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Influence of load alterations to optimal network configuration for loss reduction

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ABSTRACT

The paper investigates how load alterations in distribution systems influence optimal configurations for loss minimization. In the proposed methodology network reconfigurations are implemented utilizing heuristics techniques while load variations are simulated by stochastic procedures. For the examined topologies initial available load data are considered as mean values and new altered load values are produced using uniform distribution. Various scenarios examined are assumed to simulate actual load conditions in order to examine how load variability may change the optimal configuration derived from the initial mean load values. The proposed algorithm was applied in three well known distribution networks from published literature and to a real urban distribution network. The results indicate that for altered load conditions, groups of adjacent sectionalizing switches participate in all the configurations procedures. The work concludes that real management of the distribution networks for loss reduction could rely on a realistic approach which considers limited reconfigurations of the network, derived for the mean load values of the assumed time period. Divergences from optimal solutions are shown to be insignificant compared to the reduction of switching operations.

1. Introduction

Loss reduction in power systems has constituted one of the most important objectives for researchers and engineers. The constant growth of energy demand along with the polluting conventional power plants has forced engineers in searching methods to reduce losses in all three stages of a power systems' operation; generation, transmission and distribution. It is estimated that the largest proportion of losses in power networks corresponds to distribution networks; for a typical system in a developing country, distribution losses account approximately 13% of the total energy produced [1].

Over the past three decades considerable research has been conducted for loss minimization in the area of distribution systems. The basic concept for loss reduction, developed by Merlin and Back [2], aimed to take advantage of the distribution networks' structure. Although distribution systems are designed as meshed networks, they operate as radial ones due to reliability and short circuit issues. The existence of tie switches that interconnect feeders and permit load transfer among them has lead to the idea of network reconfiguration for loss reduction. Changes of the network topology are performed by opening sectionalizing (normally closed) switches and closing tie (normally open) switches. All the needed switching operations are implemented in such a way that a number of constraints, i.e. voltage and current limits, radial structure of the network, etc., are not violated.

Network reconfiguration for loss reduction has been treated by many researchers and through a great number of different approaches. Although Merlin and Back [2] were the first who introduced the concept of distribution system reconfiguration (DSR), Civanlar et al. [3] proposed a purely heuristic algorithm based on a branch exchange method. By this approach they proposed an approximate formula in order to estimate whether a particular switching operation would increase or reduce losses. Shirmohammadi and Hong [4] based their algorithm on the approach of Merlin and Back including optimal power flow as the basic criterion for the switches that should open. Baran and Wu [5] attempted to improve Civanlars' method by introducing two approximation formulas for power flow. Moreover, in [6] the methods concerning loss minimization algorithms published in IEEE transactions between years 1988 and 2002 are presented. The reconfiguration algorithms may be classified by their solution methods in three basic categories; mathematical optimization methods, heuristics, and those based on Artificial Intelligence. In [7] the authors present a mathematical model for loss minimization which consists in introducing non-conventional group of variables instead of the classical bus complex voltages. The main idea is to simplify the mathematical optimization problem by eliminating continuous and binary variables. The result is to formalize the minimization problem with a linear objective function. Heuristics have kept being proposed by researchers for loss minimization due to their simplicity. In [8] a heuristic algorithm is proposed based on the direction of the branch

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power flows while in [9] the reconfiguration problem is solved by a heuristic approach and rules base. The proposed simple rules are formed based on the system operation experiences which in turn enhances the heuristic nature of the algorithm. Some more sophisticated approaches involve artificial intelligence techniques like the genetic algorithms presented in [10,11]. More specific the algorithm presented in [10] is actually a meta-heuristic searching algorithm that combines high local search efficiency with global search ability of intelligent algorithms. The latter constitutes the basic idea presented in [12] where the proposed algorithm is based on a fuzzy approach with some heuristic rules.

In all aforementioned papers loss reduction by network reconfiguration is treated for fixed operational points, assuming constant load demand for all nodes of the examined topologies. In most of these cases, load demand is considered as the peak value. Although this practice offers a common base for the evaluation of the efficiency of all proposed algorithms, it is not suitable for simulation of real operating conditions. In practice, load patterns indicate load variations concerning the networks' consumers, which can fluctuate in high levels for different customer types. Therefore, it becomes obvious that optimal reconfiguration should adapt to account for load variability, in such way, that the frequency of the reconfigurations coincides with the assumed time periods for which minimization of losses is desired.

Broadwater et al. [13] were one of the first teams that tried to incorporate load variability in the reconfiguration problem. A simple case study was used to illustrate that when different load patterns are applied, optimal reconfiguration can actually alter subject to the aforementioned different load conditions. Moreover, in [14] the concept of short and long term operation of distribution systems is introduced. The above approach aims to simulate actual load conditions. An hourly optimal switching algorithm is utilized for the determination of the hourly optimal configuration, whereas concerning the long term operation a method is adopted for the seasonal operation of the network. Peponis et al. [15] focused their analysis in load modelling for the purposes of network reconfiguration, but they also examined load variation with respect to optimizing reconfiguration decisions. In [16] an on-line approach for loss reduction is presented based on artificial intelligence. The proposed method is based on learning classifier systems which continually propose configurations in the case of time-varying profiles of energy requirement. Huang and Chin [17] also applied actual load patterns for different customer types in their examined topology in order to identify the switches that had to change their status during specific time periods of the day. In [18] an hourly reconfiguration is evaluated compared to fixed topologies, considering maximum and average demand of the system. The paper concludes that hourly reconfiguration seems not to be so effective as compared to a simple maximum or average demand configuration. Bueno et al. [19] examined in their work a typical 24-h period for low, medium and high load values. In this case, they concluded that although the optimum loss reduction is achieved when network configurations are altered to adapt to load variations, however, an optimal fixed configuration for a specific load level and time period does not necessarily lead to a significant increase of losses.

In this paper, network reconfiguration for loss reduction has been originally obtained for a fixed operational point. Load variations, considered to simulate actual load conditions, are taken afterwards into account in order to investigate if the previous configuration is modified. The methodology adopted in this work has been applied to some of the most common used distribution topologies in the published literature, i.e. 16, 33 and 69 bus systems, as well as to a real urban distribution network of the city of Thessaloniki, Greece. In this work, stochastic active power of each examined networks' nodes is assumed to be a stochastic variable following uniform distribution.

This paper is organized as follows. In Section 2, the problem formulation is illustrated along with aspects concerning the time-varying loads. In Section 3, the algorithm developed for loss reduction taking into account the load variability is presented. In Section 4, case studies along with their specific parameters are shown. In Section 5 the results of the simulations are presented and finally in Section 6 the conclusions derived are discussed.

2. Problem formulation

2.1. Fixed operational point

Active power electrical losses in power systems are proportional to the square of branch current. The problem of loss minimization in distribution networks can be written for a fixed operational point in a simple form as follows [18,20–22]:

$$\min imize \quad \sum_{k=1}^{m} R_k \cdot \left|I_k\right|^2 \tag{1}$$

subject to:

$$A \cdot I = C \tag{2}$$

$$I_k \le I_{k\,\max} with (k = 1, \ldots, m) \tag{3}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{4}$$

$$m = n - n_s \tag{5}$$

where n is the total number of nodes, m is the total number of branches, n_s is the number of sources, I is the m-vector complex branch current with, C is the n-vector complex nodal current, V_i is the node voltage at node i, A is the $n \times m$ node-to-branch incidence matrix, I_k is the rms current of branch k and $I_{k,\max}$ is the maximum thermal rms current of branch k.

Eq. (2) corresponds to the balance of the load currents in each node. Eq. (3) indicates the thermal limits of the conductors that must not be violated. Eq. (4) defines the down and upper thresholds of voltage in each node. Finally Eq. (5) indicates the radiality restriction in primary distribution systems. This particular condition is not being fulfilled during the algorithm's implementation by a specific term. At the initial stage of the analysis, before the algorithm is applied, radiality is ensured since the analysis in this paper considers only radial distribution networks. During the algorithm implementation the condition is never violated due to the utilized heuristic rules. These rules define that whenever a loop is formed in a network, i.e. closing of a tie-switch, radiality is therefore achieved by the opening of a respective sectionalizing switch. It is also clarified that the link between voltages and currents is expressed by the power flow equations which are utilized for power flow analysis by the proposed algorithm.

2.2. Actual load conditions

In the case where actual load conditions, i.e. load changes defined by actual load curves, are included in the minimization function, Eq. (1) may be written as follows:

$$\sum_{\Delta T=1}^{z} \sum_{k=1}^{m} R_k \cdot \left|I_k\right|^2 \tag{6}$$

where ΔT is the time interval for which loss minimization is calculated, z is the number of time intervals that constitute the examined time period within energy minimization is aimed.

It becomes obvious from (6) that if ΔT is chosen as 1 h and z is considered equal to 24, the loss minimization problem reduces