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Brief paper

A real-time control framework for smart power networks: Design methodology and stability☆

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ABSTRACT

Demand response is being actively considered as a useful mechanism for balancing supply and demand in the future power network. Relevant research to date has paid little attention to the interaction of this mechanism with the dynamics of the power network, focusing mainly on solving an appropriately formulated optimization problem. However, the coupling between the two should not be ignored due to fluctuations resulting from increased distributed energy resources and variability in both supply and demand. In this paper, we present a distributed control architecture that implements real-time economic optimization for the power network under exogenous disturbances. In particular, we consider a transmission level network with tree topology. Motivated by optimization decomposition methods, we first formulate a constrained Optimal Power Flow (OPF) problem and then use a primal–dual decomposition approach to design a dynamic feedback controller. We prove the asymptotic stability of the equilibria of the overall system. Numerical investigations illustrate that the proposed controller balances power flow in the network quickly, and achieves OPF in the steady state, even in the face of disturbances and contingencies.

1. Introduction

The future power network will need to operate reliably in the face of fluctuations resulting from distributed energy resources and variability in both supply and demand. One of the feedback mechanisms that have been identified for managing this uncertainty is demand response, i.e., a price-based mechanism that will encourage consumers to modify their demand when it is most difficult for the network to achieve a balance between supply and demand (Borenstein, Jaske, & Rosenfeld, 2002). Price-based mechanisms were first suggested by Fred Schweppe and his co-workers in the 1980s (Caramanis, Bohn, & Schweppe, 1982; Schweppe et al., 1980), and were extended and developed by researchers such as Hogan (Hogan, 1992) by introducing market and economic analysis and Alvarado (Alvarado, 1999; Alvarado, Meng, DeMarco, & Mota, 2001) by considering market stability. Nowadays, demand response is recognized as a potential mechanism for ensuring reliability in the face of fluctuations in the future grid.

Generally speaking, price-based control aims to solve the Optimal Power Flow (OPF) problem (Kirschen & Strbac, 2004), i.e., to minimize operating cost subject to practical constraints. There are several versions of OPF problems, depending on the type of constraints that are considered. The most general OPF, AC OPF, includes constraints relating to both real and reactive power flow and is nonlinear. However, solving an AC OPF problem directly is difficult: for this reason, a corresponding DC OPF problem is often used as an approximation (Kirschen & Strbac, 2004), which only considers real power. In fact, during the past decade, significant research has focused on DC OPF problems using price-based control. For example, Kiani and Annaswamy (2011) presented a dynamic model of the wholesale energy market, which incorporated the interaction between DC OPF and price-based control. In Roozbehani, Dahleh, and Mitter (2012), the authors proposed a mechanism for real-time retail pricing of electricity in a power network and investigated price stability. A common feature of most previous work is that it does not consider the dynamics of the power network itself in the analysis, but just focuses on solving the optimization problem, i.e., designing market dynamics. The assumption is that the

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power system dynamics evolve at a much faster time-scale than the market dynamics, which means that power system dynamics can be ignored when designing market dynamics. However, due to fluctuations resulting from increasing distributed energy resources and variability in both supply and demand, this time-scale separation is fading away and the power network is losing inertia. Thus, breaking the time-scale separation when designing price-based control becomes more and more necessary.

The problem of considering the coupling between the dynamics of the power network and the market has been considered in Alvarado et al. (2001). It was shown that the stability region of the coupled system was very different from that of the market-only system, and therefore that the feedback signal (market price) must be properly designed to maintain the stability of the interconnected system. Also, a novel control scheme to achieve DC OPF in power systems via nodal prices was presented in Jokic (2007), extending (Alvarado et al., 2001) to a more practical scenario. In Andreasson, Dimarogonas, Johansson, and Sandberg (2013), the authors proposed both a decentralized controller and a centralized controller for frequency regulation and generation cost minimization in power systems. In Li, Chen, Zhao, and Low (2014), the conventional Automatic Generation Control (AGC) was incorporated with OPF automatically and dynamically, providing an optimization view to modifying AGC. In Mallada and Low (2014), a frequency preserving optimal load control scheme was proposed, which was used to balance power and restore the nominal frequency after a disturbance. In Dörfler, Simpson-Porco, and Bullo (2014), decentralized and distributed primary, secondary, and tertiary control strategies in microgrids were studied, showing that the adoption of droop control was necessary and sufficient to achieve economic optimization in microgrids.

In this paper, motivated by price-based control, we propose a distributed control architecture to realize real-time economic optimization for the power network under exogenous disturbances. Unlike most previous work, the feedback signals in our control architecture are not prices from a centralized market but information and feedback signals flowing between neighbouring components in the system. Moreover, we consider nonlinear active power flow equations which are more practical than linear equations used in conventional DC OPF problems. In particular, we focus on a power network with tree topology to demonstrate how the design methodology and stability analysis can be performed. Compared with research in the literature, our work directly combines the dynamics of the power network with the solution of an appropriately formulated optimization problem. The proposed controller can asymptotically stabilize the power network to the equilibria which maximize system efficiency. It operates within the time-scale of seconds to minutes in a distributed manner. The design framework can be scaled to networks of large size and more complexity. This paper extends the work in our conference papers (Zhang & Papachristodoulou, 2013, 2014) significantly to a more practical scenario.

This paper is organized as follows: in Section 2, the complete problem description is presented, including the power network architecture and the stability constrained OPF problem for a tree network. In Section 3, we design a distributed dynamic feedback controller and show its scalable stability. In Section 4, we present numerical examples, illustrating the properties of the controller. Future work is presented in Section 5.

1.1. Notation

$x \in \mathbb{R}^n$ is a column vector where $\mathbb{R}^n$ is the n-dimensional Euclidean space, and $[x]_i$ denotes its ith entry. x^T denotes the transpose of x. $X \in \mathbb{R}^{m\times n}$ is an $m \times n$ real matrix. diag$\{\star\}$ is a diagonal matrix with corresponding entries $\star$ on the diagonal, and diag(x) is a diagonal matrix whose entries are the elements of a vector x. $\mathbf{1}_{m\times n}$ ($\mathbf{0}_{m\times n}$) denotes an m by n matrix whose entries are 1 (0) and I_m denotes an identity matrix of size $m \times m$. $x \succeq 0$ ($x \succ 0$) denotes that all components of a vector x are non-negative (positive). $X \succeq 0$ ($X \succ 0$) denotes that a square matrix X is positive semi-definite (positive definite). x^* denotes the equilibrium of a state variable/vector x. $(h(y))^+_x$ denotes the positive projection of a function $h(y)$ on a variable x where

$$(h(y))^+_x = \begin{cases} h(y) & \text{if } x > 0 \\ \max(0, h(y)) & \text{if } x = 0. \end{cases}$$

2. Problem setup

2.1. Network architecture

The current power network consists of a number of regions, divided by areas, energy source types, etc. Each region corresponds to a transmission level network which contains generators, loads, transmission lines and buses. Each load corresponds to a distribution level network which is an aggregation of a certain amount of users at the bus it is connected to. A user could be an industrial company, a street with a certain amount of buildings, or a combination of several users (industrial companies, houses, etc.). By introducing fictitious buses, we can change the topology of a given transmission level network so that each bus is connected to either a generator (we call such a bus a generator bus) or a load (we call such a bus a load bus) (Bergen & Hill, 1981).

In order to deal with the problems of low predictability and high uncertainty that the current power network is faced with, we consider a real-time control architecture with demand response. This means that loads are allowed to adjust their demand based on feedback signals (not prices from a centralized market), i.e., each user in the power network can respond to feedback from the network. In this approach, every transmission level network can run in a distributed way: each generator receives a feedback signal from the generator bus it is connected to, and adjusts its power generated based on that signal and local information. So does each user to the load bus it is connected to. Each bus calculates feedback signals based on local information and signals from transmission lines and buses it is connected to. The local information contains cost functions, utility functions, capacity constraints, local frequency and power imbalance. All feedback signals are transmitted through the communication system which lies in the network (over transmission lines, or through a wired Internet system). There is also information exchange between different regions. Fig. 1 shows the architecture.

In the rest of the paper, we study a transmission network with tree topology containing an arbitrary number of synchronous generators, loads and users (a 3-generator-3-load network with tree topology is illustrated in Fig. 2). Tree structures are important as: (i) they are sufficiently complicated to offer promising approaches to handle more complicated cases; (ii) the (AC) OPF problem in a tree can be convexified (Lavaei, Tse, & Zhang, 2012), which is the technical reason for giving priority to tree networks in this paper; (iii) if the use of phase shifters is allowed, the OPF problem for a mesh network can be simplified to one for a tree (Sojoudi & Lavaei, 2012).

2.2. System model

Consider an m-generator-n-load network with tree topology (the number of transmission lines is $m + n - 1$). We number the generator buses $1, \ldots, m$, the load buses $m + 1, \ldots, m + n$, and the transmission lines $1, \ldots, m + n - 1$ (corresponding to