

## Reactive Power Reserve Management by Using Improved Particle Swarm Optimization Algorithm

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### Abstract

A power system needs to be with sufficient reactive power capability to maintain system voltage stability and system reliability. Reactive power reserve can be ensured by installing var sources or optimizing the reactive power generation from the existing var sources. This work aims to optimize the total reactive power generation by adjusting the power flow pattern in a system. Generator bus voltage magnitudes, transformer tap positions and static var compensator(SVC) settings are taken as control parameters. Total reactive power generation is taken as the objective function value. An enhanced version of PSO algorithm, the improved PSO (IPSO) is suggested for the optimization task. The likelihood for trapping into local minima by PSO is overcome in this enhanced version. The effectiveness of the proposed algorithm is tested on the standard IEEE-30 bus system. The performance is compared with the basic version of PSO and improved results are seen.

**Key Words:** Reactive power reserve, PSO, IPSO, Voltage stability, SVC, var sources.

### I. INTRODUCTION

Voltage instability is generally associated with power systems which are heavily stressed or loaded. The stressed condition is usually caused by disturbances and characterized by shortage of fast-acting adequate reactive reserves. Voltage instability is related to reactive power demands not being met because of limitations on the production and transmission of reactive power [1]. Reactive power demand generally increases with a load increase. The fast reactive sources are generators, synchronous condensers and power electronics-based flexible ac transmission systems (FACTS) devices.

During disturbances, reactive power resources should supply power to compensate for load bus voltage levels. This action reduces reactive losses of transmission lines and transformers, and increases line charging and shunt capacitor outputs. Generally, one or two critical resources reaching their limits can lead to cascading limiting effects at neighboring units. Hence it is wise to keep enough reserves in order to improve the voltage stability margin. Reactive power margins have always been linked with voltage stability.

The minimum reactive power margin is determined by the voltage-var (V-Q) curve method. The V-Q method has been well studied [2]–[3]. Reference [4] discusses a reactive management program for a practical power system. The authors discuss a planning goal of supplying system reactive demands by installation of properly sized and properly located capacitor banks which will allow generating units to operate at or near unity power factor. However, it is a cost-intensive proposition. Besides, this strategy is not always very effective since not all the shunt capacitors are fully utilized.

In [5], reactive power margins are used to evaluate voltage instability problems for coherent bus groups. These margins are based on the reactive reserves of generators and SVCs that exhaust reserves in the process of computing a V-Q curve at any bus in a coherent group or voltage control area. In [6], the authors introduce a methodology to reschedule the reactive injection from generators and synchronous condensers with the aim of improving the voltage stability margin. Their method is formulated based on modal participations factors and an optimal power flow (OPF) wherein the voltage stability margin, as computed from eigenvectors of a reduced Jacobian, is maximized by reactive rescheduling.

However, the authors avoid using a security-constrained OPF formulation and thus the computed voltage stability margin from the Jacobian would not truly represent the situation under a stressed condition. In [7], the authors employ a security-constrained OPF for optimal var expansion planning design.

For optimal reactive power reserve management, an effective optimization algorithm is necessary for proper settings of the control variables. A number of conventional optimization methods have been exploited for engineering optimization. Techniques such as non linear programming technique [8] and gradient based optimization algorithm [9] are some of them. But they have several disadvantages like large numerical iteration and insufficient convergence properties which leads to large computation and more execution time. The recently developed meta-heuristics based algorithms are proving better performance than the conventional methods. They find global best or nearly global best solutions for engineering problems. These algorithms are better utilised for power system optimization. Some of them are Tabu Search (TS) [10], Simulated Annealing (SA) [11], Genetic Algorithm (GA) [12], Evolutionary Programming (EP) [13], Hybrid Evolutionary Programming (HEP) [14], Particle Swarm Optimization PSO [15], Chaotic Ant Swarm Optimization (CASO) [16] and Differential Evolution (DE) [17] are developed which provides fast and optimal solution for reactive power optimization.

In this work, a reactive reserve management program based on IPSO algorithm is proposed to manage reactive power generation from its sources. The IPSO overcomes the problem of trapping into local minima by updating the velocity some crazy particles by a random manner. A balance between velocity updating by the standard equation and random manner is maintained. The proposed method is tested on the IEEE-30 bus test system.

## II. REACTIVE POWER RESERVES

The reactive power sources of a power system include synchronous generators and static var compensators. During disturbances, the real power component of line loadings does not change significantly, whereas the reactive power flow can change dramatically. This is due to the fact that the voltage drops resulting from the contingency decreases the reactive power generation from line charging and shunts capacitors, thereby increasing reactive power losses. Sufficient reactive reserves should be made available to meet additional var demand. Simply speaking, the reactive power reserve is the ability of the generators to support bus voltages under increased load condition or system disturbances. How much more reactive power the system can deliver depends on the operating condition and the location of the reserves, as well as the nature of the impending change. The reserves of reactive sources can be considered a measure of the degree of voltage stability. The available reactive power reserve of a generator is determined by its capability curves [9]. It is worth noting that for a given real power output, the reactive power generation is limited by both armature and field heating limits.

$$Q_g^{max} = -\frac{V_g^2}{x_d} + \sqrt{\left(\frac{V_g^2 I_{fd}^{max}}{x_d^2}\right) - P_g^2} \quad (1)$$

The maximum reactive power of the generator is determined by the maximum field current. The relationship (1) also shows that the maximum reactive generation is a function of the terminal voltage.

The maximum reactive power output should also satisfy the armature current limitation as follows:

$$Q_g^{max} = \sqrt{(V_g^2 I_a^2_{max} - P_g^2)} \quad (2)$$

The reactive power reserve of the  $i^{th}$  generator can be written as

$$Q_{g\text{res}}^{max} = Q_g^{max} - Q_g \quad (3)$$

In this work, the reactive power reserve is maximized by minimizing the reactive power generation from the generators and var sources.

## III. FORMULATION

The objective function of this optimization problem is to minimize the reactive power generation. Therefore, the following objective function is used.

$$F(X, U) = \min \sum_{i=1}^{N_{PV}} Q_{gi} \quad (4)$$

Where  $X$  stands for the system state variables or dependent variables, which are usually bus voltages and angles;  $U$  represents the system control variables or independent variables like generator bus voltage or tap or SVC var outputs.  $Q_{gi}$  is the reactive power generation of the  $i^{th}$  generator,  $i=1, \dots, N_{PV}$ .

The constraints to the problem are as follows:

### 3.1 Equality constraints:

Real power balance equation at all buses

$$P_i = P_g - P_d = V_i \sum_{j=1}^{NB} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (5)$$

Reactive power balance equation at all buses

$$Q_i = Q_g - Q_d = V_i \sum_{j=1}^{NB} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (6)$$

### 3.2 Inequality constraints:

Reactive power generation limit

$$Q_g^{\min} \leq Q_g \leq Q_g^{\max} \quad (7)$$

Voltage magnitude limit

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad i \in N_{PV} \quad (8)$$

Tap changer limit

$$t_i^{\min} \leq t_i \leq t_i^{\max} \quad i \in N_T \quad (9)$$

SVC MVAR output limit

$$Q_{svc}^{\min} \leq Q_{svc} \leq Q_{svc}^{\max} \quad (10)$$

Line MVA flow limit

$$MVA_{ij} \leq MVA_{ij}^{\max} \quad (11)$$

Where:

$V_i$ : Voltage magnitude at load bus;  $\theta_{ij}$ : Voltage angle difference between bus  $i$  and bus  $j$ ;

$G_{ij}, B_{ij}$ : Elements of the admittance matrix;

$P_i, Q_i$ : Active/reactive power injected into the network at bus  $i$ ;

$N_T, N_{PV}, N_{PQ}$ : Number of transformers, generators, and loads, respectively;

$Q_g^{\min}, Q_g^{\max}$ : Reactive power capacity limits at generator bus.

$V_i^{\min}, V_i^{\max}$ : Limits of voltage at  $i^{th}$  load bus;

$t_i^{\min}, t_i^{\max}$ : Limits of tap setting of transformer  $i$ ;

$MVA_{ij}^{\max}$ : MVA capacity limit of transmission line between buses  $i$  and  $j$ .

Equation (4) is the objective function, which minimizes the sum of the reactive power generation. Equations (5) and (6), show the bus injections in terms of flows in the lines and the static power flow equations at sending and receiving ends in terms of steady state values of bus voltage magnitudes and bus angles.

#### IV. PARTICLE SWARM OPTIMIZATION (PSO)

PSO is a recently developed bio inspired optimization algorithm based on the food foraging behavior of swarm of fish or birds [18]. The particle swarm optimization method has become quite popular for solving complex problems during the last decade. Its excellent random parallel search capability and constraint handling mechanism make it very efficient for locating good solution in the complex search domain.

**4.1 Basic Particle swarm optimization (BPSO):** The PSO is a simple and powerful optimization tool which scatters random particles i.e. solutions into the problem space. These particles, called swarms collect information from each other through an array constructed by their respective positions. The particles update their positions using the velocity of particles.

Position and velocity are both updated in a heuristic manner using guidance from a particle's own experience and the experience of its neighbors. The position and velocity vectors of the  $i^{th}$  particle of a D-dimensional search space can be  $X_i = (x_{i1}, x_{i2}, \dots, x_{iD})$  and  $V_i = (v_{i1}, v_{i2}, \dots, v_{iD})$ . Each particle keeps track of the solutions visited and remembers the best one as the  $P_{best}$ . The particle best may be represented as  $P_{besti} = (p_{besti1}, p_{besti2}, \dots, p_{bestiD})$ . The best among the particle bests is called global best, the  $G_{best}$ .

The particle tries to modify its position using the current velocity and the distance from  $P_{best}$  and  $G_{best}$ . The modified velocity and position of each particle for fitness evaluation in the next iteration are calculated using the following equations.

$$v_{id}^{k+1} = wv_{id}^k + c_1 rand_1 (P_{best\ id} - x_{id}) + c_2 rand_2 (G_{best\ id} - x_{id}) \quad (12)$$

$$x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \quad (13)$$

Here  $w$  is the inertia weight parameter which controls the global and local exploration capabilities of the particle.  $c_1$  and  $c_2$  are cognitive and social coefficients, and  $rand_1$ ,  $rand_2$  are random numbers between 0 and 1. A larger inertia weight factor is used during initial exploration and its value is gradually reduced as the search proceeds. The time varying inertial weight is given by:

$$w = (w_{max} - w_{min}) \times \frac{(iter_{max} - iter_{min})}{iter_{max}} \quad (14)$$

where  $max\ iter$  is the maximum number of iterations. Constant  $c_1$  pulls the particles towards local best position whereas  $c_2$  pulls it towards the global best position.

**4.2 Improved PSO:** The basic PSO searches in the solution space by the guidelines of the  $P_{best}$  and  $G_{best}$ . as the new particles take new positions that are based on the  $P_{best}$  and  $G_{best}$ , there may be solutions that are not visited. This increases the probability of PSO to trap into local minima. Instead of adjusting the velocities of all particles by the standard equation of PSO, some particles are given randomly generated velocities [19]. These particles are called crazy particles. The particles that are to be given random velocity are selected randomly. A proper balance is maintained between exploration (global search) and exploitation (local search) and random search.

Then velocities of particles are randomized as per the following logic:

$$V_j^k = \begin{cases} rand(0, V_{max}); & \text{if } p_{cr} \geq rand(0,1) \\ V_j^k, & \text{otherwise} \end{cases} \quad (15)$$

**4.3 IPSO applied to reactive reserve management:** IPSO algorithm involves the steps shown below in reactive power generation control.

**Step 1:** Form an initial generation of NP particles in a random manner respecting the limits of search space. Each candidate is a vector of all control variables, i.e.  $[V_g, T_k, Q_{svc}]$ . There are 6  $V_g$ 's, 4  $T_k$ 's and 2  $Q_{svc}$  in the IEEE-30 system and hence a candidate is a vector of size  $1 \times 12$ .

**Step 2:** Calculate the fitness function (objective function) values of all candidate solutions 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 reactive power generation corresponding to different candidates are calculated.

**Step 3:** Identify  $P_{best}$  of all particles. Compare the fitness values of a particle in all the iterations until the current iteration.  $P_{best}$  of a particle is the best solution the particle ever visited. Determine the  $G_{best}$  by comparing the  $P_{best}$ 's of all particles in the current iteration.

**Step 4:** Update the velocity and position of each particle by the standard equations. Select some particles for assigning random velocities.

**Step 5:** Repeat steps 2-4 until stopping criteria has not been achieved.

### V. NUMERICAL RESULTS AND DISCUSSIONS

The proposed IPSO algorithm based method for reactive power reserve management is tested on the standard IEEE-30 bus test system [20]. The algorithm is coded in MATLAB 7.6 language tool. The test system has the following parameters.

Table 1. System parameters

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

There are six generator buses, four tap changer transformers and two SVCs in the test system. These 12 control variables are found to be suitable for reactive power reserve management. The upper and lower limits of these parameters are given in table 2.

Table 2. Range of control parameters

Parameters	Quantity	Range
Generator bus voltage( $V_g$ )	6	0.9-1.1(p.u.)
Transformer tap setting( $T_{ij}$ )	4	0.9-1.1(p.u.)
SVC setting	2	2-30 (MVAR)
Total control variables		12

The IPSO algorithm based optimization approach is with few parameters. In most of the population based algorithms their performance is greatly affected by the parameter values. Therefore tuning of the parameters is necessary and it is not very easy. IPSO being with only one parameter is easy for implementation

and produces better results. The algorithm converges when number of individuals is taken as 30 and run for 200 iterations. The optimal parameter values of the algorithm are shown in table 3.

Table 3. IPSO parameter values

Sl. No	Parameter	Optimal value
1	No of individuals ( $NP$ )	30
2	Self accelerating constant ( $c_1$ )	1.2
3	Global accelerating constant ( $c_2$ )	1.2
4	Inertia constant ( $w$ )	Linearly decreasing

The optimal values of control parameters that minimizes the total reactive power generation are as shown in table 4. The proposed algorithm adjusted the control parameter values within the limits. PSO algorithm suggests additional 44.4416 MVAR of reactive power support from SVCs. The IPSO recommends a reduced level of reactive power support by SVCs and it is 42.7959 MVAR. This alone reserves 1.6457 MVAR of reactive power.

Table 4. Optimal values for control parameters

Sl. no	Parameter	Initial value	PSO	IPSO
1	$V_{g1}$	1.05	1.0369	1.0478
2	$V_{g2}$	1.04	1.0282	1.0479
3	$V_{g5}$	1.01	1.0062	1.0170
4	$V_{g8}$	1.01	1.0221	1.0400
5	$V_{g11}$	1.05	1.0356	0.9755
6	$V_{g13}$	1.05	1.0299	1.0341
7	$T_{6-9}$	0.978	0.9918	1.0352
8	$T_{6-10}$	0.969	1.0078	0.9789
9	$T_{4-12}$	0.932	0.9855	0.9862
10	$T_{28-27}$	0.968	1.0197	1.0716
11	$Q_{SVC10}$	19	23.6268	26.1354
12	$Q_{SVC24}$	4.3	20.8148	16.6605

Reactive power generation minimization offers other benefits like real power loss minimization. Table 5 compares the performance of IPSO with that of basic PSO. IPSO performs better than PSO in reactive power generation and loss minimization.

Table 5. Benefits of reactive power generation optimization

Reactive power generation		Real power losses	
PSO	IPSO	PSO	IPSO
102.711	102.075	5.468	5.454

Voltage magnitudes of generator buses are varied for achieving the goal without violating its limits. Voltage profile of the system buses are maintained at about 1.0 p.u. Figure 1 depicts the voltage profile of the test system that most of the bus voltages are in the acceptable range of 0.95 p.u. to 1.05 p.u.

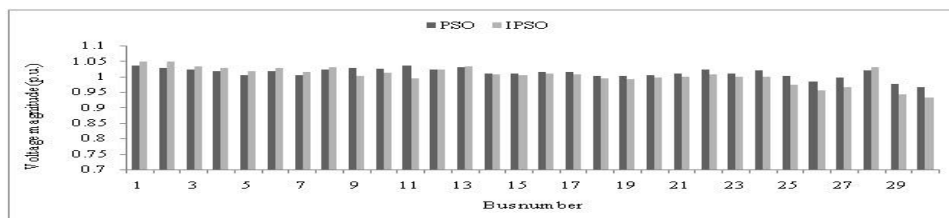


Figure 1. Voltage profile of the IEEE-30 bus system

## VI. CONCLUSIONS

This work proposes an efficient method to improve stability and reliability of a power system. Optimized reactive power generation ensures better utilization of the available var sources and reactive power reserve. This delays the need for the installation of additional var sources in the near future. The numerical results show that this method minimizes the total reactive power generation considerably and leaves the system

with sufficient reactive capability. The improved version of PSO algorithm overcomes the drawback of trapping into local minima and produces improved results. This enhanced version of PSO can be an optimization tool for many other power system optimization tasks as well. When a power system has sufficient reactive power capability, the increased reactive power demand during faults can be easily met and voltage instability can be avoided. Optimization of reactive power also minimizes the real power loss and hence increases the economy of power system operation.

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