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A robust possibilistic mixed-integer programming method for planning municipal electric power systems

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ABSTRACT

In this study, a robust possibilistic mixed-integer programming (RPMP) method is developed for planning municipal electric power systems (EPS) under uncertainty. RPMP incorporates the concept of robustness within a possibilistic mixed-integer programming framework to handle ambiguous uncertainties in the objective function and constraints. It is superior to existing fuzzy possibilistic programming method by accounting for recourse actions of deviation of objective function with imprecise parameters from its optimal value, as well as economic penalties as corrective measures of possible violation for constraints with imprecise parameters. A RPMP-based electric power system (RPMP-EPS) model is then formulated for planning EPS of the City of Shenzhen, China, while cost-effective and sustainable electricity generation schemes can be achieved through analyzing city's electricity consumption mix, electricity balance condition, as well as energy self-sufficiency. Results demonstrate that (i) power export contracts based on national and regional energy policies bring significant effects on the municipal EPS, particularly in energy supply schemes and electricity consumption mix; (ii) although city can be basically self-sufficient in power supply if nuclear power is not enforced for export, import dependency of fuels remains extremely high, leading to the insecure fuel supply and vulnerable EPS; (iii) uncertainties have significant effects on the city's energy source supply as well as the relevant electricity-generation scheme. The findings are helpful for formulating policies of electricity generation as well as analyzing interactions among system cost, environmental objective, and electricity supply security.

Introduction

Electric power systems (EPS) currently face a significant obstacle in reliable and sufficient electricity supply which support a series of energy activities and play important roles in municipal/regional sustainable development [1,2]. Over the recent decades, with speedy population growth as well as accelerating industrialization and urbanization processes, the electricity demand, particularly in energy-intensive sector, has been undergoing a soaring increment. Such a tendency has exacerbated the contradiction between supply and demand as well as brought about potential insecurity problems of insufficient supply and heavy dependence on fossil fuels and/or import electricity. Correspondingly, in order to provide sufficient, secure and cost-effective electricity supply, effective planning of EPS has become a major priority for many municipal governments.

Uncertainties existed in electricity generation processes, impact factors (i.e., economic, social, technical and political), as well as related parameters (i.e., technical and economic parameters), create complexities which are challenging the capabilities of conventional deterministic optimization techniques [3–5]. The inherent complexities of EPS are further multiplied by multi-period, multi-objective and multi-facility features of system component. These uncertainties have significant effects on energy source supply, electricity consumption mix, and even relevant decision alternatives. Therefore, such challenges call for more solid methods for planning ESP under uncertainty and generating optimal decision alternatives.

Previously, a number of inexact mathematical models were developed for EPS planning in response to the above challenges [6–12]. For example, Lotfi and Ghaderi [13] advanced a possibilistic price-based mixed integer linear programming approach for mid-term electric power planning in deregulated markets, where possibilistic distribution functions were used for simulating some key ambiguous parameters. Carlos et al. [14] formulated a multiobjective optimization model for uncertain maintenance planning of

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nuclear power plant, where uncertainty was addressed by Particle Swarm optimization technique and tolerance interval based approach. Zhou et al. [15] developed a fractile-based fuzzy stochastic programming approach for planning regional electric power systems under uncertainty. Heleno et al. [16] proposed a linearization method of the symmetric fuzzy power flow for Portuguese transmission system planning, which could tackle load uncertainties represented by triangular fuzzy numbers and reduce the computational effort. Ji et al. [17] put forward an inexact two-stage stochastic risk-aversion programming model for regional carbon constrained electricity system planning under uncertainty. Koltsaklis et al. [18] presented a stochastic multi-regional multi-period mixed-integer linear programming model for Greek generation expansion planning, where uncertain parameters were characterized by Monte Carlo method with demand response mechanism.

Fuzzy possibilistic programming (FPP) can effectively cope with the ambiguous information in decision-making problems which is modeled by possibilistic distribution with subjective knowledge/-experience of decision makers [19–21]. However, the conventional FPP only presents the average system performance; it has difficulties in ensuring any realization of uncertain parameters and may encounter challenges in obtaining risk-averse solutions under high variability conditions [20]. An attractive technique that can improve the above weaknesses is robust possibilistic programming, which can avoid imposing a high risk to decision makers and help seek for robust solutions through controlling both optimality robustness and feasibility robustness.

Under these considerations, this study aims to develop a robust possibilistic mixed-integer programming (RPMP) method. In RPMP, ambiguous uncertainties in a series of key parameters in the model can be treated. RPMP could help decision makers obtain more robust solutions through undertaking recourse actions of deviation of imprecise objective function and potential violation of imprecise constraints. The proposed method will be applied to a real case of Shenzhen's electric power systems (EPS) planning. Through solving RPMP-based electric power system (RPMP-EPS) model, cost-effective and sustainable schemes for electricity generation, as well as various economic costs under various robustness levels and necessity degree levels are to be examined and analyzed.

Methodology

Fuzzy possibilistic programming (FPP) can deal with ambiguous coefficients expressed as possibilistic distributions [19]. A possibilistic mixed-integer programming model can be formulated as follows:

$$\text{Min } \underset{\sim}{f} = \sum_{j=1}^{n} \underset{\sim}{c_j} x_j \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \geqslant \underset{\sim}{b_i}, \quad i = 1, 2, \ldots, m \tag{1b}$$

$$x_j \geqslant 0, \quad j = 1, 2, \ldots, n \tag{1c}$$

where x_j are non-fuzzy decision variables that are divided into two categories: continuous and binary variables; $\underset{\sim}{c_j}, a_{ij}$ and $\underset{\sim}{b_i}$ are coefficients of the objective function and constraints, respectively. Among them, $\underset{\sim}{c_j}$ and $\underset{\sim}{b_i}$ are fuzzy coefficients with possibility distributions which can be treated as fuzzy membership functions.

Model (1) can present the average system performance through tackling ambiguous uncertainties in the objective function and constraints. However, it could neither account for the deviation of objective function with imprecise parameters from its optimal value, nor reflect the economic penalty as corrective measures of possible violation for constraints with imprecise parameters. In this sense, the solution of model (1) cannot be termed to be robust. Robust possibilistic programming, through incorporating concept of robustness into possibilistic programming framework, can handle above difficulties [20]. This leads to a robust possibilistic mixed-integer programming (RPMP) model, which can account for the robustness of recourse costs of objective function and constraints and seeks for a reasonable trade-off among average performance, optimality robustness, and feasibility robustness. Thus, we have:

$$\text{Min } \underset{\sim}{f} = \sum_{j=1}^{n} \underset{\sim}{c_j} x_j + \gamma O_j + P_i F_i \tag{2a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \geqslant \underset{\sim}{b_i}, \quad i = 1, 2, \ldots, m \tag{2b}$$

$$x_j \geqslant 0, \quad j = 1, 2, \ldots, n \tag{2c}$$

where the first term of objective function shows the expected (average) performance of system; γ is robustness level and ranges from 0 to 1, denoting the risk attitude of decision makers; O_j indicates minimization of maximum deviation over and under the expected optimal values of x_j; the second term of objective function controls the optimality robustness of the solution vector; P_i denotes the penalty cost per unit of possible violation of each constraint with imprecise parameter; F_i implies the difference between the worst case value of imprecise parameter and the value that is used in constraint; the third term of objective function controls the feasibility robustness of the solution vector.

According to Lai and Hwang [22], the selection of membership function in fuzzy systems depends on the particular problem we have to solve. Since trapezoidal membership function is simple to implement and fast for computation, it becomes one of the most popular possibility distributions in optimization problems [22–27]. In this study, trapezoidal membership function is employed to reflect ambiguous uncertainty. Considering a trapezoidal fuzzy number $\underset{\sim}{b}$ expressed by a tetrad $(b_{(1)}, b_{(2)}, b_{(3)}, b_{(4)})$ of crisp numbers, its membership function can be denoted as follows:

$$\mu_{\underset{\sim}{b}}(x) = \begin{cases} (x - b_{(1)})/(b_{(2)} - b_{(1)}), & \text{if } b_{(1)} \leqslant x \leqslant b_{(2)} \\ 1, & \text{if } b_{(2)} \leqslant x \leqslant b_{(3)} \\ (x - b_{(4)})/(b_{(3)} - b_{(4)}), & \text{if } b_{(3)} \leqslant x \leqslant b_{(4)} \\ 0, & \text{if } x < b_{(1)} \text{ or } x > b_{(4)} \end{cases} \tag{3}$$

In practical applications, decision makers prefer that constraints should be satisfied under high necessity (certainty) degree. Thus, the concept of necessity is utilized to address fuzzy coefficients in the right-hand side of constraint, while the satisfaction of system performance is optimized. Eq. (2b) can be converted into the following necessity constraint which is satisfied with at least level of α [28]:

$$\text{Nes}\left\{\sum_{j=1}^{n} a_{ij} x_j \geqslant \underset{\sim}{b_i}\right\} \geqslant \alpha, \quad i = 1, 2, \ldots, m \tag{4}$$

where $N_{es}(\cdot)$ denotes the necessity (certainty) degree of the event in $\{\cdot\}$; α means the predetermined necessity degree level; vectors x_j are feasible when the necessity measure of the event that $\sum_{j=1}^{n} a_{ij} x_j \geqslant \underset{\sim}{b_i}$ is greater than or equal to α level; α level controls the satisfaction degree of constraints with ambiguous parameters