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Gray theory based energy saving potential evaluation and planning for distribution networks

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ABSTRACT

A systematic method is proposed to quantitatively evaluate the energy saving potential (ESP) combining a microscopic analysis and the macro statistics of the distribution network. An energy saving modification (ESM) investment planning model, constrained by the funds available, is developed based on the ESP evaluation method. In the model, the modification investment amount of each measure is set as a variable, and the core parameters including gray correlation coefficient, index inferior degree and loss reduction efficiency are obtained from gray correlation analysis. Given the investment constraints and weighting factors, the problem of energy saving investment allocation of the whole distribution system is solved within the fund constraint. An example shows that the proposed method is ideal for quantifying the loss reduction space and modification demand of distribution systems while improving the efficiency of investment for ESM.

1. Introduction

Traditionally, energy saving potential (ESP) evaluation is one of the important aspects in the optimization of distribution systems, using e.g. optimal capacitor planning [1], optimal operation management [2], and distribution network reconfiguration [3]. The method is used to evaluate the efficiency of the investment or the effectiveness of an adopted strategy. Accurately evaluating ESP of distribution systems is fundamental for energy saving and emission reduction in the power supply industry. It is not only the premise for energy-saving modification work, but also the pre-requisite of guiding energy saving operation and expansion planning of distribution systems. Energy saving modification (ESM) is a systematic engineering approach including equipment replacement, network reconstruction and operation optimization, which aims to reduce energy losses at minimum investment.

Distribution network ESP evaluation is a new research focus in line with the global demands of energy saving and emission reduction. With the rapid increase of load demand in some parts of the world, many distribution networks now appear to be out dated resulting in high energy losses. It is necessary to modify or upgrade the feeders, transformers and other equipment based on energy saving planning of distribution systems. Existing evaluation methods are mainly concerned with the impacts of distributed generation [2] and network reconstruction [3]. In literatures which are related to network loss or energy saving assessment, algorithms to assess and predict line losses in the distribution system are one of the emphases, and developed are the BC Hydro method [4], clustering technique [5] and fuzzy logic theory [6].

The potential evaluation for individual energy saving measures was taken into account in some previous studies. Ref. [7] proposed a network loss assessing method for the use of distribution network reconfiguration based on loss reduction space evaluation; Ref. [8] evaluated the total energy saving space of all EU countries by switching to new energy-saving distribution transformers; and Ref. [9] was concerned with the evaluation of the reductions in the technical and non-technical distribution losses in the case of widespread use of compact fluorescent lamps in buildings in Serbia. However, the above evaluation lacked the flexibility and completeness since several means can be adopted to reduce the power losses of distribution networks and the ESPs of each and for all measures need to be evaluated. Distribution network energy saving is indeed a systematic under-taking, which affects the network structure, equipment, operation, management and other engineering aspects. It needs not only to calculate the whole energy saving space, but also to reflect the energy saving efficiency and differentiate among various measures in order to provide guidance to the corresponding ESM and planning.

On the other hand, distribution network planning techniques have grown to maturity with recent addition in the aspects of distributed generation [10], micro-grid planning [11], uncertainty of

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expansion planning [12], reference network model [13], plug-in electric vehicles [14] and reactive power planning [15]. Although energy saving is the subject of distribution network planning, studies on ESM planning have rarely been reported. In the power networks of China, India and other rapidly-developing countries, ESM technology is a flexible and efficient strategy [16]. However, under the dual restrictions in terms of investment fund and technology available, wastes of money and/or energy often occur. The difficulties of ESM planning are how to optimize the integrated modification measures and how to rationally allocate and make full use of the limited fund. This must be based on ESP evaluation.

This paper develops an ESP evaluation method and a modification investment planning model for distribution networks, based on the system decomposition and coordination method. Since the information the system engineers already have is usually limited for a quantitative evaluation, gray theory [17,18] is adopted to solve the above-mentioned problems.

2. Evaluation of energy saving potential in distribution networks

2.1. General concept

The load dependent energy loss on a component (A_{loss}) in the distribution network can be described as follows:

$$A_{\text{loss}} = \int_0^T \frac{(P^2(t) + Q^2(t))}{U^2(t)} R \, dt \tag{1}$$

where $P(t)$ and $Q(t)$ are the transmitted active and reactive power, $U(t)$ the nodal voltage, R the equivalent resistance, and T indicates the measurement period.

It is shown in Eq. (1) that the energy loss is the result of many factors, such as the resistance, voltage and load curve. So energy loss reduction can be achieved by replacing the conductor or transformer upgrading, optimal reactive power compensation, load fluctuation suppressing and voltage controlling [19]. Since a regional distribution system consists of thousands of feeders, it is not realistic to calculate one by one when assessing the comprehensive ESP for the system. So the decomposition evaluation technique, as shown in Fig. 1, is used to improve the efficiency.

The whole network can be categorized into several types of feeders according to the topological and loading characteristics, and sample feeders can be selected proportionally. On this basis, by using of the energy saving analysis software developed by the authors or a similar load flow analysis software, ESP of each sample feeder can be evaluated. Finally, after weighting and combining the above micro assessing results proportional to the feeders in the network, the result of comprehensive energy saving assessing can be obtained.

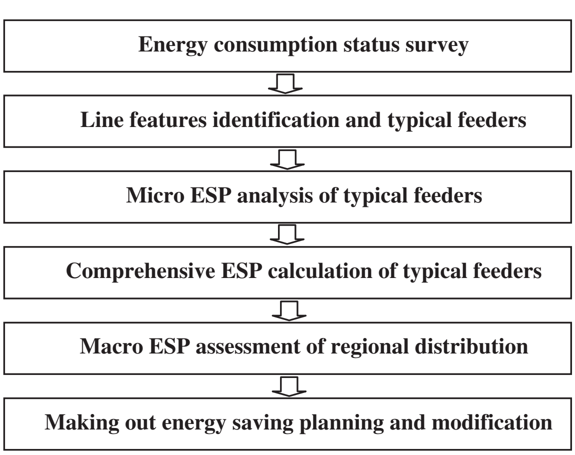

Fig. 1. Process of energy-saving potential evaluation.

During the stage of micro ESP analysis of typical feeders, the power loss reduction of each sample feeder should be calculated separately, assuming that some modification measures can be adopted to decrease the power losses to a targeted level, which includes replacing larger conductors, changing Var compensation strategies or increasing the compensation, adjusting the bus voltage, reducing the power supply radius, attaching distributed generation sources, upgrading the high-loss transformers, reducing the daily loading fluctuations, balancing the loads on three phases, etc.

2.2. Evaluation method of comprehensive energy saving potential

For a single sample feeder, the ESP corresponding to modification measure d, namely the expected loss reduction rate, is expressed as ε_d $(0 \leqq \varepsilon_d < 100\%)$. The comprehensive ESP of the feeder ε_Σ is described as follows:

$$\varepsilon_\Sigma = \left[1 - \prod_d (1 - \varepsilon_d)\right] \varsigma \tag{2}$$

where ς is the discount factor, used for removing the overlapping part of energy-saving effects from the comprehensive functions of multiple measures. According to the engineering experience, $\varsigma \in (0.7, 0.9)$, and the specific value depends on actual operation characteristics and parameters of the network.

Dividing all the sample feeders into g categories by comparing the feeder's comprehensive ESP, the expected comprehensive ESP ε_{N} of the whole network can then be obtained below through weighted combination.

$$\varepsilon_{\text{N}} = \sum_g \varepsilon_{\Sigma g} \eta_g \tag{3}$$

where $\varepsilon_{\Sigma g}$ is the average comprehensive ESP of the feeders of category g, and η_g is the percentage of feeders of category g in the whole network.

As a result, the demand distribution and efficiency sorting of various energy saving measures can be determined. The expected loss reduction rating, implementation difficulty rating and overall performance rating can also be evaluated and thereby used for guiding distribution network planning, renovation and operational optimization.

3. Basic concepts of gray correlation analysis

The gray theory determines the gray relational grades of all the selected factors by choosing the highest gray relational grade, even under incomplete information circumstances especially containing both the known and unconfirmed information [17]. This theory describes random variables as a changeable interval number that varies with time factors and uses color to represent the degree of uncertainty in a dynamic system [18]. Gray correlation analysis is used to describe the influence of various factors in a system or their contributions to the primary behavior of a system.

3.1. Gray correlation coefficient

This paper focuses on the relation between power loss factors and line loss rate of distribution systems so as to measure the correlation degree between line loss reduction and various factors such as bus voltage, power supply radius, ratio of high-loss transformer, power factor, load rate and passing rate of feeder diameter. When different modification measures are implemented in a