Electrical Power and Energy Systems 53 (2013) 540–547

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Two-level optimal load–frequency control for multi-area power systems

Mehdi Rahmani [a], Nasser Sadati [a,b,*]

[a] Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran
[b] Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, BC, Canada

ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 2 May 2013
Accepted 3 May 2013

Keywords:
Load–frequency control
Optimal control
Interconnected power systems
Hierarchical structures
Decentralized control

ABSTRACT

In large-scale power systems, classical centralized control approaches may fail due to geographically distribution of information and decentralized controllers result in sub-optimal solution for load–frequency control (LFC) problems. In this paper, a two-level structure is presented to obtain optimal solution for LFC problems and also reduce the computational complexity of centralized controllers. In this approach, an interconnected multi-area power system is decomposed into several sub-systems (areas) at the first-level. Then an optimization problem in each area is solved separately, with respect to its local information and interaction signals coming from other areas. At the second-level, by updating the interaction signals and using an iterative procedure, the local controllers will converge to the overall optimal solution. By parallel solving of areas, the computational time of the algorithm is reduced in contrast to centralized controllers. This approach is applicable to any interconnected large-scale power system. However, for simulation purposes, a three-are power system is presented to show advantages and optimality of the proposed algorithm.

1. Introduction

1.1. Literature review

The control of real power output of generating units, in response to changes in system frequency and tie-line power interchange within specified limits, is known as load frequency control (LFC) [1] and is considered in this paper. During past three decades, different types of controllers are applied to LFC. In early 1970 Fosha and Elgerd in their pioneering work applied classical optimal control methodology to solve LFC problems [2]. Many aspects of their approach were also studied by others [3–6]. In these studies, centralized controllers have been obtained using large number of equations which had to be solved simultaneously for optimization purposes. Of course this was time consuming and costly, especially in power systems which are large-scale by nature and the concept of centrality may fail. In expense of losing optimality, capability of decomposing multi-area power systems into a number of sub-systems, and obtaining parallel solution, favored decentralized control schemes in solving LFC problems. Davison and Tripathi defined necessary conditions for existence of decentralized controllers for LFC problems. Their approach was based on a parameter optimization algorithm [7]. In [8], Park and Lee presented a near optimum solution based on singular perturbation theory. In [9], Malik et al. proposed a decentralized algorithm based on minimum error excitation using all areas information. Feliachi in [10] also presented a decentralized control scheme determined by a fixed mode evaluation algorithm based on eigenvalue dynamics. In [11], Yazdizadeh et al. proposed a decentralized MISO PID controller and in [12], Tan and co-workers used IMC based decentralized PID controllers for LFC problems.

In recent years, other control strategies, such as linear matrix inequalities [13], adaptive gain scheduling [14,15], evolutionary algorithms, e.g. HPSO algorithms [16], fuzzy controllers [17,18], learning-based intelligent control [19], artificial Bee colony algorithms [20], robust analysis of decentralized LFC [21], and hierarchical optimal robust control [22], were also applied to load–frequency control problems.

It is remarkable that for most large scale power systems, the centralization assumption does not hold due to the geographical distribution of the information. This implies that the concept of centrality may fail by nature and there is no centralized solution. Moreover, all decentralized control schemes lead to sub-optimal solution for large scale optimization problems.

1.2. Hierarchical structures

Large-scale systems can be described as complex systems composed of a number of constituents or smaller sub-systems serving particular functions, shared resources and governed by interrelated goals and constraints. Although interactions among sub-systems can take many forms, one of the most common is hierarchical,

* Corresponding author at: Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. Tel.: +98 2166164365.
E-mail addresses: sadati@sharif.edu, sadati@ece.ubc.ca (N. Sadati).

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.05.020

which appears somewhat natural in power systems. Multi-level or hierarchical structures are feasible structures that reduce complexity of large-scale systems and considerably improve the solution through decomposition, coordination and parallel processing [23,24]. Its various levels exchange information iteratively until the overall feasible optimal solution is obtained through coordination of the sub-systems solutions.

In this paper, a two-level hierarchical control strategy is used to solve the optimal LFC problem. At the first-level, the overall problem is decomposed into several sub-systems, where the optimization problem is redefined for each one of them. Under a two-level control strategy, each local controller at the first level receives a set of coordination parameters from the second-level (coordinator) to solve its own optimization problem and then to send back some function of its solution to the coordinator. The coordinator mainly evaluates the next update of the coordination parameters and continue to exchange the new updates with the local controllers at the first level, so that the overall optimum solution is achieved iteratively.

Two main coordination principles, namely "interaction prediction principle" and "interaction balance principle", for "model coordination" and "goal coordination" of large-scale systems were proposed by Mesarovic et al. [25]. The classical gradient-type coordination approach of Mesarovic et al. [25], and the substitution type algorithms of Hassan and Singh [26] and the costate prediction method of Magdi et al. [27], were pioneering works and most effective algorithms among all. However, the speed of convergence of the coordination parameters and convergence region of these algorithms, due to strategy taken and the initial selection of coordination parameters, were the main issues to present new gradient-type coordination strategies by Sadati [28–30], to mainly improve most aforementioned problems.

For linear systems with quadratic cost function, Takahara [31] proposed an interaction prediction method and obtained a closed-form solution for optimal control of large-scale systems. The approach converges with a simple substitution-type coordination algorithm.

1.3. Contribution and paper organization

In this paper, a new two-level control strategy is presented to obtain an optimal solution for LFC problems in large-scale power systems. In this approach, using decomposition/coordination framework of large-scale hierarchical systems, the overall power system is first decomposed into several sub-systems (areas), at the first-level. Then by using a coordinator, at the second-level, the interaction signals are updated so that the local solutions at the first level converge to the feasible optimal centralized solution, by means of a multi-level iterative algorithm.

The remainder of this paper is organized as follows. In Section 2, the problem statement is discussed and decomposition of the overall problem into local sub-problems with regards to sub-systems (areas) is presented. The optimization problem for each area at first-level is considered in Section 3 and the second-level strategy (coordination) is discussed in Section 4. In Section 5, for a three-area power system, the simulation results are obtained and comparisons with centralized and decentralized control approaches are made. Finally, concluding remarks are given in Section 6.

2. Problem statement

Although power systems are non-linear in nature, but the use of linearized model is permissible for the load frequency control problem, because during the normal operation only small changes in load are expected [1].

Let us consider the following discrete-time linear multi-area power system

$$\underline{X}[k+1] = A\underline{X}[k] + B\underline{U}[k] \tag{1}$$

where $\underline{X}$ is $n \times 1$ state vector and $\underline{U}$ is $m \times 1$ input vector. A is $n \times n$ state matrix and B is $n \times m$ input matrix. The optimal control is to find $\underline{U}[k]$ in the interval $0 \leqslant k \leqslant N$ that minimizes a quadratic cost function given as

$$J = \frac{1}{2}\underline{X}^T[N+1]P\underline{X}[N+1] + \frac{1}{2}\sum_{k=0}^{N}[\underline{X}^T[k]Q\underline{X}[k] + \underline{U}^T[k]R\underline{U}[k]] \tag{2}$$

where R is a positive definite matrix and P and Q are positive semi-definite matrices, with appropriate dimensions.

2.1. Decomposition of the overall problem

For the purpose of decomposition, we consider the physical meaning of multi-area power plants. In these systems, each area works separately and different areas influence the performance of each other, through tie-line powers. Each area has been considered as sub-system and the tie-line power as interactions in the interaction prediction method used in this paper.

Assume that the centralized model (1) is decomposed into N_s sub-systems as follows

$$\underline{X}[k] = \left[x_1^T[k], \ldots, x_i^T[k], \ldots, x_{N_s}^T[k]\right]^T, \tag{3}$$

$$\underline{U}[k] = \left[u_1^T[k], \ldots, u_i^T[k], \ldots, u_{N_s}^T[k]\right]^T. \tag{4}$$

where N_s corresponds to the number of sub-systems (areas). Also x_i is the $n_i \times 1$ state vector and u_i is the $m_i \times 1$ input vector of the ith area, such that

$$\sum_{i=1}^{N_s} n_i = n, \quad \sum_{i=1}^{N_s} m_i = m \tag{5}$$

Then, the model of each area can be written as

$$x_i[k+1] = A_i x_i[k] + B_i u_i[k] + \sum_{\substack{j=1 \\ j\neq i}}^{N_s} C_{ij} x_j[k] \tag{6}$$

where $\sum_{j=1}^{N_s} C_{ij}x_j[k]$ is the interaction signals presenting the impact of the other areas on the ith one. This signal which models the interconnection of the multi-area power system is usually neglected or considered as a norm on interactions or even as disturbances in decentralized optimal control strategies, which lead to suboptimal solutions for the overall problem [9]. In contrast of solving LFC problems using decentralized approaches, the proposed two-level control strategy considers the interactions as part of sub-system's model in the optimization process to obtain the overall optimal solution.

For simplicity, let us define C_i and $z_i[k]$ as follows

$$\begin{aligned} C_i &= [C_{i1} \ldots C_{ij} \ldots C_{iN_s}], \quad j = 1, \ldots, N_s, \ j \neq i \\ z_i[k] &= \left[x_1^T[k], \ldots, x_j^T[k], \ldots, x_{N_s}^T[k]\right]^T \end{aligned} \tag{7}$$

Now, the ith area model (5) becomes

$$x_i[k+1] = A_i x_i[k] + B_i u_i[k] + C_i z_i[k] \tag{8}$$

Each sub-system's state space equation is a function of interaction signals (7) which are obtained with respect to other areas' states. If the jth area is not related to the ith one, then the corresponding matrix C_{ij} in C_i will be zero. In addition, we assume that the overall cost function is separable and can be written as follows