Electrical Power and Energy Systems 43 (2012) 20–28

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

A coordinated voltage/reactive power control method for multi-TSO power systems

Anan Zhang [a,*], Hongwei Li [a], Fan Liu [b], Honggeng Yang [c]

[a] School of Electrical Engineering and Information, Southwest Petroleum University, Chengdu 610500, People's Republic of China
[b] Sichuan Electrical Power Research Institute, Chengdu 610000, People's Republic of China
[c] School of Electrical Engineering and Information, Sichuan University, Chengdu 610065, People's Republic of China

ARTICLE INFO

Article history:
Received 10 August 2011
Received in revised form 3 January 2012
Accepted 29 April 2012
Available online 17 June 2012

Keywords:
Voltage control
Reactive power control
Coordinated control
Active and reactive power decoupled network equations
Multi-Objective Evolutionary Algorithm

ABSTRACT

Multi area power systems work most often with a poor inter-regional coordination about reactive power concerns. Poor coordinated operation may not achieve significant improvements in the quality and efficiency of power system operation, and may even increase the risk of blackout for multi-TSO (Transmission System Operators) power systems. This paper focused on the voltage/reactive power coordinated control. Voltage/reactive power interactions between interconnected power networks were derived from the augmented active and reactive power decoupled network equations. According to distribution computing concept, a novel voltage/reactive power control model was presented in this paper, which could optimize the active power losses of both local network and its interconnected areas. And the model's data communication was simple: only an equivalent susceptance matrix and the optimal reactive power injection value for external network need be communicated irregularly. Moreover, this model could avoid raising confidentiality issues because it need not exchange explicit structure and constraints information between different TSOs. Efficacy of the proposed model was illustrated through simulations on two IEEE systems and an application to an actual system.

1. Introduction

Several large-scale disturbances emphasized that secure operation of interconnected power systems requires coordination between transmission system operators (TSOs). In particular, articles [1–3] report several major disturbances whose consequences were leveraged by the lack of coordination between the TSOs. To address the problem of coordination in multi-TSO systems, a great deal of effort has been devoted [4–22]. On one hand, the emergence of some Mega voltage/reactive power control center resulted from the aggregation of several smaller ones. For example, the hierarchical voltage control systems named Coordinated Voltage Regulation (CVR) or Secondary and Tertiary Voltage Regulations (SVR and TVR), depending on their hierarchical level, have been studied in Italy [4,5], France [6,7], Belgium [8,9], Spain [10,11], South Africa [12] and China [13–15]. And some studies about voltage/reactive power coordinated control with distributed generators are based on the similar method also, e.g. [16]. Those methods are characterized as hierarchical systems based on Pilot Nodes and control subdivision, but, to some extent, are applicable expedients. On the other hand, where the consolidation of control areas has not occurred, new strategies to coordinate the actions of those entities have been studied and implemented. Li and Venkatasubramanian outline in [17] a scheme for coordinating path transfers to increase transfer capability. Marinakis et al. present a solution in [18] which requires each TSO gets the information of entire system to coordinate reactive power control by arriving at the Nash equilibrium of a sequence of optimizations. In article [19] Marek Zima et al. analyze the behaviors of uncoordinated control centers and highlight the fact that they may lead to different, sometimes counterintuitive, collective dynamics. Also, Ilic et al. emphasize in [20] the danger that decentralized optimization may have on power system security when conflicting local strategies result in a reduction of each TSO's own performance criterion. Phulpin and Begovic analyze in [21] the problem of decentralized optimization for a power system partitioned into several areas controlled by different TSOs, based on the external equivalents of PV, PQ, REI and Thévenin-Like Equivalent, and find out that decentralized control scheme can converge to nearly optimal global performance for relatively simple equivalents and simple procedures for fitting their parameters. And Phulpin also highlights a fair method [22] based on cost functions for centralized optimization of multi-TSO power systems, which is typical in multi-TSO coordinated voltage/reactive power control.

As, whether for hierarchical (centralized) control systems or for distributed control systems, it is impossible and unnecessary to depend on only one control center to accomplish voltage/reactive power control for a large-scale network, coordination between the operations of different TSOs or control centers is necessary. This paper presents a simple coordinated control model for inter-

* Corresponding author.
E-mail address: ananzhang@swpu.edu.cn (A. Zhang).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.04.046

connected power systems. The study focused on deriving some interactive laws of voltage/reactive power control within a multi-TSO framework, and on establishing a multi-objective optimization model aiming at minimizing the active power loss both in the local TSO area and in the interconnected ones. Considering voltage/reactive power control is coupled with angle/active power weakly, we augmented fast decoupled load flow equations [23] by including PV buses and derived the interactive laws of multi-TSO voltage/reactive power control. According to these laws, each TSO could evaluative the effect of its operations on the interconnected areas, and minimized the active power loss both in local area and in the interconnected zones by a Pareto-solution based multi-objective algorithm.

The paper is organized as follow. In the next section (Section 2), the derivation concerning interactive effect in a multi-TSO framework is obtained. In Section 3, the method of Optimal Matching Injected Flow (OMIF) [24] is introduced to solve the optimal reactive power injection in the interface between different TSOs. In Section 4, a multi-objective optimization model is established and the reason why to choose a Pareto-solution based algorithm is presented; moreover, the model's data exchange load is compared with several typical decentralized control schemes. Section 5 reports the comparison outcomes between the proposed model and three typical methods published in voltage/reactive power control, and test systems are IEEE 14 nodes based system and IEEE 118 nodes system. The performance of the model in an actual system is outlined in Section 6. Finally, some conclusions are drawn in Section 7. And Appendices A and B present the relevant information about the OMIF method and the AeMOEA used in this paper respectively.

2. Interactive laws of reactive power control for multi-tso

Let us consider a two-area power system, shown in Fig. 1, where AREA A and AREA B were controlled by different TSOs (or voltage/reactive power control centers). The areas were connected through a series of transmission lines, and i, j and e, h denoted the number of start nodes and end nodes, i.e. boundary nodes, of these lines respectively.

According to the fast decoupled load flow [23], the $\Delta \boldsymbol{Q} - \Delta \boldsymbol{V}$ equations of the interconnected power systems can be described as following:

$$-\boldsymbol{B}\Delta\boldsymbol{V} = \Delta\boldsymbol{Q} \tag{1}$$

where $\Delta\boldsymbol{Q}$, $\Delta\boldsymbol{V}$ are difference vectors of all nodes' reactive power and voltage, excluding PV nodes; and $\boldsymbol{B}$ is the susceptance matrix of the network. We augmented (1) by including all PV nodes. And, for each area, its nodes could be divided into two categories: one was the inner nodes which were disconnected from other areas, and the other was boundary nodes which were interface nodes between two areas. For the system shown in Fig. 1, we denoted the inner nodes of AREA A and AREA B by $\mathbf{A}^d$ and $\mathbf{B}^d$ respectively, and denoted the boundary nodes by $\mathbf{A}^b$ and $\mathbf{B}^b$. Then (1) could be expanded and rearranged to (2), where, for facilitating analysis, all inner nodes were arrayed at the top of matrix while boundary nodes were at the bottom of matrix.

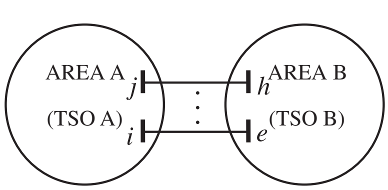

Fig. 1. Illustration of interconnected power systems.

$$-\begin{bmatrix} \boldsymbol{B}_{A^d} & & \boldsymbol{B}_{A^{db}} & \\ & \boldsymbol{B}_{B^d} & & \boldsymbol{B}_{B^{db}} \\ \boldsymbol{B}_{A^{bd}} & & \boldsymbol{B}_{A^b} & \boldsymbol{B}_{A^bB^b} \\ & \boldsymbol{B}_{B^{bd}} & \boldsymbol{B}_{B^bA^b} & \boldsymbol{B}_{B^b} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{V}_{A^d} \\ \Delta\boldsymbol{V}_{B^d} \\ \Delta\boldsymbol{V}_{A^b} \\ \Delta\boldsymbol{V}_{B^b} \end{bmatrix} = \begin{bmatrix} \Delta\boldsymbol{Q}_{A^d} \\ \Delta\boldsymbol{Q}_{B^d} \\ \Delta\boldsymbol{Q}_{A^b} \\ \Delta\boldsymbol{Q}_{B^b} \end{bmatrix} \tag{2}$$

Assuming that the voltage or reactive power of AREA A need be regulated for some reasons, for example load fluctuation, and the reactive power of AREA B need not to be adjusted, we could obtain, approximately, $\Delta\mathbf{Q}_A \neq 0$ and $\Delta\mathbf{Q}_B \approx 0$. Therefore, we got

$$-\begin{bmatrix} \boldsymbol{B}_{A^d} & & \boldsymbol{B}_{A^{db}} & \\ & \boldsymbol{B}_{B^d} & & \boldsymbol{B}_{B^{db}} \\ \boldsymbol{B}_{A^{bd}} & & \boldsymbol{B}_{A^b} & \boldsymbol{B}_{A^bB^b} \\ & \boldsymbol{B}_{B^{bd}} & \boldsymbol{B}_{B^bA^b} & \boldsymbol{B}_{B^b} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{V}_{A^d} \\ \Delta\boldsymbol{V}_{B^d} \\ \Delta\boldsymbol{V}_{A^b} \\ \Delta\boldsymbol{V}_{B^b} \end{bmatrix} = \begin{bmatrix} \Delta\boldsymbol{Q}_{A^d} \\ 0 \\ \Delta\boldsymbol{Q}_{A^b} \\ 0 \end{bmatrix} \tag{3}$$

We eliminated the inner nodes of AREA B by premultiplying the $\Delta\mathbf{V}_{B^d}$ equations by $-\boldsymbol{B}_{B^{bd}}(\boldsymbol{B}_{B^d}^{-1})$ and added the resulting equations to the $\Delta\mathbf{V}_{B^b}$ equations, and following equations could be obtained,

$$-\begin{bmatrix} \boldsymbol{B}_{A^d} & \boldsymbol{B}_{A^{db}} & \\ \boldsymbol{B}_{A^{bd}} & \boldsymbol{B}_{A^b} & \boldsymbol{B}_{A^bB^b} \\ & \boldsymbol{B}_{B^bA^b} & \widetilde{\boldsymbol{B}}_{B^b} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{V}_{A^d} \\ \Delta\boldsymbol{V}_{A^b} \\ \Delta\boldsymbol{V}_{B^b} \end{bmatrix} = \begin{bmatrix} \Delta\boldsymbol{Q}_{A^d} \\ \Delta\boldsymbol{Q}_{A^b} \\ 0 \end{bmatrix} \tag{4}$$

where

$$\widetilde{\boldsymbol{B}}_{B^b} = \boldsymbol{B}_{B^b} - \boldsymbol{B}_{B^{bd}}\left(\boldsymbol{B}_{B^d}^{-1}\right)\boldsymbol{B}_{B^{db}} \tag{5}$$

In a similar way, we could eliminate the inner nodes of AREA A and got

$$-\begin{bmatrix} \widetilde{\boldsymbol{B}}_{A^b} & \boldsymbol{B}_{A^bB^b} \\ \boldsymbol{B}_{B^bA^b} & \widetilde{\boldsymbol{B}}_{B^b} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{V}_{A^b} \\ \Delta\boldsymbol{V}_{B^b} \end{bmatrix} = \begin{bmatrix} \Delta\widetilde{\boldsymbol{Q}}_{A^b} \\ 0 \end{bmatrix} \tag{6}$$

where

$$\widetilde{\boldsymbol{B}}_{A^b} = \boldsymbol{B}_{A^b} - \boldsymbol{B}_{A^{bd}}\left(\boldsymbol{B}_{A^d}^{-1}\right)\boldsymbol{B}_{A^{db}} \tag{7}$$

$$\Delta\widetilde{\boldsymbol{Q}}_{A^b} = \Delta\boldsymbol{Q}_{A^b} - \boldsymbol{B}_{A^{bd}}\left(\boldsymbol{B}_{A^d}^{-1}\right)\Delta\boldsymbol{Q}_{A^d} \tag{8}$$

Basically, (6) indicated the influence on the boundary nodes of both AREA A and AREA B when the reactive power distribution in AREA A changed. However, we should notice that different relationship between AREA A and AREA B would lead to different solutions. In general, there were two situations:

1. the power system of AREA B supplies power to AREA A, which means the system in AREA B is dominant;
2. the power systems of AREA A and AREA B are parallel, which means the power flow in the transmission lines between them could be bidirectional.

To the first situation, the boundary nodes are treated as slack node or PV nodes usually, which means their voltages are constant. Basically, the premise is true for the nodes of AREA B, because the effect of reactive power distribution of AREA A on the node voltage of AREA B is weak. However, for AREA A, it is not the case. Because there are not real generators in boundary nodes of AREA A, the voltage in boundary nodes will change according to reactive power injection. We premultiplyed the $\Delta\boldsymbol{V}_{B^b}$ equations in (6) by $-B_{A^bB^b}(\widetilde{B}_{A^b})^{-1}$ and added the resulting equations to $\Delta\boldsymbol{V}_{A^b}$ equations. Then a new equation was obtained which eliminated the effect of node voltage in AREA B on the node voltage in AREA A as (9).

$$-\begin{bmatrix} \widetilde{\widetilde{\boldsymbol{B}}}_{A^b} & 0 \\ \boldsymbol{B}_{B^bA^b} & \widetilde{\boldsymbol{B}}_{B^b} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{V}_{A^b} \\ \Delta\boldsymbol{V}_{B^b} \end{bmatrix} = \begin{bmatrix} \Delta\widetilde{\boldsymbol{Q}}_{A^b} \\ 0 \end{bmatrix} \tag{9}$$

where