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A sustainable risk-averse approach to power generation planning with disruption risk and social responsibility considerations

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ABSTRACT

Power expansion planning is one of the key challenges in power systems management, both in theory and application. Power generation significantly affects society and the environment in several ways, such as greenhouse gas emissions, air and noise pollution, hazardous waste, life-threatening issues and social expectations. These factors become more important in power systems facing hazards and disasters that may result in system disruptions. This paper considers generation expansion planning using a sustainable risk-averse approach that addresses both the socio-environmental factors and the disruption risks involved in a power system. The approach uses a mathematical formulation that can be linearized as a mixed-integer linear programming model. The approach is applied to the case of Iran's southwestern power grid. The computational results demonstrate the importance of incorporating disruption risks and sustainability issues into power systems planning.

1. Introduction

Energy supply has become one of the most challenging problems of the 21st century. Satisfying the growing demand for energy emphasizes the need to adopt new management policies that can assist in resolving this issue. However, the increasing consumption of fossil fuels such as coal, oil and natural gas as the main resources used in producing electricity is alarming. Moreover, price variations, greenhouse gas (GHG) emissions, air and noise pollution, water usage, hazardous waste, climate change and social impacts are other aspects that are involved in power generation. If we add to these the mixed uncontrollable situations such as natural and man-made disasters, we encounter a complex and multi-dimensional problem that reflects the changing reality of power systems management.

When considering the impacts of recent disasters, such as Hurricane Katrina in 2005, which caused oil spills from a number of facilities, the 2011 Tohoku earthquake, which led to the Fukushima Daiichi nuclear disaster, and Hurricane Sandy in 2012, which caused a widespread power outage, we get a better sense of the outcomes that such situations can cause. Unfortunately, natural disasters have become more frequent during the last decade (Guha-Sapir et al., 2013). According to the International Disaster Database (EM-DAT, 2014), the impact of natural disasters has intensified compared to past decades. Therefore, we need to be prepared for such incidents and to make decisions based on our understanding of their potential impacts.

In response to the above-mentioned sustainability concerns involved in resolving the problems of power systems management under disruption events, this paper intends to introduce a new sustainable approach to the design and planning of power generation networks. From this point of view, as will be seen later, a single-dimensional approach to managing these complex systems is not only inadequate, but can also lead to poor decision making. To the best of our knowledge, there is not a single approach that addresses disruption risk and sustainability concerns within a unified framework for renewable and non-renewable power generation technologies in this area of power management. Another aspect that has been excluded from this strategic planning problem is the social dimension of the issue and how it affects the decision-making process. Based on these matters, we develop a socially responsible framework for generation expansion planning that considers disruption risk. This approach considers our responsibilities toward society and the environment in line with economic objectives.

The remainder of the paper is organized as follows. Section 2 provides a brief literature review on generation expansion planning. Section 3 introduces the notation and presents a nonlinear mathematical programming model based on a sustainable

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approach to power generation expansion planning. It also shows how the model can be linearized for handling the nonlinearity of the proposed model. Section 4 presents the implementation of the proposed model in Iran's southwestern power grid as a case study and analyzes the computational results to achieve managerial insights. Finally, Section 5 concludes the paper.

2. Literature review

Generation expansion planning (GEP) deals with extending the generation capacity in order to satisfy power requirements at a minimum cost, including the cost of opening new generating units and their operating and maintenance costs. GEP is typically formulated as a mixed-integer nonlinear programming model. A large number of studies have been conducted on this subject under deterministic assumptions (Fukuyama and Chiang, 1996; Kannan et al., 2005; Murugan et al., 2009). In addition, other attempts have been made to consider GEP under uncertainty regarding future electricity demand and fuel prices (Feng and Ryan, 2013; Jin et al., 2011).

Wang et al. (2009) studied the competitive behavior among individual generating companies and proposed an incomplete information game model in which each generating company is modeled as an agent. They formulated this game model as a bi-level optimization problem. Roh et al. (2009) presented a stochastic coordination model for generation and transmission expansion planning in a competitive electricity market. They considered random outages in the generating units and transmission lines as well as inaccuracies in the long-term load forecasting, by applying Monte Carlo simulation and scenario reduction techniques.

Kamalinia and Shahidehpour (2010) considered GEP in wind-thermal power systems. They studied the optimal expansion planning of fast-response generating capacity to respond to the uncertainty of wind generation, using a mixed-integer linear programming model. Baringo and Conejo (2011) presented a stochastic bi-level model to identify the optimal level of wind power investment for a wind power investor in an electric energy system with a fixed transmission capacity, which works under a pool-based electricity market. Baringo and Conejo (2013) considered a profit-oriented private investor interested in building electricity-production facilities in a competitive pool-based electricity market. The investor faced uncertainties related to demand growth, production level, and investment cost. They formulated this problem as a stochastic complementarity model by adopting a multi-stage approach.

Kazempour et al. (2011) provided a method to assist a strategic producer in making informed decisions on generation investment in a pool-based market through supply strategies. They formulated the model as a stochastic mathematical program with equilibrium constraints (MPEC) that is recast as a mixed-integer linear programming problem. Then, Kazempour et al. (2012) analyzed the effect of futures markets on the investment decisions of a strategic electricity producer. Kazempour and Conejo (2012) proposed a Benders' decomposition algorithm for solving the generation investment problem faced by a strategic power producer.

Recently, some researchers have included environmental impacts in this context. Meza et al. (2007) formulated GEP considering CO_2 emissions and fuel-price risks. Sirikum et al. (2007) developed GEP by incorporating environmental costs and limitations for emissions of air pollutants (SO_2 and PM_{10}). Careri et al. (2011) considered the impacts of feed-in tariffs, quota obligations, emissions trading and a carbon tax on GEP. Gitizadeh et al. (2013) proposed a multi-objective mixed-integer linear model for GEP in which CO_2 emissions and energy price risk are considered. Rebennack (2014) developed a decomposition algorithm that takes emissions quotas and inflow uncertainty into account in GEP for hydrothermal power systems. However, to the best of our knowledge, no paper has yet considered any social aspects.

As far as we are aware, there is no adequate study of GEP with disruption risk. However, incorporating disruption risks into the planning of product distribution networks has been extensively considered by the literature on facility location and supply chain management. Snyder et al. (2014) reviewed the operations research literature on supply chain disruptions and organized it into six categories: evaluating supply disruptions, strategic decisions, sourcing decisions, contracts and incentives, inventory, and facility location. Rangel et al. (2014) conducted a literature review on different risk types in supply chain management where these risk types are sorted on the basis of existing conceptual similarities and related to the main management processes in a functional supply chain to outline a more unified supply chain risk classification. Ahmadi-Javid and Seddighi (2013) considered a location-routing problem in a supply chain network under disruption risk. They formulated and solved the problem under three risk-measurement policies. Li et al. (2013) presented two models for the design of reliable distribution networks: a reliable *p*-median problem and a reliable uncapacitated fixed-charge location problem. They proposed nonlinear integer programming models and developed Lagrangian relaxation algorithms for these problems. An et al. (2014) proposed a set of two-stage robust optimization models to design reliable *p*-median facility location networks subject to disruptions. They presented an exact algorithm based on the column-and-constraint generation method with customized enhancement strategies to solve the problem. Medal et al. (2014) integrated facility-location and facility-hardening decisions to reduce the disruption risk of a distribution system using mixed-integer programming.

3. Problem statement and formulation

We consider a power grid, consisting of some existing generating units and transmission lines, which is subject to disruption by natural and man-made disasters in a multiperiod planning horizon. The disruption events impose an extra cost on the power network and may have social and environmental impacts. In addition, there are a number of potential locations for new generating units. The goal is to locate new generating units and to determine the power generated at each node and power flow in each transition line in order to fulfill the power requirements at a minimum cost with considering socio-environmental impacts under disruption risk. The linear DC power flow method is employed to model power flow in the transmission network in this paper (Bahiense et al., 2001; Romero et al., 2005; Wood et al., 2013).

It is assumed that the power system has a vertically integrated utility structure in a regulated market environment. Similar assumptions are widely used in the literature (Jenabi et al., 2013; Koltsaklis et al., 2014; Meza et al., 2007; Sharan and Balasubramanian, 2012) and are also applicable to real cases in different countries such as Canada (Zacher and Reed, 2014), Costa Rica (ECA, 2010), Honduras (ECA, 2010), Iran (TEHC, 2012c), Ireland (DPER, 2010), Malaysia (See, 2011) and South Africa (EIA, 2014).

We first introduce our sustainable approach to GEP. Then, we define the required sets, decision variables and parameters. Finally, a mixed-integer nonlinear programming model is presented to mathematically address the problem.

Decision-makers are responsible for the impacts of their decisions on society and the environment. This viewpoint originates