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A new approach combing connection number and fuzzy simulation to calculating power flow of distribution network considering uncertainty

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ABSTRACT

The power flow calculation considering uncertainty is the most basic way for solving the security issue of the system under uncertain conditions. As the renewable energy characterized by randomness and uncertainty, such as wind and solar power, has been applied to the distribution network, it is especially essential to study on power flow of distribution network considering uncertainty. The traditional models of uncertainty have the problem of singleness in expressing uncertainties while the uncertainty objectively shares two or more than two kinds of characteristics. A new model for describing the uncertainties, which combines connection number and fuzzy number and describes the interval quality and fuzziness of uncertain information comprehensively, is presented. Through improving the calculation of sample value and possibility measure, the traditional fuzzy simulation is modified and then applied to the power flow calculation in consideration of wind and solar power output uncertainty and load uncertainty. Two definitions, which are satisfaction index and degree of uncertainty, are introduced to measure the results accuracy with sample number changing and to represent the variation range of uncertain parameters respectively. The proposed model and modified algorithm are verified by case studies based on IEEE 33-bus system. The results are compared with those obtained from Monte Carlo simulation and proved to be correct. In addition, several other numerical examples are presented and discussed in order to achieve the influences of sample number, degree of uncertainty and membership function change on results. Through analysis of the power flow results considering uncertainty, we may find out the weak links of network, which can provide references for making electrical accident premeditation and then adjusting operation scheme.

1. Introduction

The power market environment is faced with abundant uncertainties, the randomness and unpredictability of which bring difficulties to planners and dispatchers. These uncertainties mainly come from the variation of load and energy prices, the fluctuation of future electricity price and the change of environmental management policy [1]. The distribution network is the basic form connecting power energy with consumers. However, the widely existing uncertainties decrease the power quality. In recent years, the renewable energy of PV power generation and wind power generation has been developed and introduced into the traditional distribution network. The high randomness of solar radiation intensity and wind speed strengthens the uncertainty of distribution network [2–4]. The above uncertainties invalidate traditional power system analysis methods and classical mathematical models can hardly describe the development trend of power grid any more. Therefore it's necessary to build the model and algorithm considering uncertainty.

The power flow calculation is the foundation of power network planning and dispatching. The traditional deterministic planning and scheduling models were devoted to the minimization of initial investment and production cost [5–8], which usually results in poor ability of coping with uncertainties and transmission capacity limit violation and voltage limit violation with small fluctuation from uncertainties. The power flow calculation considering uncertainty can ensure certain safety margins of network, and provide references for finding weak links of network and making electrical accident premeditation and then adjusting operation scheme. In a word, the power flow calculation considering uncertainty is the most basic way for solving the security issue of the system under uncertain conditions.

There are two major classes of treatment methods with uncertainty. The first is the scenario technique [9,10] which is used for dealing with uncertainties hardly expressed in mathematical models. The other one is mathematical description method based on uncertain information which can be divided into three types: Probability Analytic Method [11–13] including simulation method [14],

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analytic method [15] and approximate method [16], Fuzzy Mathematic Method [17–20], and Interval Analytic Method [21–23] and so on. For scenario technique, the distinction and relation between each scenario are overlooked and the calculation amount will increase with growing number of scenarios. While mathematical description method has the problem of singleness in expressing uncertainties. Objectively, the uncertainty usually shares two or more than two kinds of characteristics like randomness, fuzziness and interval quality. So it is necessary to search for a model considering multiple uncertainties.

The uncertainty of a parameter can be essentially represented by fluctuations based on a deterministic value, which embodies the coexistence of determinacy and uncertainty. The connection number is just a research method which takes the determinacy and uncertainty as a whole. However, the connection number only presents an interval range and cannot express the distribution characteristics in the interval. Considering the probable dimension disasters for Probability Analytic Method and the big result deviation produced by a little difference between the selected probability density function and the real, we introduce the fuzzy membership functions for describing the variation of the uncertain parameter in the interval. Through combing connection number and fuzzy simulation and taking the interval quality and fuzziness of wind power output, solar power output and load into the comprehensive consideration, the numerical examples give the power flow results of distribution network with distributed generation.

2. The model for uncertainty

2.1. The connection number

The connection number is derived from the connection degree in set pair analysis [24]. The set pair analysis, a kind of new system theory developed from philosophical angle that determinacy and uncertainty are unity of opposites, was first proposed by a Chinese scholar named Keqin Zhao. The basic concept of set pair analysis is set pair connection degree. The so-called set pair is the pairs consisting of two sets with certain connection. Through system analysis focusing on some characteristic, we can find out the identical, contrary and discrepancy characteristics of two sets and establish the identical–discrepancy–contrary (IDC) connection degree expression as follows:

$$\alpha = a + bi + cj \tag{1}$$

where a denotes identical degree, b denotes discrepancy degree, c denotes contrary degree, i and j represent the symbol for discrepancy and contrary respectively. Further, $a, b, c \in [0, 1]$ and must satisfy the normalizing condition, i.e. $a + b + c = 1$, the value of i ranges from -1 to 1, and value of j is set at -1.

The connection degree expresses the deterministic and uncertain connection between two sets under some background. It is a new form of quantity expression in the normalizing condition for deterministic parameter and uncertain parameter. Everything and its development encompass a wealth of information. Some of them are recognized by people and transformed into relatively deterministic parameters, while the others not recognized are characterized uncertain parameters. The connection number is a kind of number connecting the deterministic parameter with uncertain parameter within the identifiable limits, and the most general form is $a + bi$. The following is the generalized definition of connection number.

Suppose $\alpha = A + Bi$, then α is called the connection number. In this expression, A represents the deterministic part and can be obtained from the statistical average of historical data, while Bi refers to the uncertain part. The value of i ranges from -1 to 1 and B can be obtained by taking average value from maximum value. i and B together determine the directional revision and numerical revision of A.

The connection number can not only connect a specific number with an interval in which the number lies, but also connect a specific number with the determinacy and uncertainty of the interval and make the mutual connection, permeation, restraint and transformation of determinacy and uncertainty within certain limits reflected in quantity.

2.2. The fuzzy number

For fuzzy uncertainties, they can be dealt with fuzzy mathematical method. The fuzzy membership functions are introduced to express the fuzzy numbers. The two most commonly used are triangular membership function and trapezoidal membership function, which are shown in Fig. 1.

The triangular fuzzy numbers can be expressed as $\widetilde{N} = (n_1, n_2, n_3)$, where $n_1 \leqslant n_2 \leqslant n_3$, and n_1, n_2, n_3 represent the probable minimum value, the most probable value and the probable maximum value respectively. The triangular fuzzy membership function can be expressed as follows:

$$\mu_{\widetilde{N}}(x) = \begin{cases} (x - n_1)/(n_2 - n_1) & x \in [n_1, n_2) \\ (n_3 - x)/(n_3 - n_2) & x \in [n_2, n_3) \\ 0 & \text{others} \end{cases} \tag{2}$$

The trapezoidal fuzzy numbers can be expressed as $\widetilde{L} = (L_1, L_2, L_3, L_4)$, which implies that the fuzzy number probably ranges from L_1 to L_4 and most likely lies between L_2 and L_3. The trapezoidal fuzzy membership function is given as follows:

$$\mu_{\widetilde{L}}(x) = \begin{cases} (x - L_1)/(L_2 - L_1) & x \in [L_2, L_3) \\ 1.0 & x \in [L_3, L_4) \\ (L_4 - x)/(L_4 - L_3) & \text{others} \\ 0 & \end{cases} \tag{3}$$

The credibility theory, which is an axiomatic system of fuzzy theory corresponding to probability theory, was established to study on fuzzy uncertainties. There are several definitions related closely to the credibility theory [25], including possibility measure, necessity measure, credibility measure and fuzzy expected value.

Let ξ be a fuzzy variable with the membership function of μ, and suppose u and r are real numbers. Then the possibility measure of $\{\xi \geqslant r\}$ is defined as:

$$\mathrm{Pos}\{\xi \geqslant r\} = \sup_{u \geqslant r} \mu(u) \tag{4}$$

where sup stands for supremum, i.e. the least upper bound. In mathematics, the supremum of a set is a minimum element that is not smaller than any elements in this set.

The necessity measure of $\{\xi \geqslant r\}$ is defined as:

$$\mathrm{Nec}\{\xi \geqslant r\} = 1 - \mathrm{Pos}\{\xi < r\} = 1 - \sup_{u < r} \mu(u) \tag{5}$$

Based on possibility measure and necessity measure, the definition of credibility measure of $\{\xi \geqslant r\}$ is as follows:

$$\mathrm{Cr}\{\xi \geqslant r\} = 0.5 \cdot (\mathrm{Pos}\{\xi \geqslant r\} + \mathrm{Nec}\{\xi \geqslant r\}) \tag{6}$$

Thus, the expected value of fuzzy variable ξ is given as:

$$\mathrm{E}[\xi] = \int_0^{+\infty} \mathrm{Cr}\{\xi \geqslant r\}\mathrm{d}r - \int_{-\infty}^{0} \mathrm{Cr}\{\xi \leqslant r\}\mathrm{d}r \tag{7}$$

and the mean square error of ξ is given as:

$$\sigma = \sqrt{\mathrm{E}\{[\xi - \mathrm{E}(\xi)]^2\}} \tag{8}$$