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Black-start decision-making with interval representations of uncertain factors

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ABSTRACT

Finding an optimal black-start scheme plays an important role in speeding up the restoration procedure of a power system after a blackout or a local outage. In a practical black-start decision-making procedure, uncertainties are inevitable. Some factors such as index values and indexes' weights can be better described as uncertain interval values. So far, the black-start decision-making problem with uncertainties has not yet been systematically investigated. Given this background, a new approach for black-start decision-making based on interval values is developed. First, a decision-making matrix with interval values is normalized by using the error propagation theory. Then, a linear goal programming model is developed to seek the ideal vector of index weights and the evaluation values of all candidate black-start schemes can be obtained. A risk attitude factor based method is presented to sort the schemes. Finally, a sample example is served for demonstrating the essential feature of the proposed method, and comparisons with three existing methods are also carried out. Simulation and comparison results show that the proposed method could not only take different kinds of uncertainties into account, but also overcome several shortcomings of the existing methods.

Introduction

In recent years, several large-area blackouts happened all over the world [1,2], such as the power failure in US and Canada on August 14th in 2003, the interconnected power gird blackout in Western Europe on November 4th in 2006, and the recent blackout in India on July 30th in 2012. Although the self-healing capacity of a power system can be enhanced by the development of smart grids, it is not possible to avoid large-area blackouts completely. Therefore, it is necessary to study the issues associated with power system restoration after a complete blackout or a local outage, so as to implement rapid, intelligent and efficient power recovery [3–6]. The power system restoration process after a blackout can be divided into three stages: black-start, network reconfiguration and load restoration. Among these three stages, the black-start stage is defined as the one in which the black-start units, after a large blackout, supply power to the units that cannot start independently without the help of other systems or units [7]. Therefore, black-start represents the first restoration stage after a blackout, and finding the optimal black-start scheme is one of the key issues having impacts on the restoration speed of the power system concerned. The black-start decision support system is an important module of the future decision support system in a smart grid environment, with an objective of speeding up the restoration procedure after a blackout or local outage.

So far, much research work has been done in developing black-start decision-making and system restoration methods. An expert system based decision-making for power system restoration is proposed in [8,9]. In [10], an optimal restoration approach based on the Wide Area Measurement System (WAMS) is presented. In [11], a hierarchical case-based reasoning method is presented for determining the black-start schemes. In [12], the vague set is first employed to deal with the black-start decision-making problem

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with interacting attributes, and then a concept of the vague-valued fuzzy measure presented and a mathematical model for black-start decision-making developed. In [13], a new service restoration system for distribution systems is described, and more practical solutions can be obtained through the multiple criteria fuzzy evaluation for the candidate schemes. In [14], a real-time restoration decision support system is presented and a detailed design framework of the system introduced. The proposed system is combined with the dispatcher training simulation system of EdF (Electricite de France) in France, and is demonstrated by real-time data. In [15], a black-start decision-making method based on an intuitionistic fuzzy set and further the intuitionistic fuzzy Choquet integral operator are presented. In [16], a novel method using the entropy weight-based decision-making theory is developed to evaluate and optimize the black-start schemes.

It can be seen that in the existing research literature the index values of alternative black-start schemes and the weights of the indexes for evaluating black-start schemes are mostly treated as deterministic. However, some of index values and the indexes' weights are uncertain in practical black-start decision-making, and are better represented by interval ranges. To the best of our knowledge, the black-start decision-making problem considering uncertain quantities described as interval values has not yet been investigated thoroughly. In addition, the weights are acquired from the subjective experience of experts, or calculated based on the objective entropy weight theory in which the authority of each expert in the weight determination is not well reflected. As a result, ideal indexes' weights should be determined by a combination of the subjective and objective methods, so as to make the final decision-making result more reasonable.

Given this background, a new approach for black-start decision-making based on interval values is first developed. The method is able to deal with uncertain quantities described by interval values, which can better reflect actual black-start decision-making procedures. First, some theories of interval values and error propagation are introduced. A black-start decision-making method based on interval values is then proposed. Finally, a case study is employed to demonstrate the new method and to compare the proposed method with some existing methods.

The theories of interval values and error propagation

Definition of an interval value

A closed interval $[b^L, b^U]$ is denoted as an interval value $\tilde{b}$, where $b^L \in \boldsymbol{R}$, $b^U \in \boldsymbol{R}$, $b^L \leqslant b^U$. A matrix (or vector) with interval elements is denoted as an interval value matrix (or vector). Taking the error distribution into account, the interval value $\tilde{b}$ can also be described as $\tilde{b} = \overline{b} \pm \Delta b$, with the interval midpoint defined as $\overline{b} = (b^L + b^U)/2$ and the limit error as $\Delta b = (b^U - b^L)/2$.

A sorting method for interval values

Interval values cannot be sorted by traditional sorting methods because there are intersections among them. Therefore, a risk attitude factor based method is introduced to sort interval values [17].

For an interval value $\tilde{b} = [b^L, b^U]$, an interval mapping function $\varphi_\varepsilon(\tilde{b})$ can be introduced to transform an interval value into an actual value, and described as follows.

$$\varphi_\varepsilon(\tilde{b}) = \frac{b^U + b^L}{2} + \varepsilon(b^U - b^L) \tag{1}$$

where ε is the risk attitude factor ($|\varepsilon| \leqslant 0.5$), and represents the attitude or degree that a decision-maker is willing to take risks. It can be seen from Eq. (1) that $\varphi_\varepsilon(\tilde{b})$ can map an interval value, which is represented by its midpoint, width and risk attitude factor, into an actual value, and then the interval values can be sorted easily.

The error propagation theory

In the well-established measurement theory, the error of an indirect measurement can be obtained through the error function of a direct measurement, and this is the so-called error propagation [18], which is described as follows.

Suppose that a group of direct measurement values is as follows: $u_1, u_2, \ldots, u_m$; an indirect measurement value is v; and there exists a continuous and differentiable function: $v = f(u_1, u_2, \ldots, u_m)$. In addition, suppose that the random errors of $u_1, u_2, \ldots, u_m$ are $\delta_{u_1}, \delta_{u_2}, \ldots, \delta_{u_m}$, respectively; the random error of v is δ_v; and the random errors δ_{u_i} are independent. Thus, the random error propagation relationship can be expressed as

$$\delta_v^2 = \sum_{i=1}^{m} \left(\frac{\partial f}{\partial u_i}\right)^2 \delta_{u_i}^2 \tag{2}$$

A black-start decision-making method based on interval values

Power system restoration is a complex process with many uncertain factors. For example, the start-up power required by each unit is affected by the operating state of the power system concerned and may not be simply described by an accurate value. Given this background, an interval value is more suitable for describing it with its uncertainties taken into account. Thus, the decision-making method based on interval values is useful for optimizing candidate black-start schemes in practical black-start decision-making, since different kinds of uncertain information can be taken into account in this method.

Black-start decision-making process

Generally speaking, the framework of a decision-support system for black-start consists of three functional modules in practice, i.e. formation, verification and optimization of black-start schemes. First, in the formation module of initial black-start schemes, the power system topology database is first searched automatically by the breadth first search philosophy according to the distribution of local black-start power. All the awaiting start-up power plants and possible black-start paths are determined, thus all the possible black-start schemes are generated automatically and an initial scheme database formed. Secondly, in the verification module of feasible black-start schemes, relevant simulation and analysis software packages need to be employed to compute and verify all the initially determined black-start schemes, on aspects including unit self-excitation checking, no-load switching overvoltage checking, power frequency overvoltage checking, frequency checking, and low frequency oscillation checking. The technical feasibility of each scheme is such checked, and feasible schemes are picked out as the candidate ones. Finally, in the optimization module of candidate black-start schemes, an optimal black-start scheme will be selected from the candidate schemes by using one of black-start decision-making methods. The selection of the optimal black-start scheme is of great significance and plays an important role in the black-start decision-support system [19]. In this paper, the third black-start functional module is mainly focused. Thus, a new black-start decision-making method based on interval values is presented for optimizing black-start schemes with uncertain information.