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Multistage distribution substations planning considering reliability and growth of energy demand

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ABSTRACT

The reliability of energy distribution is not usually considered in the planning of LV (low voltage) networks. However, the reliability cost has increased because of the appearance of the penalty schemes for the customer energy outage. In this paper, an approach is proposed for the planning of the LV distribution networks in which the distribution transformers are optimally organized. The size, number, and placement of the distribution transformers are optimally determined in order to improve the system reliability and to minimize the power and energy losses under the energy demand growth. An objective function is constituted, composed of the investment cost, maintenance cost, losses cost, and reliability cost. The proposed approach is applied to a test system consisting of 42 electric load points. It is observed that the appropriate placement of the distribution substation can reduce the interruption cost considerably, while the investment cost increased slightly. The total cost of the planning also decreased.

1. Introduction

The economic and reliable design of distribution networks is a main challenge of distribution network companies. The distribution system planning is an important topic in the electrical energy supplying systems. A distribution system consists of MV (medium voltage) and LV (low voltage) networks. In the planning of LV networks, the optimal locations and ratings of distribution transformers and LV feeder routes are determined. But in the planning of MV networks, the location and rating of HV/MV substations and MV feeder routes are determined. Different approaches of the distribution system planning have been presented during recent years. The literatures [1–5] are presenting comprehensive review of the trend in this field. Several methods such as particle swarm optimization [6], genetic algorithm [7], Ant colony system algorithm [8], dynamic programming [9], teacher learning algorithm [10], and evolution strategies [11] have been used to solve the distribution planning problem. However, most of these research works are discussing about the MV level [7–10] and less study has been done about LV networks [11]. The main part of the losses associated with a distribution system belongs to its LV networks [12]. Moreover, the cost of MV networks of a distribution system is comparable to that of its LV networks [13]. Therefore, pay more attention to LV distribution networks is necessary. As mentioned above, the planning of LV network can be divided into two sub-problems: distribution transformer allocation and feeder routing. In this paper, the optimal placement of distribution transformers is discussed.

A solution to the problem of distribution transformer placement is presented in Ref. [14] where an adapted genetic algorithm optimization technique is used to determine the size, number, and location of distribution transformers. The paper employs an overload factor to prevent the thermal aging problem due to the overloading in peak hours as well as a factor for annual growth of the energy demand over the analysis interval. An integrated planning method is presented in Ref. [15]. Secondary distribution circuits are the scope of this method. It models the problem using a MINLP (mixed integer nonlinear programming) then resolves it by means of a TS (tabu search) algorithm. In Ref. [16], the optimization of distribution transformers and associated feeders are presented combinatory. It also considers the street layout connecting different customers. The planning of LV distribution networks as an MINLP problem is investigated in Ref. [17] where dedicated EA (evolutionary algorithm) is used to solve the problem. The wires replacement investments, transformers placement, energy losses of

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feeders, and load balancing are contained in the objective function. It also considers the maximum available financial resources of investments in addition to typical constraints.

The reliability worth is not usually considered in the optimization of the distribution substation placement. However, it may be effective on the planning problem. In recent years, reliability and security of energy are seriously considered in the distribution planning researches. A multiobjective expansion planning of distribution network is presented in Ref. [6], where reliability and voltage stability indicators have been considered in the optimization process. In Ref. [18], distribution feeder reconfiguration from the reliability point of view is investigated. To perform a reliable analysis, the uncertainty of the forecast error of the energy demand, failure rate and repair rate parameters are modeled through a probabilistic load flow.

In this paper, a method for optimal placement of distribution transformers in LV networks is proposed and the effect of reliability worth in the planning solution is investigated. In the presented approach, the optimal site (location), size (capacity), and number (quantity) of the distribution transformers are determined. An MINLP formulation is utilized for modeling the problem. Optimized solution is calculated by GAMS software using some mathematical methods and tools. The main contributions of this work are the improvement of the reliability using the optimal placement of distribution transformers and considering energy demand growth through a multistage planning. This paper is organized as follows: Section 2 describes the objective and the constraints of the problem. Section 3 introduces the proposed models of the problem. Section 4 discusses the numerical results of the proposed method. Finally, section 5 concludes the paper.

2. Optimal planning to improve the reliability

A mathematical model is presented in this paper for optimal placement of distribution transformers in a low voltage network as a Greenfield planning. The optimal size, quantity, and location of distribution transformers are determined in this planning. The optimization problem is formulated as a mixed integer nonlinear programming problem.

2.1. Objective function

The objective function of the problem includes the costs of the investment, the operation and maintenance, and the losses. The interruptions cost is not usually considered in the optimization of the distribution substation placement. In this paper, the importance of the reliability of energy distribution is investigated. Thus, the decision variable ξ determines the approach of optimization. The value of ξ can be equal to 0 or 1. If ξ would be 0, the reliability worth is not considered. If ξ would be 1, the reliability worth is considered in the objective function. This objective function should be minimized. In order to perform a correct comparison of the projects, the cash flows have been translated to the beginning point of the project by the NPV (net present value). The NPV translates the cash flows to a single monetary value. It is broadly used in analyzing the financial procedures. NPV of a project is the sum of discounted flows of costs and benefits over an assumed time horizon [19].

In accordance with [20], the mathematical model of the objective function in the multi-stage planning can be represented as:

$$OF=\sum_{yr=0}^{N_y}\frac{1}{(1+r_d)^{yr}}\left(C_{Inv}^{yr}+C_{OM}^{yr}+C_{L}^{yr}+\xi\cdot C_{Int}^{yr}\right) \tag{1}$$

where: C_{Inv}^{yr}: The investment cost for year yr ($); C_{OM}^{yr}: The operation and maintenance cost for year yr ($); C_{L}^{yr}: The losses cost for year yr ($); C_{Int}^{yr}: The interruptions cost for year yr ($); N_y: Number of years in the study timeframe (year); r_d: discount rate; ξ: The decision variable for considering the interruptions cost.

2.2. Constraint of the problem

The constraints of the optimization problem are radial structure of the distribution network, transformer loading, and voltage drop limits. In the following, these constraints are mathematically expressed.

The purpose of this paper is the placement of transformers, and feeder configuration is not the main issue. Thus, each load point is connected to the corresponding transformer directly and the real configuration of feeder is neglected as done in Ref. [21]. In this approach, each load point must be supplied only from one transformer to have a radial structure, otherwise some loops are formed. Also, all the load points should be supplied. This constraint can be stated as:

$$\sum_{t}\beta^{yr}(t,l)=1 \quad \forall l \tag{2}$$

where: β^{yr} (t,l): Binary decision variable for a feeder from the candidate position t to the load point l in the year yr.

Voltage drop on each feeder does not exceed specific allowable limit. It can be expressed as an inequality:

$$D(t,l)\beta^{yr}(t,l)\frac{S^{yr}(l)}{V}(R\cos\varphi+X\sin\varphi)\le\Delta V_{\max} \quad \forall t,l \tag{3}$$

$$D(t,l)=|xpos(t)-xpos(l)|+|ypos(t)-ypos(l)| \tag{4}$$

where: V: nominal voltage of the LV network (kV); R: Resistance of the conductor used in LV lines (kΩ/km); X: Reactance of the conductor used in LV lines (kΩ/km); $\cos\phi$: The power factor associated to load point l; S^{yr} (l): Maximum power of lth load point (kVA) in the year yr; $\Delta V_{\max}$: Maximum allowed voltage drop (kV); D (t,l): Distance between the candidate position t and the load point l (km); $xpos$ (t or l): X coordinate of the candidate position t or the load point l (km); $ypos$ (t or l): Y coordinate of the candidate position t or the load point l (km).

The load concentration points are dummy points; therefore, their path cannot be found through the streets. The distance between the candidate positions and the load points can be calculated based on radial and straight distances. However, this is not a practical method because it is unlikely to construct such an LV line. Therefore, in the equation (4), the distance is calculated using the summation of the vertical and horizontal distances [22].

The last constraint is related to transformers. Transformer loading must be in an acceptable margin. Transformer loading is in accordance with the proposed method discussed in subsection 3.3.

3. Proposed model

3.1. Proposed cost model

A. Investment cost

The investment cost includes the capital cost of transformers installation and the capital cost of low voltage feeder constructions. It is expressed mathematically in equation (5). It should be noted