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Decentralized control and fair load-shedding compensations to prevent cascading failures in a smart grid

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ABSTRACT

Evidence shows that a small number of line contingencies in power systems may cause a large-scale blackout due to the effects of cascading failures. With the development of new technologies and the growing number of heterogeneous participants, a modern/smart grid should be able to self-heal its internal disturbances by continually performing self-assessment to deter, detect, respond to and restore from unpredictable contingencies. Along this line, this research focuses on the problem of how to prevent the occurrence of cascading failures through load shedding by considering heterogeneous shedding costs of grid participants. A fair load-shedding algorithm is proposed to solve the problem in a decentralized manner, where a load-shedding participant need only monitor its own operational status and interact with its neighboring participants. Using an embedded feedback mechanism, the fair load-shedding algorithm can determine a marginal compensation price for each load-shedding participant in real time based on the proportional fairness criterion, without knowing the shedding costs of the participants. Such fairly determined compensations can help motivate loaders/generators to actively participate in the load shedding in the face of internal disturbances. Finally, the properties of the load-shedding algorithm are evaluated by carrying out an experimental study on the standard IEEE 30 bus system. The study will offer new insights into emergency planning and design improvement of self-healing smart grids.

Introduction

Historical data shows that power systems have suffered from series of internal and external disturbances leading to various degrees of blackouts due to the effect of cascading failures [13,25,11]. An unpredictable blackout may severely affect activities reliant on electricity, such as railway and air transportation, water supply and hospital services. For example, during the U.S.-Canada blackout of August 14, 2003, over 400 transmission lines and 531 generating units tripped and approximately 50 million people were affected [31]. According to the modern grid initiative conducted by the National Energy Technology Laboratory of the U.S. Department of Energy, many types of electrical generation (e.g., distributed energy resources), storage options [17], advanced metering infrastructure [12,21], as well as the active participation of consumers (e.g., demand-response programs), will in future be integrated to form a huge network of heterogeneous intelligent participants. This will introduce more rigorous reliability and security requirements due to the increasing interdependency and complexity of electric elements. In this context, this work is dedicated to tackling the problem of how to prevent the occurrence of cascading failures by taking into consideration autonomous behaviors and real-time interactions of heterogeneous participants in a smart grid.

Current reliability policies in power systems focus mainly on secure their normal operation under the most severe single or at most two contingencies, known as the $N-1$ and $N-2$ criteria. Many academic studies have been conducted to impose power balance by solving various contingency-constrained unit commitment problems in a centralized manner [20,30]. The results have shown that, to extend the policy to more tighter criteria (i.e., $N-k$ criteria, where $k>2$) becomes intractable due to the computational burden for the huge number of contingency states $\left(\text{i.e., } \sum_{i=1}^{k}\binom{N}{k}\right)$. Along this line, Street et al. [30] have proposed a computationally efficient framework using robust optimization, which does not depend on the size of the set of credible contingencies. However, in their work, the number of contingencies is required as prior knowledge. Recently, to avoid the computational burden, an inverse problem have been proposed, that is, to identify a small group of line contingencies that can trigger a blackout with a certain level of severity [26,10]. For example, Pinar et al. [26] have

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shown that such a problem can be approximately transferred to be a combinatorial network inhibition problem. Although the centralized optimization approaches adopted by above-mentioned studies are beneficial to analyze and improve system reliability, they are practically infeasible to control power flow in real time and handle multiple and simultaneous contingencies affecting several parts of a power system [27]. Therefore, it would be desirable to control power systems in a decentralized manner [33].

As Amin and Schewe [4] argued, a smart grid that automatically responds to emergencies could reduce the rising number of debilitating blackouts. The last few years have witnessed the development of new technologies, services and concepts to improve grid reliability and security in the face of system disturbances. Specifically, to facilitate the real-time monitoring and control of a grid, a series of advanced communication infrastructure, modern sensors, real-time simulation tools, as well as intelligent protection applications have been introduced. For example, advanced metering infrastructure, which is a means to facilitate two-way communications, will let utilities send real-time pricing signals to consumers and thus encourage consumers to implement direct control of demand-side management [12]. By doing so, a look-ahead simulation tool may send corrective instructions to control devices in less than half a second [4]. All these research and development efforts offer new opportunities for us to systematically design the "immune system" of a smart grid [21], where each individual participant continually performs self-assessments to deter, detect, respond to and restore grid components from unpredictable contingencies, and at the same time optimizing its performance in a decentralized manner [2,16].

Technically speaking, loads and generation in a smart grid must ultimately balance in real time to maintain stable. When line contingencies happen, the power flow will be redistributed to other lines based on the operational conditions of the system. Further, due to the physical capacity constraint of transmission lines, a small number of line contingencies may result in overload or failures in other lines. In this case, it would be necessary to shed some amount of loads and generation such that the power overload on other lines can be avoided. Specifically, this work aims to address two important issues to prevent the occurrence of cascading failures. The first and most important is to quickly shed a *minimum* amount of loads and generation to secure the grid after contingencies happen. This is because both under-shedding and over-shedding may cause unnecessary damages/costs for grid participants. The second is to make appropriate *compensations* for heterogeneous load-shedding participants. In current power systems, the compensations are usually determined by pre-signed contracts [32], which cannot reflect the real-time operational status of the system during the contingencies. As for the increasing number of active participants in a smart grid, it would be desirable to make compensation for individual participants by taking into consideration their heterogeneous shedding costs in real time. By doing so, if the compensations can cover the shedding costs for each individual participant, power loaders and generators will be motivated to participate in the autonomous load shedding process during line contingencies.

To mathematically formulate the above-mentioned two issues, this work first approximate the complex power flows in a smart grid using a dc model, i.e., the linearized active power flow model [14]. Then, the grid is modeled as a directed network, where each node represents a bus and each edge represents a transmission/distribution line. By doing so, the load-shedding problem is formulated as a network optimization problem for minimizing the total shed amount under the power flow constraints. Further, to fairly compensate load-shedding participants, the concept of load-shedding fairness is introduced based on the criterion of proportional fairness [29,23].

This work presents a fair load-shedding algorithm to solve the load-shedding problem in a decentralized manner. Based on the algorithm, each agent representing a loader/generator in a grid need only monitor the operational situations in their local areas and interact with their neighboring agents to coordinately determine the amount of loads/generation they should shed during line contingencies. From the perspective of grid security, there are two major steps in the algorithm: the first step aims to prevent the contingencies spreading to other lines by shedding a necessary amount of loads and generation, while the second step aims to recover as many shed loads/generation as possible to reduce the total amount of load shedding. From the perspective of load-shedding fairness, an embedded feedback mechanism is involved in the first step to facilitate communications among agents in terms of load-shedding compensations. Specifically, a focal loader (or generator) determines the total amount of compensations based on compensation requests from its downstream (or upstream) neighbors on the one hand, and adjust its request to its upstream (or downstream) neighbors on the other hand. During this process, the focal loader (or generator) does not need to know the exact cost functions of its downstream/upstream neighbors. By doing so, the marginal compensation prices for per unit of shed loads/generation can be collectively and fairly determined by all load-shedding participants.

The remainder of this paper is organized as follows. In Section 'Problem statement', we briefly introduce the dc power flow model and formally formulate the load-shedding problem by taking into consideration the load-shedding fairness. In Section 'A decentralized fair load-shedding algorithm', we present the decentralized fair load-shedding algorithm associated with an embedded feedback mechanism. In Section 'Experimental results and discussions', we validate and demonstrate the properties of the algorithm by carrying out experimental studies on the standard IEEE 30 bus system. Finally, we conclude this paper and list several issues that are worth to be further pursued in Section 'Conclusion and future work'.

Problem statement

In this section, we formally define the load-shedding problem in the face of line contingencies and present the issue of load-shedding fairness.

Active power flow model

A power system can be modeled as a directed network $G(V, E)$, where each node $v_i \in V$ represents a bus and each edge $e_{kl} \in E$ represents a transmission/distribution line from v_k to v_l. Similar to existing studies [10,26,8], this work focuses mainly on the active power flow in $G(V, E)$, which can be further simplified to be the dc power flow model $P_{kl} = -b_{kl}(\theta_k - \theta_l)$. Here, θ_k represents the phase angle variable at node v_k and b_{kl} represents the susceptance of e_{kl}.

To describe the power flow at the network level, we define an arc-node incidence matrix A of $G(V, E)$ with n nodes and m edges. The ith row represents the ith edge in $G(V, E)$ and the jth column represents the jth node v_j in $G(V, E)$. Specifically, each entry $a_{ij} \in A$ is defined as follows:

$$a_{ij} = \begin{cases} -1, & \text{if the } i\text{th edge is an out-edge from } v_j, \\ 1, & \text{if the } i\text{th edge is an in-edge to } v_j, \\ 0, & \text{otherwise}. \end{cases} \tag{1}$$

Denote D as a $n \times 1$ vector representing the power generation (i.e., $D_i > 0$) or loads (i.e., $D_i < 0$) on each node. Based on the property of flow conservation [19], for each node in $G(V, E)$, the power