Swarm and Evolutionary Computation 6 (2012) 25–38

Contents lists available at SciVerse ScienceDirect

Swarm and Evolutionary Computation

journal homepage: www.elsevier.com/locate/swevo

Regular Paper

Optimum load shedding based on sensitivity to enhance static voltage stability using DE

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ARTICLE INFO

Article history:
Received 14 July 2011
Received in revised form
1 June 2012
Accepted 1 June 2012
Available online 16 June 2012

Keywords:
Schur's inequality
Sensitivity
Load shedding
Differential Evolution
Voltage stability

ABSTRACT

This paper proposes a methodology to optimize the load curtailments necessary to restore the equilibrium of operating point by accounting for operating and stability inequality constraints. To get desired stability margin Schur's inequality based proximity indicator has been selected whose threshold value along with minimization of load shedding assures desired static voltage stability margin. The methodology anticipates the risk of voltage instability in a time frame using sensitivity of proximity indicator of load flow Jacobian with respect to load. If the normal controls are exhausted, the proposed algorithm based on sensitivity, sheds, required amount of low priority loads in advance. This makes the system to survive voltage instability threat even during worst system period. The buses which are having large sensitivity are selected for load shedding. A computational algorithm for minimum load shedding at selected load buses has been developed using Differential Evolution (DE), Self-adaptive Differential Evolution (SaDE) and Ensemble of Mutation and Crossover Strategies and Parameters in Differential Evolution (EPSDE). Developed algorithm accounts inequality constraints not only in present operating conditions (after load shedding) but also for predicted next interval load (with load shedding). Proposed methodology has been implemented on IEEE 14-bus and 25-bus test systems. Performance of the methodology has been compared with Davidon–Fletcher–Powell's (DFP), Particle Swarm Optimization (PSO), Co-ordinated Aggregation based Particle Swarm Optimization (CAPSO) and Genetic Algorithm (GA) techniques based on statistical inference. Simulation results have been obtained which confirm that the proposed methodology provide considerable mitigation in the load shedding and enhancement in voltage stability. By using this methodology various power system blackouts can be prevented.

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1. Introduction

When an extended period of reduced generation is anticipated, generation limits may be forecasted for the entire period. During this emergency, system operators have to decide in a very short time which load circuits are to be shed when overloading occurs either due to increased demand or circuit restoration, so that power balance can be achieved and the nominal value of frequency and voltage can be regained. Well planned preventive actions are required for this purpose. Load shedding is initialized as last line of defense. Load shedding is a coordinated set of controls which results in decrease of the electric load in the system [1]. It is one of the possible corrective actions aimed at forcing perturbed system to a new stable equilibrium state. Load-shed criterion may be based on some proximity indicator whose magnitude indirectly reflects the stability margin and provides information for initialization of load shedding. Under such situations the magnitude of the indicator may be monitored during normal operating conditions and when it falls below a threshold value an alarm is actuated. If the indicator continues to decline and reaches to another lower value, load-shed is to be initiated. Such situations may arise due to (i) sudden loss of generation/increase in load which may result in decrease in frequency, (ii) outage of one or more transmission line thus reducing network loadability and may cause load bus limit violations and (iii) overloading of transmission line. In view of this load shedding may be adopted based on (i) under-frequency consideration, (ii) overload alleviation of transmission lines and (iii) voltage limit violation/voltage stability consideration. Tuan et al. [2] presented viable load shedding algorithm based on indicators of risk for voltage instability, based on sensitivities of these indicators to

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http://dx.doi.org/10.1016/j.swevo.2012.06.002

Nomenclature

J	objective function
τ	Schur's inequality based proximity indicator of load flow Jacobian
λ_{min}	minimum eigen value of load flow Jacobian
J'	load flow Jacobian
NL	number of load buses
ls_i	total load (real and reactive power) shedding at ith load bus
NLS	number of load buses selected for load shedding
τ_{th}	threshold value of proximity indicator of load flow Jacobian
τ_o	proximity indicator of load flow Jacobian under current operating condition accounting load shed
τ_p	proximity indicator of load flow Jacobian under predicted load condition accounting load shed
$\underline{P}_{gk}, \underline{Q}_{gk}$	lower bound on active and reactive power generation at kth bus
$\overline{P}_{gk}, \overline{Q}_{gk}$	upper bound on active and reactive power generation at kth bus
P^o_{gk}, Q^o_{gk}	active and reactive power generation at kth bus under current operating condition accounting load shed
P^p_{gk}, Q^p_{gk}	active and reactive power generation at kth bus under predicted load condition accounting load shed
NG	total number of generator buses
V^o_i	load bus voltage at ith load bus under current operating condition accounting load shed
V^p_i	load bus voltage at ith load bus under predicted load condition accounting load shed
$\underline{V}_i, \overline{V}_i$	lower and upper bound on ith load bus voltage
σ	standard deviation
μ	mean

changes in load to be shed. Balanathan et al. [3] presented a technique for practically calculating the shedding necessary to assure the power system voltage stability following a disturbance. A computational method is based on the Monte Carlo simulation approach [4,5] can be used for comparing and selecting the most appropriate load shedding strategies. Wiszniewski [6] presented a methodology which gives new criteria of voltage stability margin for the purpose of load shedding. Girgis and Mathure [7] presented a methodology that shows the rate of change of frequency can be utilized to determine the magnitude of generation–load imbalance, while the rate of change of voltage with respect to active power can be utilized to identify the sensitive bus for load shedding. Fu and Wang [8] presented an algorithm which was developed for studying the load shedding problem in emergencies, where an ac power flow solution cannot be found for the stressed system. Amraee et al. [9] proposed an adaptive undervoltage load shedding scheme using model predictive control to protect power system against voltage instability. A specified outage from a set of multiple contingencies was modeled with a homotopy function including a parameter representing the outage. Outage-continuation power flow traces the path of solutions satisfying the power-flow equations with respect to variations of the parameters. At the nose point, it performs a sensitivity analysis with a normal vector to identify the most effective control variables. With the sensitivity information, location of load shedding is determined; then, an adequate amount of control is decided by applying a searching method [10]. In this paper a new algorithm has been developed for optimum load shedding based on voltage stability consideration. Schur's inequality has been used as proximity indicator. A threshold value of this indicator can be assumed for a specific system. During emergency load shedding is required, if the value of proximity indicator falls below the threshold value. The value of Schur's inequality proximity indicator is very small or close to zero at collapse point. The proposed algorithm consists of two parts, one of it identifies load buses for load shedding using sensitivity of proximity indicator with respect to real and reactive load, the other determines the optimum load to be shed at selected load buses using Differential Evolution and improved DE variants (SaDE and EPSDE) subject to operating and stability constraints. Results have been obtained using proposed methodology are compared with PSO, CAPSO, DFP and GA. Section 2 presents sensitivity derivation of proximity indicator with respect to load shedding at load buses. Section 3 presents problem formulation. Section 4 presents an overview of DE technique, bounce back technique and handling of inequality constraints. Section 5 presents implementation of the developed algorithm (DE, SaDE and EPSDE) for optimizing objective function. Section 6 gives results and discussions. Section 7 presents conclusions and highlights of the paper.

2. Sensitivity derivation of proximity indicator with respect to load shedding at load buses

Schur's inequality is given as follows [11]:

$$\lambda_{max} \leq \sqrt{\sum_{ij} a_{ij}^2} \tag{1}$$

where, a_{ij}—ijth element of load flow Jacobian $[J']$; λ_{max}—greatest eigen value of load flow Jacobian.

Magnitude of greatest eigen value is less than or equal to square root of sum of square of each element of the matrix. Eq. (1) is used to derive lower bound on the minimum eigen value of load flow Jacobian. Sensitivity matrix $[S]$ is given as follows:

$$[S] = [J']^{-1} \tag{2}$$

Now using inequality (1) upper bound on maximum eigen value of $[S]$ is given as follows:

$$S\lambda_{max} \leq \sqrt{\sum_{ij} s_{ij}^2} \tag{3}$$

where, $S\lambda_{max}$ denotes maximum eigen value of $[S]$; and s_{ij} is its element. It is known from matrix theory that:

$$J'\lambda_{min} = 1/(S\lambda_{max}) \tag{4}$$

where, $J'\lambda_{min}$ is the minimum eigen value of load flow Jacobian. Using Eq. (4), inequality Eq. (3) can be written as:

$$J'\lambda_{min} \geq 1/\left(\sqrt{\sum_{ij} s_{ij}^2}\right) = \tau \tag{5}$$

where, $J'\lambda_{min}$ is the minimum eigen value of load flow Jacobian.

In fact, right hand side of Eq. (5) is lower bound on the minimum eigen value of load flow Jacobian and defined as a proximity indicator (τ). Magnitude of this proximity indicator reflects the distance to voltage collapse from the current operating point and has been used for voltage stability monitoring.

It is assumed that load flow Jacobian at current operating point is known. If one of the disturbance variable (active and reactive

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