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Preventive Corrective Rescheduling for Reactive Power Reserve Maximization using Generation Participation Factors

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Abstract: This paper presents an evolutionary-based approach for preventive control of load bus voltage. Developed algorithm optimizes a set of reactive power control variables and maximizes reactive reserve available at generating buses. Voltage dependent reactive power limits have been accounted. The optimal settings of reactive power control variables have been obtained for next interval predicted loading condition. These optimized settings satisfy the operating inequality constraints in predicted load condition as well as in present base case loading conditions. Differential evolutionary algorithm is a simple population-based search algorithm for global optimization and has a minimum number of control parameters. A population based differential evolutionary (DE) strategy has been used for optimization. Obtained results using DE have been compared with those obtained using another population based techniques PSO and CAPSO.
Keywords: Reactive power reserve, generation participation factor, differential evolutionary algorithm, static voltage stability limit.

1. Introduction:

The problem of reactive power optimization has played an important role in optimal operation of power system. The adjustment methods of reactive power flow consist of the adjustments of generator voltages, transformer taps, shunt capacitors and inductors. Since the generator voltages are continuous, the transformer ratios and shunt capacitors and inductors are discrete. Reactive power optimization (RPO) has complex and non-linear characteristics with large number of inequality constraints. Conventional optimization techniques, such as linear programming and nonlinear programming take advantages in computing speed and convergence with the objective function of continuous, differentiable and single peak value[1]. Yet conventional methods cannot handle the discrete–continuous problem in reactive power optimization. Recently, computational intelligence-based techniques have been proposed in the application of reactive power optimization such as genetic algorithm (GA), Tabu search, simulated annealing, particle swarm optimization (PSO) and differential evolution (DE). These are considered practical and powerful solution schemes to obtain the global or quasi-global optimum solution to engineering optimization problems. At times such schemes are termed as heuristic optimization techniques[2]. Differential evolution algorithm can obtain high-quality solutions within short calculation time and have stable convergence performance. Wu et al[3] proposed optimal reactive power dispatch using an adaptive genetic algorithm. Varadarajan and Swarup[4] proposed differential evolution algorithm for optimal reactive power dispatch. Zhang et al[5] have presented dynamic multi-group self-adaptive differential evolution algorithm for reactive power optimization. The problem was a mixed-integer, non-linear optimization problem with inequality constraints. Availability of reactive power at sources and network transfer capability are two important aspects, which should be considered while rescheduling of reactive power control variables. Nedwick et al[6] have presented a reactive management program for a practical power system. They have discussed a planning goal of supplying system reactive demand by installation of adequately sized and adequately located capacitor banks which will permit the generating unit near to unity power factor. Dong et al[7] developed an optimized reactive reserve management scheme using Bender's decomposition technique. Yang et al[8] presented a technique for reactive power planning based on chance constrained programming accounting uncertain factors. Generator outputs and load demands modeled as specified probability distribution. Monte-Carlo simulation along with genetic algorithm has been used for solving the optimization problem. Wu et al[9] described an OPF based approach for assessing the minimal reactive power support for generators in deregulated power systems. HE et al[10] proposed a method to optimize reactive power flow (ORPF) with respects to multiple objectives while maintaining voltage security. Zhang et al[11] developed a computational method for reactive power market clearing. Reactive power reserve available at a source is an important and necessary requirement for maintaining a desired level of voltage stability margin. Power network may have the transfer capability of reactive power but if reserve is not available and reactive power limit violation occurs than the static voltage stability limit may be inadequate. Further reactive reserves available at sources will not be of much help in maintaining desired level of stability margin, if network transfer capability is limited. This paper proposes a methodology for voltage stability enhancement accounting network loading constraint as well as optimizing reactive power reserves at various sources in proportion to their participation factors decided based on incremental load model. Voltage dependent reactive power model has been used for determining reactive power reserves, which utilizes field heating as well as armature heating limit[12]. Inequality constraints in base case as well as for next predicted interval loading condition have been considered in anticipation. Section-2 explains problem formulation. Section-3 presents implementation of the developed algorithm for optimizing objective function. Section-4 gives results and discussions. Section-5 gives conclusions and highlights of the paper.

2. Problem formulation

2.1 Mathematical formulation

The reactive reserve optimization problem is formulated as a search problem whose objective is to maximize the effective reactive reserve subject to various operating and stability constraints[12,13]. Objective function is given as follows:

$$J = \sum_{k} p_{gk} (\overline{Q}_{gk} - Q_{gk}) \tag{1}$$

Above objective function is optimized subject to following constraints:

(i) Power flow constraints under current operating condition as well as next predicted loading condition, accounting reactive power rescheduling:

$$\begin{aligned} \underline{P} &= \underline{f}(\underline{V}, \text{¢}) \\ \underline{Q} &= \underline{g}(\underline{V}, \text{¢}) \end{aligned} \tag{2}$$

(ii) Inequality constraint on load bus voltages in present as well as for next predicted interval load that is load bus voltages are within limit, accounting reactive power rescheduling:

$$\begin{aligned} &\underline{V}_i \le V_i^o \le \overline{V}_i \\ &\underline{V}_i \le V_i^p \le \overline{V}_i \\ &i \in NL \end{aligned} \tag{3}$$

V_i^o - i^{th} load bus voltage under base case loading condition. $\underline{V}_i$, $\overline{V}_i$ - Lower an upper bound on i^{th} load bus voltage V_i^p - i^{th} load bus voltage for predicted next interval loading condition.

(iii) Inequality constraint on minimum eigen value of load flow Jacobian at current operating point as well as next predicted load condition accounting reactive power rescheduling:

$$\text{a}^{o}_{\min} \geq \text{a}^{th}_{\min}$$
$$\text{a}^{p}_{\min} \geq \text{a}^{th}_{\min} \qquad (4)$$

(iv) Reactive power generation constraint under base case condition as well as at next predicted loading condition accounting reactive power rescheduling:

$$\underline{Q}_{gk} \leq Q^{o}_{gk} \leq \overline{Q}_{gk}$$
$$\underline{Q}_{gk} \leq Q^{p}_{gk} \leq \overline{Q}_{gk} \qquad (5)$$
$$k = 1,2,\ldots, NG$$

$\underline{Q}_{gk}$, $\overline{Q}_{gk}$ -Lower an upper bound on reactive power generation at k^{th} bus.

Q^{p}_{gk} - Reactive power generation at k^{th} bus for predicted next interval load.

Q^{o}_{gk} - Reactive power generation at k^{th} bus under base case loading condition

It is stressed here that $\overline{Q}_{gk}$ is voltage dependent. It is further clarified that $\underline{Q}_{gk}$ based on minimum rotor current limiter, the purpose of which is to avoid very small rotor current (these may cause problem for excitation systems) are of interest for synchronous compensators not for synchronous generators.

(v) Inequality constraint on control variables:

$$\underline{X}_{i} \leq X_{i} \leq \overline{X}_{i} \qquad (6)$$
$$i \in NC$$

NL and NC denotes set of load buses and number of control variables.

In objective function relation (1), Q_{gk} denotes reactive power generates at k^{th} generator bus and p_{gk} is the generator participation factor for k^{th} generator bus.

2.2 Determination of generator participation factor:

p_{gk} is generation participation factor which is obtained at next predicted load as follows:

(i) Obtain minimum eigen value and corresponding eigen vector of reduced load flow Jacobian. The reduced load flow Jacobian is obtained as follows:

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \text{¢} \\ \Delta V \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta Q \end{bmatrix}$$

$$J_1 \Delta \text{¢} + J_2 \Delta V = 0$$

$$\Delta \text{¢} = -J_1^{-1} J_2 \Delta V \qquad (7)$$

$$[J_4 - J_3 J_1^{-1} J_2][\Delta V] = [\Delta Q]$$

$$J_R = J_4 - J_3 J_1^{-1} J_2 \qquad (8)$$

Minimum eigen value of J_R and associated eigen vector $¶_i$ are obtained then put [12].

$\Delta Q = [¶_i]$ Obtain $\Delta V = ¶_i / ª_i$

$\Delta ¢$ is calculated as: $\Delta ¢ = -J_1^{-1} J_2 \Delta V = -(J_1^{-1} J_2 ¶_i) / ª_i$

Calculate

$V = V + \Delta V$ and $¢ = ¢ + \Delta ¢$

Calculate reactive power injection changes at the generator buses $\Delta Q_{g,k}$.Obtain generation participation factor p_{gk} as follows:

$$p_{gk} = \Delta Q_{gk} /(\max_{p} \Delta Q_{g,p}) \tag{9}$$

3. Implementation of differential evolutionary algorithm to solve formulated problem:

Step-1: Data input; Reactive power control variables and system parameters (resistance, reactance, and susceptance etc.)

Step-2: Base case load flow solution is obtained.

Step-3: Next interval predicted load.

Step-4: Load flow for the predicted next interval load.

Step-5: Initialization; Generate population of size 'M' for control variables $[X_1^0, X_2^0, ..., X_M^0]$ from uniform distribution between $X_{ij(\min)} < X_{ij} < X_{ij(\max)}$, $j = 1,2,..., NC$

Step-6: Run load flow for each sampled vector $X_i = 1,2,..., M$.

Step-7: If a vector satisfies all inequality constraints in base case condition as well as in next predicted interval call it 'F' (feasible) otherwise call it 'NF' (not- feasible).

Step-8: Select target vector $i = 1$.

Step-9: Select base vector X_{base} which is feasible and gives the best value of objective function using Eq. (1).

Step-10: Select two vectors X_p and X_q such that $base \neq i \neq p \neq q$

Step-11: Obtain a mutated vector $\underline{V}_i^{(k)}$

$$\underline{V}_i^{(k)} = X_{base}^{(k)} + \sim (X_p^{(k)} - X_q^{(k)})$$

$\sim$ - is known as scale factor usually lies in the range [0, 1]. $X_p^{(k)}$ and $X_q^{(k)}$ - are two randomly selected vectors. $X_{base}^{(k)}$ - is known as base vector. $\underline{V}_i^{(k)}$ - is a mutant vector.

Step-12: Generate trial vector $\underline{t}_i^{(k)}$

$$t_{i,j}^{(k)} = \begin{cases} v_{i,j}^{(k)}, if \ (rand_j \leq C_r or . j = j_{rand}) \\ x_{i,j}^{(k)}, Otherwise \end{cases}$$

Crossover probability (C_r) lies in the range [0, 1].

Step-13: If any components of the trial vector crosses the boundary then apply bounce back technique used. Thus it is assumed that all components of trial vectors are within limit.

Step-14: The trial vector $t_i^{(k)}$ is selected in the new population according to Lampinen's criteria[14].

4. Results & Discussions

The developed algorithm has been implemented on 6-bus IEEE standard test systems.

6-Bus System

This system consists of two generator buses and four load buses. This system has in all six reactive power control variables namely two generator bus voltages, shunt compensations at buses 4th and 6th and OLTCs at line number 4th and 7th. Maximum internal voltages and synchronous reactances were assumed as $E_{\max 1} = 2.20\,pu$, $E_{\max 2} = 2.05\,pu$, $X_{d1} = 1.00\,pu$ and $X_{d2} = 1.15\,pu$. The limits of PV-bus voltages, shunt compensations and OLTCs have been assumed as $0.95\,pu$ to $1.15\,pu$, $0.00\,pu$ to $0.055\,pu$ and 0.90 to 1.10 respectively. Reactive power limits (lower and upper) of generating bus 1, lying between $-0.0500\,pu$ to $2.0000\,pu$ and generating bus 2 are lying between $-0.0500\,pu$ to $1.0000\,pu$ [15]. Total base case real and reactive power load on the system are $1.3973\,pu$ and $0.3312\,pu$ respectively. Value of proximity indicator at base case condition is $\alpha_{\min} = 0.4572$ and objective function $J = 1.0432$. The static voltage stability limit is $2.2071\,pu$. Table 1 shows PV- bus voltage and all other load bus voltages under base case condition. The desired range of load bus voltage is $0.95\,pu$ and $1.05\,pu$. Threshold value of proximity indicator has been assumed as $\alpha_{\min,th} = 0.6400$. Initially, 100 populations of each control variable have been generated randomly using Excel software according distribution characteristic of control variable. Only five particles (control variables) were selected which satisfied all inequality constraints. Fig. 1 gives a plot between reactive power control variables $(V_1, V_2, Bsh_4, Bsh_6, Tap_4, Tap_7)$ satisfying all inequality constraints and objective function (J). Fig. 2 shows variation of objective function (J) with respect to number of iteration of a selected sample which has $\sim = 0.50$ and $c_r = 0.60$. After 157 iterations no variation is found in objective function (J). Table 2 gives optimized set of control variables and all load bus voltages. Total reactive reserve available is $2.4177\,pu$. Static voltage stability limit has been obtained as $2.3573\,pu$. Best initial solution (particle) selected as $V_1 = 1.0936\,pu$, $V_2 = 1.0881\,pu$, $B_{SH4} = 0.0021\,pu$, $B_{SH6} = 0.0017\,pu$, $TAP_4 = 0.9350\,pu$ and $TAP_7 = 1.0631\,pu$. Reactive reserves at bus No. 1 and 2 with best initial solution were $1.4325\,pu$ and $0.8515\,pu$ respectively. Whereas, with optimized solution these reactive reserves are obtained as $1.5095\,pu$ and $0.9082\,pu$ respectively. Magnitude of proximity indicator with optimized solution is $\alpha = 0.6400$, objective function is $J = 1.4785$. Table 3 shows the comparison of differential evolutionary with PSO & CAPSO methods based on proximity indicator, stability limits and reactive reserves.

Table-1 Load flow solution for 6-bus test system under stressed condition.

Total load $(P_d) = 1.4360\,pu$, **Proximity indicator** $(\alpha_{\min}) = 0.4572$

Static voltage stability limit. = $2.2071\,pu$

S. No	Control variables	Control variables magnitude(pu)	Load bus voltages	Load bus voltage magnitude(pu)
1	V1	1.0936	V3	0.8523*
2	V2	1.0738	V4	0.9654
3	BSH4	0.0021	V5	0.9397*
4	BSH6	0.0017	V6	0.9051*
5	TAP4	0.9350		
6	TAP7	1.0631		

*** - Load bus voltage level below the specified limit**

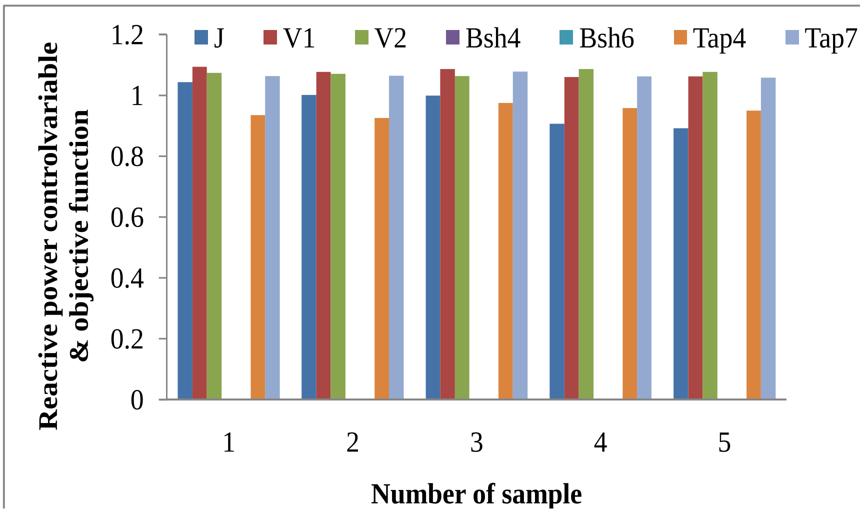

Figure 1 Initial population of particles (reactive power control variables) which satisfy all specified inequality constraints for 6-bus test system.

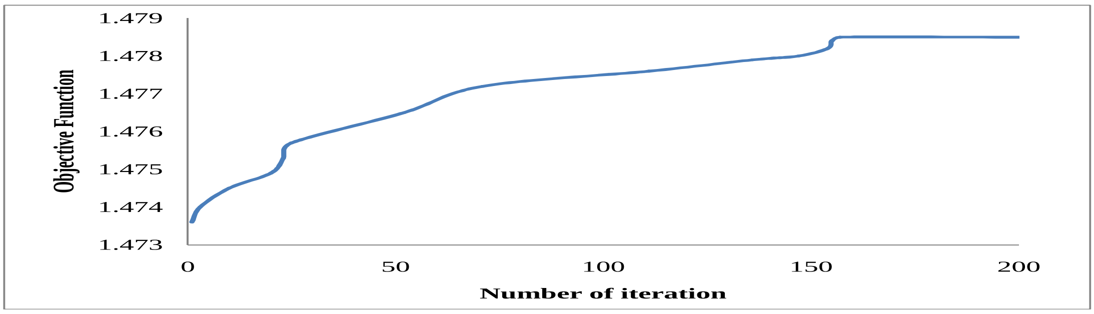

Figure 2 Plot of objective function (J) with respect to number of iterations for 6-bus system.

Table-2 Optimized set of control variables and all load bus voltages for 6-bus system.

Total load $P_d = 1.4360\,pu$ **, Proximity indicator** $a_{\min} = 0.6463$

S. No	Control variables	Control variables Magnitudes (pu)	Load bus voltages	Load bus voltages Magnitudes (pu)
1	V1	1.0878	V3	0.9502
2	V2	1.0680	V4	0.9708
3	BSH4	0.0532	V5	0.9500
4	BSH6	0.0494	V6	0.9500
5	TAP4	0.9486		
6	TAP7	0.9969		

Table-3 Comparison of Differential Evolutionary method with PSO & CAPSO methods for 6-bus test system.

S. No.	Methodology	Proximity Indicator		Stability Limit (pu)		Objective Function (J)		No of Iteration	Reactive reserve (pu)	
		Base case	Optimi-zed	Base case	Optimi-zed	Base case	Optimi-zed		Base case	Optimi-zed
1	PSO	0.4572	0.6444	2.2071	2.2892	1.0432	1.4868	22	2.2840	2.3933
2	CAPSO	0.4572	0.6459	2.2071	2.3034	1.0432	1.4845	29	2.2840	2.3977
3	DE	0.4572	0.6463	2.2071	2.3573	1.0432	1.4785	57	2.2840	2.4177

6. Conclusion

This paper has presented an algorithm for maximization of reactive power reserves in order to maintain voltage profile for the next predicted loading condition. This has been achieved via a DE algorithm. Advantage of DE algorithm is that its mechanization is simple without much mathematical complexity. Moreover global optimal solution is obtained and local optimal solution is avoided via bounce back search procedure. Important about the methodology is that not only reactive reserve is optimized but inequality constraint on proximity indicator provides required static voltage stability margin. Network as well as source capabilities are important from voltage instability viewpoint. Result and performance of the DE based algorithm have been compared with other two population based on PSO and CAPSO.

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