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Shunt capacitor placement in radial distribution networks considering switching transients decision making approach

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ABSTRACT

This paper provides a new approach in decision making process for shunt capacitor placement in distribution networks. The main core of the evaluation process is a multi-objective framework to allocate the capacitor banks. The power loss and the total harmonic distortion (THD) are the objective functions of the system under study in a long-term planning horizon. In order to select the executive plan introduced by using a multi-objective model, transient switching overvoltages have been considered. As the size and location of shunt capacitors may result in unacceptable overvoltages, the proposed technical decision making framework can be applied to avoid corresponding damages. In this paper, an iterative conventional power flow technique is introduced. This technique can be applied to evaluate THD for distribution networks as well as other power flow based objectives, such as power losses calculation and voltage stability assessment. The presented framework is a two stage one where at the first stage, a non-dominated sorting genetic algorithm (NSGA-II) augmented with a local search technique is used in order to solve the addressed multi-objective optimization problem. Then, at the second stage, a decision making support technique is applied to determine the best solution from the obtained Pareto front. In order to evaluate the effectiveness of the proposed method, two benchmarks are addressed in this paper. The first test system is a 9-bus distribution network and the second one is an 85-bus large scale distribution network. The simulation results show that the presented method is satisfactory and consistent with the expectation.

1. Introduction

Static reactive power compensation carried out by installing capacitor banks has a solid background in power distribution network compensation. Indeed, at the sub-transmission and distribution voltage levels, application of switched capacitor banks has been generally adopted. In particular, capacitors have been commonly used to provide reactive power compensation in distribution systems. Earlier approaches for addressing the capacitor placement problem differ in both the problem formulation and the solution methods. In some approaches, the savings due to energy losses reduction and peak power losses reduction against the capacitor cost are considered as the objective function in an unconstrained optimization. Other researches formulated the problem with some variations of the above objective function and some of them have also formulated the problem as a constrained optimization and have considered voltage constraints [1].

Management of the switched capacitor banks has a vital role in order to achieve power and energy losses reduction, system capacity release and acceptable voltage profile, in the operation horizon. However, the extent of these benefits depends upon the location, size, type and the number of the capacitors as well as their control settings [2]. In the planning stage, determination of optimal size, location and type of capacitor banks are the discrete design decision variables. Although the planning variables of these assets are discrete, they may have a direct impact on the continuous variables, such as bus voltage and loss [3].

Power factor correction is normally achieved by the addition of capacitors to the electrical network which are able to compensate

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the reactive power demand of the inductive loads and thus reduce the burden on the supply without any effect on the operation of the equipment [4]. However, installation of each reactive compensation devices may result in enhanced power quality, reliability and other issues.

The benefits that can be achieved by applying the proper power factor correction are:

- Environmental benefit: reduction of power consumption due to improved energy efficiency.
- Reduced power consumption means less greenhouse gas emissions and fossil fuel depletion by power stations.
- Reduction of the electricity bills
- More active power would be attained from the distribution assets.
- Reduction of active power losses in transformers and distribution equipment.
- Reduction of voltage drop in long cables
- Extended equipment life due to the reduced electrical burden on cables and electrical components.

Combinations of the circuit parameters leading to the maximum over voltages are determined in compliance with the analytical research of voltage magnification, as performed in Ref. [5]. According to the analysis, the phenomenon of voltage magnification occurs when two series connected LC loops have the same natural frequency. The results of the aforementioned analysis (further referred to as the traditional approach) have been adopted in technical literature [6]. Numerical studies of the voltage magnification performed in Refs. [7,8] which enabled to calculate the combinations of the circuit parameters that lead to the maximum over voltages.

It is also worth noting that high transient currents can occur with values higher by ten times than the capacitor nominal current with a duration of several milliseconds [9]. Several parameters that can determine the maximum inrush current have been analyzed in Ref. [10], such as pole spread, the dumping resistor inserted in the current limiting reactor, natural frequency and saturation of the current limiting reactor [11].

However, there are many research works devoted to capacitor placement problem as a vital issue in distribution networks. In this regard, Ref. [12] implemented the above-mentioned problem in order to reduce the power losses as well as improving the voltage profile using ant colony optimization algorithm. Ref. [13] proposes a two-stage framework for locating and sizing of capacitors in radial distribution systems where the loss sensitivity factors are used in the first stage to determine the candidate buses and in the second stage, flower pollination algorithm is used to specify the locations of capacitors among the buses selected in the first stage. It is noted that an improved harmony search algorithm along with power loss index has been employed in Ref. [14] for the capacitor placement in distribution systems. Besides, an optimization technique based on plant growth has been utilized in Ref. [15] to optimally locate the capacitor in power systems. Another research work investigating the optimal capacitor placement in distribution network is Ref. [16] where the problem has been solved using enhanced bacterial foraging optimization while the thermal re-rating of critical cables has been precisely modeled. Furthermore, penalty free genetic algorithm has been used in Ref. [17] for locating and sizing capacitors in distorted distribution systems which include different load models. It should be noted that all these research works have proposed a single objective framework for capacitor placement in distribution systems. However, it is noted that there are some uncertain parameters within the context of capacitor placement problem in distribution networks such as load demand and renewable power generation. In this regard, a comprehensive study on different methods has been carried out in Ref. [18].

The main contributions of this paper are as follows:

(1) Proposing a novel framework for Bi-objective Shunt capacitor placement
(2) Evaluating the Pareto solutions by analyzing the transient overvoltages
(3) Proposing a two-stage framework for the problem of shunt capacitor placement
(4) Employing NSGA-II augmented with a local search to find the Pareto solutions

This paper is organized as follows: in Section 2, the iterative distribution power flow is presented where the classic distribution power flow is modified to address the different types of loads by adopting the successive substitution technique. Section 3 provides the capacitor placement in radial networks. This section addresses the capacitor placement problem as a multi-objective optimization problem considering the power losses and the total harmonic distortion. Section 4 includes the descriptions on the augmented non-dominated sorting genetic algorithm used as the local search technique to determine the optimal Pareto front for the capacitor placement problem. The optimal Pareto set would be then evaluated by using a decision making technique. The transient overvoltage due to capacitor switching in the distribution network is considered for the decision making process in Section 5. Simulation results for the two case studies are provided in Section 6 to evaluate the feasibility and optimality criterion. Conclusion remarks are addressed in the last section.

2. Iterative distribution power flow

The Backward-Forward power flow method has been addressed in the literature to perform distribution load dispatch. As the mentioned model has been proposed for the usual frequency of 50–60 Hz, the implementation of such a technique to consider the harmonic power flow needs to be revised. The method proposed in this paper is based on classical Newton-Raphson power flow algorithm and considers the recursive equations to update the results in the presence of voltage dependent load models. The effects of various load models on the convergence pattern of the method have been verified. As the real distribution networks have several laterals and branches, it is needed to apply a fast and reliable technique with a fair convergence trend to perform the distribution power flow. The proposed successive substitutive power flow method confirms that the convergence ability of the proposed method is acceptable when compared with Ratio-Flow method, which is known for its faster convergence characteristics amongst various sweep methods [19]. In the successive power flow method, the obtained results are used to update the active and reactive demanded power at each load center. As the demanded loads are considered to be voltage dependent, it is needed to iteratively update the active and reactive power.

Since the nature of commercial, industrial and residential loads is such that their active and reactive powers are dependent on the voltage and frequency of the system, it is needed to provide a model which is able to handle these issues. In this study, for voltage depended loads, the power flow model is solved by a successive power flow method and in order to calculate the total harmonic distortion, the modified power flow algorithm should be implemented by taking into consideration the other harmonic orders. Common static load models for active and reactive power are expressed in a polynomial or an exponential form. The characteristic of the exponential load models can be given as: