tap changing transformers with 20 discrete steps of 0.01p.u each. The buses with possible reactive power source installations are 10, 12, 15, 17, 20, 21, 23, 24, 29. The available reactive powers of capacitor banks are within the interval 0 to 0.18 p.u in discrete steps of 0.06 p.u. All bus voltages are required to be maintained within the

range of 0.95–1.05 p.u. voltage stability enhancement is our objective.

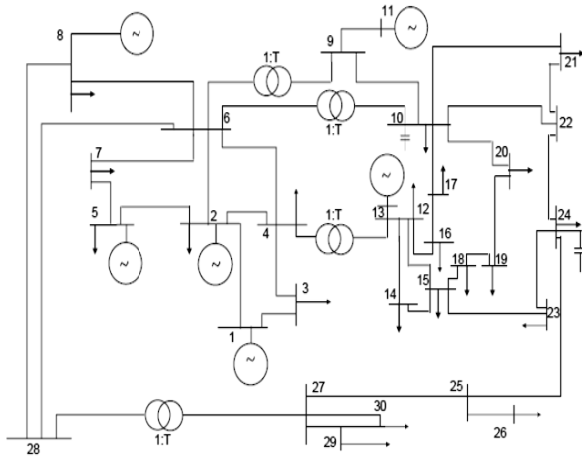


Fig. 2 IEEE-30 test system

TABLE I
DESCRIPTION OF IEEE-30 BUS TEST SYSTEM

S.no	Variables of 30- bus test system	No. of variables
1	Buses	30
2	Branches	41
3	Q_{svc}	9
4	Generators	6
5	Tap –changing transformers	4

TABLE II
VARIABLE LIMITS OF CONTROL VARIABLES

S.no	Control Variables	Limits of variables
1	Generator voltage V_g	(0.95-1.1) p.u.
2	Tap setting (t_k)	(0.9-1.1) p.u.
3	MVAR by static compensators (Q_{svc})	(0.0-5.0) p.u.

TABLE III
OPTIMAL CONTROL VARIABLE VALUES COMPARED WITH OTHER METHODS

S.no	Control variables	Base case	GA[1]	DE[2]	CSO
1	V_1	1.0435	1.0496	1.0993	1.0026
2	V_2	1.0371	1.0399	1.0967	1.0642
3	V_5	1.0226	1.0187	1.0990	1.0473
4	V_8	0.9790	1.0217	1.0346	1.0941
5	V_{11}	1.0129	1.0496	1.0993	1.0447
6	V_{13}	0.9984	1.0498	0.9517	1.0956
7	T_{11}	1.0000	0.9275	0.9038	1.0200
8	T_{12}	1.0000	0.9275	0.9029	0.9000
9	T_{15}	1.0000	0.9275	0.9002	0.9400
10	T_{36}	1.0000	0.9225	0.9360	0.9400
11	Q_{c10}	0.0000	3	0.6854	0.1800
12	Q_{c12}	0.0000	0	4.7163	0.0600
13	Q_{c15}	0.0000	2	4.4931	0.0600
14	Q_{c17}	0.0000	5	4.5100	0.0600
15	Q_{c20}	0.0000	4	4.4766	0.0000
16	Q_{c21}	0.0000	5	4.6075	0.0600
17	Q_{c23}	0.0000	3	3.8806	0.0600
18	Q_{c24}	0.0000	3	4.2854	0.0000
19	Q_{c29}	0.0000	5	3.2541	0.0600

TABLE IV
CSO PARAMETERS FOR BEST RESULTS OF OPTIMAL POWER FLOW FOR IEEE 30-BUS SYSTEM

S.no	Parameters	Values
1	Populations	70
2	Iterations	220
3	Copies	30

TABLE V
BUS VOLTAGES OF TEST SYSTEM AFTER APPLYING OPTIMIZATION TECHNIQUE

Variables(p.u)	VALUES
V_1	1.0700
V_2	1.0642
V_3	1.0473
V_4	1.0941
V_5	1.0447
V_6	1.0956
V_7	1.0389
V_8	1.0544
V_9	1.0766
V_{10}	1.0945
V_{11}	1.0501
V_{12}	1.0994
V_{13}	1.0479
V_{14}	1.0959
V_{15}	1.0885
V_{16}	1.0963
V_{17}	1.0903
V_{18}	1.0869
V_{19}	1.0818
V_{20}	1.0843
V_{21}	1.0864
V_{22}	1.0867
V_{23}	1.0809
V_{24}	1.0787
V_{25}	1.0794
V_{26}	1.0628
V_{27}	1.0880
V_{28}	1.0439
V_{29}	1.0694
V_{30}	1.0587

Here the CSO algorithm was applied to identify the optimal control variables of the system under base-load condition, with considering the voltage stability of the system and without loss minimization. Table I gives no of variables of IEEE-30 bus test system. Table II gives control variable limits. Table III gives optimal control variable settings of IEEE-30 bus test under base load condition and compare CSO values with DE and GA. It was run with different control parameter settings and the solution was obtained with the following parameter settings are shown in Table IV. Corresponding to this control variable setting, it was found that there are no limit violations in any of the state variables. Better voltage stability is obtained by the proposed method is less than the values presented in the other methods.

Bus voltages after applying optimization technique are given in Table V. Table VI shows comparison of optimal values of proposed method with other methods. The results demonstrate the effectiveness and robustness of the proposed algorithm to solve RPD problem and gives excellent results with different objective functions shows that makes the proposed CSO optimization technique is good in dealing with power system optimization problems. From the results, CSO

presents a better performance of finding the global best solution.

TABLE VI
COMPARISON OF CSO OPTIMAL RESULTS WITH DE AND GA

Variables	GA[1]	DE[2]	CSO
Ploss(p.u)	0.050129	0.070733	0.0478
Lindex(p.u)	0.2471	0.1246	0.1091

VI. GRAPHS

Graph between fitness and no of iterations

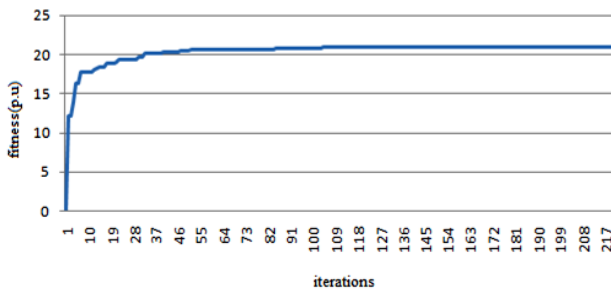


Fig. 3 Graph between Fitness and Number of Iterations

Graph between ploss and no of iterations

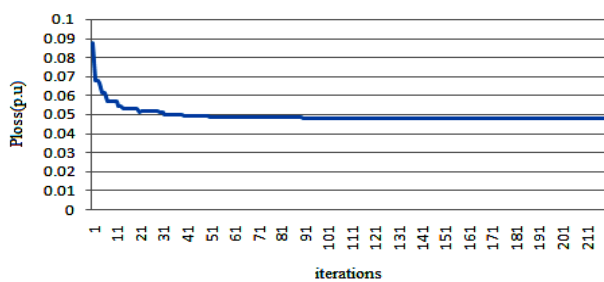


Fig. 4 Graph between Ploss and No of Iterations

Graph between L-index and no of iterations

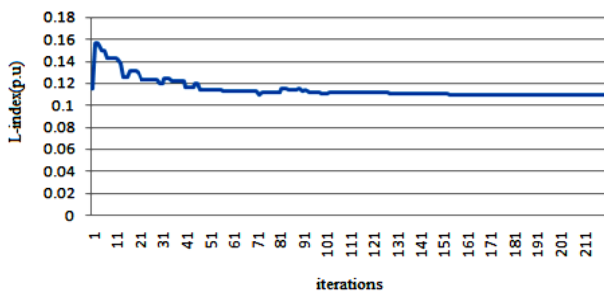


Fig. 5 Graph between L-Index and No of Iterations

VII. CONCLUSION

CSO optimization algorithm has been proposed, developed and successfully applied to solve reactive power dispatch problem. The RPD has been formulated as a constrained optimization problem where several objective functions have been considered to enhance the voltage stability and to minimize the power losses. The proposed approach has been

tested and examined on the standard IEEE 30-bus test system. The results demonstrate the effectiveness and robustness of the proposed algorithm to solve RPD problem and gives excellent results with different objective functions shows that makes the proposed CSO optimization technique is good in dealing with power system optimization problems. From the results, CSO presents a better performance of finding the global best solution.

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