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Development of a stochastic simulation–optimization model for planning electric power systems – A case study of Shanghai, China

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ABSTRACT

In this study, a stochastic simulation–optimization model (SSOM) is developed for planning electric power systems (EPS) under uncertainty. SSOM integrates techniques of support-vector-regression (SVR), Monte Carlo simulation, and inexact chance-constrained programming (ICP) into a general framework. SVR coupled Monte Carlo technique is used to predict the electricity consumption amount; ICP is effective for reflecting the reliability of satisfying (or risk of violating) system constraints under uncertainty. The SSOM can not only predict the electricity demand exactly, but also allows uncertainties presented as interval values and probability distributions. The developed SSOM is applied to a real-case study of planning the EPS of Shanghai, with an objective of minimizing system cost and under constraints of resources availability and environmental regulations. Different scenarios associated with SO_2-emission policies are analyzed. Results are valuable for (a) facilitating predicting electricity demand, and generating useful solutions including the optimal strategies regarding energy sources allocation, electricity conversion technologies, and capacity expansion schemes, (b) resolving of conflicts and interactions among economic cost, electricity generation pattern, SO_2-emission mitigation, and system reliability, and (c) identifying strategies for improving air quality in Shanghai through analyzing the economic and environmental implications associated with SO_2-emission reduction policies.

1. Introduction

Effective planning of electric power systems (EPS) plays an important role for national and/or regional sustainable development. Over the past decades, due to the rapid population growth, intensive economic development, and continually increasing electricity demand, fossil fuels have been exploiting unceasingly. Currently, more than half of electricity generation relies primarily on fossil fuels (e.g., coal, natural gas, crude oil) due to their economic advantages over renewable energy resources (e.g., wind, solar, hydro) [1,2]. For China, electricity generation coming from fossil fuels energy accounted for 72.3% of the total power generation mix in 2012 [3]. Moreover, the consumption of fossil fuels is experiencing a rapid increase over the next decades [4]. However, the fossil fuels are not renewable and have limited scale. Furthermore, the exploration and utilization of fossil fuels also bring serious environmental problems [5]. For example, fossil fuel is responsible for about 85% of the anthropogenic CO_2 emissions produced annually [6], while the increasing concentration of greenhouse gas in the atmosphere is likely to accelerate the rate of global warming [7]. Therefore, effective planning of EPS is critical to deal with electricity demand and air-pollution control from a long-term point of view.

Previously, many scholars made great efforts to develop a number of systems analysis methods for effectively planning EPS to deal with electricity demand and supply [8–11]. However, a variety of complexities and uncertainties are associated with electric power systems such as identification, generation, conversion, transmission and distribution of electric power; these processes and the related factors are also fraught with multiple forms of uncertainties, further complicating the planning of power management systems [12]. Moreover, complex interactions among multiple uncertain parameters and the increasing deregulation of power markets can further amplify the complexities and uncertainties. As a result, stochastic mathematical programming (SMP) methods were developed for handling EPS planning problems whose coefficients were represented as chances or probabilities [13,14]. For example, Pereira and Pinto [15] proposed a multi-stage stochastic

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optimization method for planning energy systems based on the approximation of the expected-cost-to-go functions through the introduction of piecewise linear functions. Dantzig and Infanger [16] introduced a stochastic linear optimization programming into the management of power generation to deal with imprecision in power flow analysis. Bath et al. [17] presented an interactive fuzzy stochastic method to optimize the power generation by minimize operating cost, NO_x-emission and risk. Spangardt et al. [18] proposed a stochastic programming model for electric-power planning to reduce greenhouse gas emissions under random demand. Beraldi et al. [19] proposed a two-stage stochastic integer programming model for the integrated optimization of power production and trading which included a specific measure accounting for risk management. Chen et al. [20] developed a two-stage stochastic programming method for electric power systems and trading carbon dioxide, through incorporating interval-parameter programming within a robust optimization framework.

In general, two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and the coefficients are random with known probability distributions [21,22]. CCP is effectively reflect the reliability of satisfying (or risk of violating) system constraints under uncertainty [23]. In a CCP model, not all of the constraints must be totally satisfied, such that the reliability of satisfying or the risk of violating individual constraint can be effectively reflected [24]. The major advantages of CCP are: (a) it could be used to convert a stochastic programming model into an equivalent deterministic version, and thus significantly reduce system complexities; (b) it is especially useful for helping the decision makers make their decisions based on given probabilities of constraint violations; (c) it could incorporate other uncertain optimization methods within a general framework. However, CCP has difficulties in reflecting the independent uncertainties existing in the left-hand-side coefficients of constraints and/or the objective function. One possible approach to address uncertainties of the left-hand-side coefficients is to integrate the interval-parameter programming (IPP) approach into the CCP framework. IPP can tackle uncertainties that generally cannot be quantified as either distribution functions or membership functions, since interval numbers are acceptable as its uncertain inputs [25,26].

Although the previous optimization methods could generate desired solutions for managing electricity generation and supply, they could encounter difficulties when the optimization models needed the input data with anticipated prediction accuracy. For example, the electricity consumption as the input data of the optimization models may mislead the optimization results if its prediction accuracy is too low. Therefore, accurate prediction of electricity consumption is crucial for designing and planning the electric power systems. Traditional methods for predicting the electricity consumption include multiple linear regression analysis and moving average analysis; they frequently count on some elements such as population and social economic factors and can be computed according to generation coefficient per person [27]. However, systems' coefficients may change as time passed, such that the methods are unavailable for reflecting the dynamic feature of EPS. Support-vector-regression (SVR) can be used for forecasting the electricity consumption amount as an artificial intelligence technique, which can assist decision makers to generate more practical and realistic results, particularly for electric power systems associated with a variety of uncertainties and complexities. SVR model is intended to alleviate the main drawback of parametric regression, which is a novel powerful learning machine based on statistical learning theory, and it adheres to the principle of structural risk minimization seeking to minimize an upper bound of the generalization error, rather than minimize the training error [28–31]. Therefore, to better account for the prediction accuracy in SVR method, one validation technique is through one thousand time's Monte Carlo runs, according to the fitting simulation results to found the distribution function, which is the best fit for the distribution of random variables.

The objective of this study aims to develop a stochastic simulation–optimization model (SSOM) for planning EPS under uncertainty. In SSOM, SVR and Monte Carlo simulation techniques will be used for predicting the electricity consumption in the future; inexct chance-constrained programming (ICP) technique will be able to tackle uncertainties expressed as intervals and probability distributions in constraints and objective function. Then, a real-case study of electric power systems of Shanghai will be provided for demonstrating availability of the developed SSOM. The results will be useful for managers in not only making decisions of electricity supply but also gaining insight into the tradeoffs between the system cost and the constraint-violation risk.

2. Model development

Considering electric power systems wherein three main components are comprised, including the energy resource supply sector, which provides energy resources with different availabilities, including fossil fuels (including coal, oil and natural gas) and renewable energies (biomass energy, hydropower and wind) to the system; the energy conversion sector, which contains various electricity conversion technology options with varied economic, environmental and technological performances; and the electricity demand sector, which involves kinds of demand side technologies that drive energy consumptions by numerous end users and is characterized by varying socioeconomic, geographical, demography, technology advancement and environmental conditions [32]. Due to spatial and temporal variations of the relationship between power demand and supply, the desired electric power generation patterns would vary under different strategies and various practical demands of electricity, furthermore, the fact that electricity cannot be stored in a large power system illustrates that it must be distributed once generated [12]. Therefore, the decision maker should be formulated the problem as minimizing the expected value of net system cost with optimized energy resource allocation patterns and capacity expansion planning schemes over the planning horizon [32]. However, during the processes of managing electricity generation and supply, the demand of total electricity generation must be known as input data, complex predicting problems may appear. Moreover, in EPS, due to the uncertainties existing in many parameters, such as the price of domestic energy carrier and electricity conversion technology, it is difficult to get economic and technical data exactly. Furthermore, there are many random variables and processes may lead to uncertainties in the right-hand-side parameters. All these will affect the model results and the practical decision outcome. Fortunately, the proposed SSOM is useful for solving these predicting and uncertainties problems. Prior to formulating the SSOM, the techniques of SVR, Monte Carlo and ICP are introduced.

2.1. Electricity demand analysis

Accurate prediction of electricity demand is crucial for planning and operation of electric power systems. The electricity demand is affected by many factors and it has complex nonlinear characteristics. A number of studies have been carried out to find important parameters affecting electricity demand, such as resident population, gross domestic product (GDP), primary industry output value, industry output value, construction industry output value and tertiary industry output value. SVR is effective for the problems with the characters of small samples, nonlinearity, high dimension and local minima [33]. It is an adaptation of recently introduced statistical/ machine earning theory based classification paradigm,