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Anticipatory reactive power reserve maximization using differential evolution

L.D. Arya [a], Pushpendra Singh [b], L.S. Titare [c,*]

[a] Department of Electrical Engg., SGSITS, 23-Park Road, Indore, MP 452 003, India
[b] Department of Electrical Engg., VITS, Satna, MP 452 003, India
[c] Department of Electrical Engg., Govt. Engineering College, Jabalpur, MP 482 010, India

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ABSTRACT

This paper presents an algorithm for anticipatory control of load bus voltages. The 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. A population based differential evolution strategy has been used for optimization. Results obtained have been compared with those obtained using another population based technique known as PSO.

1. Introduction

The problem of reactive power optimization has played an important role in optimal operation of power system. Reactive power optimization (RPO) has complex and non-linear characteristics with large number of inequality constraints. Conventional optimization techniques, such as linear programming and non-linear programming, take in 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. Yoshida et al. [4] suggested a modified PSO to control reactive power flow and alleviating voltage limit violations. Zhang and Liu [5] proposed a modified PSO algorithm to deal with multi-objective reactive power optimization. Varadarajan and Swarup [6] proposed differential evolution algorithm for optimal reactive power dispatch. Zhang et al. [7] 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. [8] 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. Vaahedi et al. [9] developed a hierarchical optimization scheme, which optimized a set of control variables such that the solution satisfied a specified voltage stability margin. Menezes et al. [10] introduced a methodology for rescheduling reactive power generation of plants and synchronous condenser for maintaining desired level of stability margin. Dong et al. [11] developed an optimized reactive reserve management scheme using Bender's decomposition technique. Yang et al. [12] 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. [13] described an OPF based approach for assessing the minimal reactive power support for generators in deregulated power systems. He et al. [14] proposed a method to optimize reactive power flow (ORPF) with respect to

* Corresponding author.
E-mail addresses: ldarya@rediffmail.com (L.D. Arya), erpsingh@rediffmail.com (P. Singh), lstitare@yahoo.co.in (L.S. Titare).

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Nomenclature

$\overline{Q}_{gk}$	maximum reactive power output of the *k*th generator	V_i^k	mutated vector at *k*th generation
$Q_{gk,(res)}$	reactive power reserve of the *k*th generator	$k_{\max}$	maximum generations specified (DE)
V_g	generator bus voltage	α	scale factor [0,1]
$\overline{E}$	maximum internal voltage of generator	X_i^k	solution vector at *k*th generation
X_d	synchronous reactance of generator	j_{rand}	random integer between [1,*D*]
$\bar{I}_{gk}$	maximum armature current of *k*th generator	D	number of decision variables
X_i	reactive power control variable	C_r	crossover rate
V	load bus voltage vector	$\underline{x}_j$ and $\bar{x}_j$	lower and upper bound on x_j
δ	voltage phase angle vector	X_i^K	position of *i*th particle
NC	total number of control variables	ρ_i^K	velocity of *i*th particle
NL	total number of load buses	w^K	Inertia weight
NG	total number of generator buses	$w_{\max}$ and $w_{\min}$	maximum and minimum values of inertia weight
$\lambda_{\min}$	minimum eigenvalue of load flow Jacobian	AF_{ij}	achievement factor
P_{gk}	generation participation factor	c_1, c_2	acceleration coefficients
J	objective function	$NIT, NIT_{\max}$	current and maximum number of iteration specified respectively
$rand_j$	random digit between [0,1]	$P^K_{best(i)}$	best position of *i*th particle
X^k_{base}	base vector	G^K_{best}	position of the best individual of the whole swarm
t_i^k	trial vector		

multiple objectives while maintaining voltage security. Zhang et al. [15] 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. Inequality constraints in base case as well as for next predicted interval loading condition have been considered in anticipation. Section 2 gives mathematical modeling. Section 3 presents an overview of DE technique. Section 4 presents implementation of the algorithm for optimizing reactive reserves. Section 5 gives results and discussions. Section-6 gives conclusions and highlights of the paper.

2. Mathematical modeling

2.1. Reactive power reserve determination

The voltage stability enhancement problem is formulated as an optimal search problem whose objective is twofold (i) maximize the reactive reserves based on the participation of reactive sources for increased loading condition and (ii) maintaining the desired stability margin with respect to current operating point. The reactive power reserve is the ability of the generators to support bus voltages under increased load or disturbance condition. Amount of reactive power, which can be fed to network, depends on present operating condition, location of the source, field and armature heating of the alternators. Availability of reactive power reserve of a generator is calculated using capability curves. For a given real power output the reactive power generation is limited by both armature and field heating limit [16]. Maximum reactive power output with respect to field current limit is expressed as:

$$\overline{Q}_{gk} = -(V_{gk}^2/X_d) + \sqrt{((V_{gk}^2 \cdot \overline{E}^2)/X_d^2) - P_{gk}^2} \tag{1}$$

Maximum reactive power output $\overline{Q}_{gk}$ of the generator is determined by internal maximum voltage $\overline{E}$ corresponding to the maximum field current. Thus, maximum reactive power output depends not only on real power output P_{gk} but also on terminal voltage V_{gk}. Maximum reactive power output due to armature current limitation is as follows:

$$\overline{Q}_{gk} = \sqrt{V_{gk}^2 \cdot \bar{I}_{gk}^2 - P_{gk}^2} \tag{2}$$

$\bar{I}_{gk}$ is maximum armature current of the generator. The reactive power reserve of the *k*th generator is then represented as:

$$\overline{Q}_{gk,(res)} = \overline{Q}_{gk} - Q_{gk} \tag{3}$$

where, $\overline{Q}_{gk}$ is the smaller of the two values obtained from Eq. (1) and (2). Reactive reserve is calculated using relation (3), if Q_{gk} is less than $\overline{Q}_{gk}$. However, if Q_{gk} reaches its limit the reactive reserve is set to zero. The bus is treated as variable voltage and internal voltage of the generator behind synchronous reactance is assumed constant. This way voltage dependent reactive power limits have been accounted in a realistic way. In such situation 'Q_{gk}' moves on the capability curve governed by Eq. (1) and (2). Hence, if 'Q_{gk}' reaches the boundary, the reactive reserve is set to zero and then 'Q_{gk}' varies as a function of terminal (bus) voltage. Such modeling (voltage dependent reactive power limit) has been adopted by many researchers [17,18].

2.2. Problem 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. Objective function is given as follows:

$$J = \sum_k p_{gk}(\overline{Q}_{gk} - Q_{gk}) \tag{4}$$

Above objective function is optimized subject to following constraints:

(i) Power flow equations: