Energy Conversion and Management 59 (2012) 66–73

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Optimal reactive power dispatch for improving voltage stability margin using a local voltage stability index

Abbas Rabiee [a,*], Maziar Vanouni [b], Mostafa Parniani [a]

[a] Center of Excellence in Power System Control and Management, Department of Electrical Engineering, Sharif University of Technology, P.O. Box 11155-9363, Tehran, Iran
[b] Department of Electrical and Computer Engineering and FREEDM System Center, North Carolina State University, Raleigh, NC, USA

ARTICLE INFO

Article history:
Received 4 October 2009
Received in revised form 10 January 2012
Accepted 1 February 2012
Available online 30 March 2012

Keywords:
Optimal power flow (OPF)
Optimal reactive dispatch (ORD)
Voltage stability index
Voltage stability margin (VSM)

ABSTRACT

Management of reactive power resources is vital for stable and secure operation of power systems in the view point of voltage stability. This paper deals with the management of on-load tap changers (OLTCs) and dynamic VAR sources (including synchronous generators, synchronous condensers, and shunt reactive power compensators) to improve voltage stability margin (VSM) of power systems. This problem is usually called optimal reactive power dispatch (ORD) in the literature. The main contribution of the paper is to introduce a new objective function for the ORD problem. The proposed objective function is derived based on a local voltage stability index, called DSY, and has a strong correlation with VSM. This strong correlation makes the objective function effective for improving VSM, which is the main purpose of ORD. The proposed objective function is tested on the New England 39-bus test system and its performance is compared with some of the most common objective functions used in ORD. The obtained results show that solving ORD problem using the proposed objective function yields considerable increase in VSM.

1. Introduction

Nowadays, power systems operate closer to their voltage stability limit due to existing trend toward market operation and heavier loadings of power systems, together with environmental restrictions for generation and transmission capacity expansion. Therefore, voltage stability is one of the main concerns of modern power systems. Voltage stability refers to the ability of a power system to maintain voltage such that when the load demand is increased, the load power also increases and both power and voltage are controllable [1]. Studies concerning this type of instability phenomenon deal with its evaluation and control. The former determines whether or not a power system operates in the safe operational region, while the latter takes necessary control actions in the case a power system approaches to/operates in unsafe operational region. Various methods have been proposed in the literature to deal with both lines of study for online and offline applications [2–4]. The focus of this paper is the second line of study, which is voltage stability control.

Three main techniques have been used for voltage instability mitigation that are reactive power management, active power redispatch, and load shedding. Reactive power management refers to the methods determining the location of new VAR sources and/or settings of the currently installed VAR sources and the settings of facilities such as on-load tap changers (OLTCs). Reactive sources generally include synchronous generators, synchronous condensers, capacitor/reactor banks, and flexible AC transmission systems (FACTS) controllers. Reactive power management is classified to reactive source planning (allocation) and reactive power dispatch. For reactive planning, the time period of concern is the next few months or years, and in addition to contemplating the optimal setting of currently installed facilities, installing new reactive sources is considered. Reactive power dispatch is carried out in online and offline manners. Offline reactive dispatch aims at the period of the next few days or weeks, whereas, online reactive dispatch is performed within the next few minutes or hours. Contrary to the reactive planning, both online and offline reactive power dispatches merely determine the optimal settings of existing facilities [5]. This paper focuses on offline reactive power dispatch.

The problem in hand, i.e. ORD, is stated as an optimization problem with an objective function and some predefined constraints. Various objective functions have been presented in the literature. The most common objective function is active power loss, [6–8]. However, minimizing active power loss does not necessarily result in increasing voltage stability margin (VSM), depending on the network topology, loading and generation level [9]. Many previous works treat ORD as a multi-objective optimization problem (MOOP) and solve it using weighted sum approach [10–14]. For example,

* Corresponding author. Tel.: +98 2166165973; fax: +98 2166023261.
E-mail addresses: a_rabiee@ee.sharif.edu (A. Rabiee), mvanoun@ncsu.edu (M. Vanouni), parniani@sharif.edu (M. Parniani).

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doi:10.1016/j.enconman.2012.02.017

Nomenclature

PQ	set of PQ buses
G	set of buses connected to synchronous generators and synchronous condensers
L	set of load buses (PQ buses with non-zero power consumption)
Sl	slack bus
C	set of buses equipped with shunt reactive power compensators
$N\tau$	set of OLTCs
P_{G_j}	active power generation at the jth bus
P_{L_j}	active power consumption at the jth bus
Q_{C_j}	reactive power injected by reactive power compensator at the jth bus
Q_{L_j}	reactive power consumption at the j-th bus
$Y_j \quad j \in PQ$	load admittance magnitude at the jth bus
$S_j \quad j \in PQ$	load apparent power at the jth bus
$V_j \quad j \in PQ$	voltage magnitude at the jth bus
$\underline{V}$	vector of voltage magnitude at PQ buses
$\underline{\Theta}$	vector of voltage phase angle at all buses except the slack bus
$\underline{V_G}$	vector of voltage magnitude at generator buses
$\underline{\tau}$	vector of on-load tap changers' settings
$\underline{Q_C}$	vector of reactive power injected by reactive power compensators
y_{jh}	magnitude of the jhth element of network admittance matrix
φ_{jh}	angle of the jhth element of network admittance matrix
LF_ℓ	transmission line flow at line ℓ
$LF_l^{\max}$	maximum transmission flow at the line ℓ
$\underline{V_G^{\max}}/\underline{V_G^{\min}}$	vector of upper/lower limit of voltage magnitude at generator buses
$\underline{V^{\max}}/\underline{V^{\min}}$	vector of upper/lower limit of voltage magnitude at PQ bus
$\underline{Q_G^{\max}}/\underline{Q_G^{\min}}$	vector of upper/lower limit of generators reactive power
$\underline{Q_C^{\max}}/\underline{Q_C^{\min}}$	vector of upper/lower limit of reactive power injected by reactive power compensators
$\underline{\tau^{\max}}/\underline{\tau^{\min}}$	vector of upper/lower limit of on-load tap changers' settings

Ref. [10] suggests the weighted sum of active power loss, voltage deviation at load busses, and reactive power generation deviation at generator buses as the objective function. Ref. [11] considers the same objective function except that reactive power deviation of generators is substituted with the minimum singular value of the load flow jacobian matrix. In [12,13], active power loss and minimum singular value of the load flow jacobian matrix are mixed linearly so that the former is minimized and the latter is maximized. In [14], weighted sum of active power loss and reactive reserve of generating units is proposed as the desired objective function. The main problem with MOOPs is that certain Pareto-optimal solutions may not be achieved in the case of a non-convex objective space [15]. Even, if it is assured that the mentioned problem does not exist, determining the weighting factors that satisfy the desired VSM is itself a complicated problem, and in most cases the weighting factors should be determined by trial and error. That is because of the fact that a uniformly distributed set of weight vectors does not necessarily yield a uniformly distributed set of Pareto-optimal solutions and this mapping is usually unknown. In [16], the weighted sum of generators reactive reserve is minimized to improve VSM. The weighting coefficients are derived based on the concept of active participation factors [17,18]. The main drawbacks of the method are as follows. Firstly, it does not include the slack bus generator in the problem. Therefore, the reactive power of slack bus generator is not used efficiently. Secondly, the minimum singular value of the jacobian matrix and the corresponding left and right vectors are to be calculated in each iteration, resulting in high computational burden. Thirdly, the performance of the method depends on the selected values of the weighting factors used to make the weighting coefficients [19]. In [19], a similar method is introduced and the weighting coefficients of generators reactive reserves are derived based on a modal analysis method introduced in [20]. It eliminates the first drawback of the previous method and utilizes the reactive power of all generators including the slack bus generator. However, it still suffers from the other two drawbacks. Some references include VSM directly as an objective function or a constraint in ORD. Despite the effectiveness of these methods, they consider at least two sets of equality and inequality constraints describing the system operation at base case and limit operating points [21–24]. This approach, however, yields very high dimensionality, especially in large scale power systems with many constraints to be incorporated.

To overcome the aforementioned shortcomings, this paper introduces a new objective function for ORD problem and the corresponding solution algorithm. The objective function is derived based on a voltage stability index called DSY [25]. The main advantage of the proposed objective function is that, contrary to the generators reactive reserve and active power loss, it is directly correlated with VSM, making it effective for improving VSM. The performance of the proposed objective function is examined on the New-England 39-Bus test system and compared with that of active power loss and weighted sum of generators reactive reserves presented in [16]. This paper considers the settings of synchronous generators and synchronous condensers terminal voltages, OLTCs and shunt reactive power compensators as the control variables participating in the ORD.

The rest of the paper is organized as follows: Section 2 provides a brief review of the employed voltage stability index, DSY, followed by detailed mathematical formulation of the proposed objective function, and the corresponding ORD problem. The simulation results are given in Section 3, and finally, concluding remarks are presented in Section 4.

2. Proposed methodology

2.1. Review of DSY index

Ref. [25] introduces a new voltage stability index using scalar local measurements to estimate closeness of an operating point to the nose points of P–V curves. The index is derived based on the fact that at the nose point, the change of load apparent power magnitude is zero in spite of voltage and current variations. This index, called DSY, is defined as follows,

$$DSY_k = \frac{1}{(V_k)^2} \times \frac{\Delta S_k}{\Delta Y_k} \quad k \in L \tag{1}$$

The subscript k refers to the bus number. The range of the index value is as follows.