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A new approach based on the experimental design method for the improvement of the operational efficiency in Medium Voltage distribution networks

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ABSTRACT

This paper presents a new approach for the improvement of the operation in Medium Voltage (MV) networks. The developed methodology is based on an innovative use of the experimental design method, the aim of which being the reduction of the total line losses while ensuring the best voltage profile possible along the feeders of the grid. Practically, it consists in the optimal positioning, sizing and real-time use of the different devices and processes that can currently be employed by the Distribution System Operators (DSOs) to operate efficiently and securely the network: the on-load tap changer (OLTC) of transformer, the reactive power compensation devices, the curtailment of distributed generation (DG) and the load-shedding. This work is divided into two complementary studies. Firstly, a planning procedure is implemented. This stage includes a screening process of the optimal positioning of the network regulation devices followed by a sizing procedure of those devices that takes technical as well as economic constraints into account. Secondly, an optimization process of the values of these parameters is implemented in order to be used in the context of a real-time management of distribution systems. The effectiveness of the proposed approach is then tested on a 28-bus radial MV network with several DG units. The simulations are carried out under various load and generation profiles over an extensive period of time and the evaluation criteria of the methodology are the costs related to the line losses and the probabilities of voltage violation.

Introduction

Over the past years, distributed generation (DG) units have become more and more widely integrated in the distribution networks. This reality mainly comes from the combined effects of the deregulation of connections to power grids and of the technical progresses recently made in renewable energy sources, such as photovoltaic and wind energy generation systems. As a result, the power systems are in a transition state. The old relatively simple structure with unidirectional power flows going from highly powered centralized generation units towards the different consumers is indeed becoming more complex, with more active networks characterized by bi-directional power flows. New technical challenges have thus emerged for Distribution System Operators (DSOs). Among them, the voltage regulation is a real issue due to the intermittent nature of these new power generators.

Traditionally, in distribution systems without DG units, the voltage progressively decreases along the feeder. The drop magnitude depends on the impedance of the line and on the amount of load demand. But with the presence of DG, if the generated power exceeds the local demand of load, the voltage will rise at the DG connected bus. Specifically, in the critical case of low demand and high distributed generation, the voltage may rise beyond the permitted range and provoke the disconnection of some generators. For this reason, both low and high voltage issues have to be taken into account in the voltage regulation of the current distribution networks. However, this objective of ensuring a good voltage profile can be in conflict with the minimization of power losses that are very costly for the DSO.

Currently, several strategies can be applied to improve the operation of the grid. The most popular method is the use of the on-load tap changer (OLTC) of the HV/MV transformer [1]. The principle is to adjust the turn ratio of the transformer winding when the voltage goes outside its acceptable limits. The reactive power compensation technologies are also very useful to get a better voltage profile in a power system but could also be used

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to optimize the reactive power flows. Devices like Static VAR Compensator (SVC) or Static Synchronous Compensator (STATCOM) have indeed the interesting ability to work in both inductive and capacitive modes [2]. Similarly, the possibility to use the reactive power produced by DG units [3] as well as the introduction of storage utilities [4,5] are also investigated solutions. Then, if the amount of power flows exceeds the network capacity, the network reinforcement could also be considered. Other methods like load-shedding (in case of overload) or curtailment of DG power (in case of oversupply) should only be used as a last resort as it often implies financial compensation for the service.

In this paper, a new procedure aiming at the line losses minimization and voltage profile improvement is proposed. The voltage, along with the grid frequency, constitute indeed the most important parameters for the stability of power systems. These are indeed essential for ensuring continuity and quality of service to the consumers. Furthermore, maintaining a good voltage profile has a beneficial effect on the aging of the network equipment, which can therefore allow the postponement of investments. Concerning the power losses, these cause significant costs for the DSO, in the range of 100 $/MVAh concerning the Belgian system. Moreover, the reduction of power flows infers automatically a decrease of the probability of line congestion.

The developed methodology is based on the experimental design method, which is also referred to as Design of Experiments (DOE), and constitutes a powerful tool to establish and study the effects of multiple inputs (factors) on a desired output (response). This statistical theory has therefore been thoroughly explored and applied to many real experiments in the last decades including in electrical engineering [6–10], but remains little known in power systems applications. In [11] and [12], the DOE is applied to analyse the significance of each component of the distribution network modeling, and to study the influence of effective parameters on the grid operation, respectively.

Here, the purpose of the work, whose general structure is represented in Fig. 1, is to assess the effectiveness of the DOE for two complementary studies. Firstly, a two-step planning procedure is conducted for identifying the devices that ensure the biggest profitable effect on the operation of the network. In order to achieve that goal, the different possible locations of OLTCs and reactive power compensators are first selected. This choice, which allows reducing the number of studied factors, is based on technical considerations. In this way, the VAR compensators are preferably installed at the line extremity in order to take advantage of the bigger line impedance. The pre-sizing of those VAR compensators is adapted to the maximum reactive load of the study case. The screening process is then performed and allows determining the optimal positioning of the selected network regulation devices. An innovative sizing process that takes technical as well as economic criteria into account is then performed by using a Response Surface Methodology (RSM) approach. The second objective is to find the optimal values of the previously selected devices under various load and generation profiles in the context of real management of the distribution grid.

The improvement of MV network operation is an important matter of concern, studied for several years. First, in [13], a planning method to determine the optimal location of devices for the voltage control in case of insertion of DG units was developed. The method made use of Reactive Tabu Search (RTS) to decide the number and the location of the devices by taking into account the installation costs. In [14], the optimal allocation of FACTS devices for fair and equitable procurement of reactive power is considered. In [15,16], the benefits of FACTS devices for voltage control in electrical grids are highlighted. More recently, in [1], a new voltage control method combining the benefits of OLTC action and D-STATCOM response was proposed. According to the authors' knowledge, DOE was never used to solve the issue of the optimization of the MV systems operation, which makes this contribution original. Furthermore, this method proposes to use reactive power support devices operated with an external command coming from a centralized control. Indeed, the current SVC/STATCOM devices are comparing the voltage at their connection node to a fixed reference voltage in order to bring back the voltage at the defined reference level. But sometimes, it could be interesting to change that reference depending on the location of the device in the grid. For example, to lower it when there is an increased power generation coming from DG units combined with a low demand.

Finally, this paper is structured as follows. First, in Section 'The experimental design method', the DOE method is introduced. Then, in Section 'Application of the DOE method for improving the MV network operation', the proposed methodology is presented and applied to a 28-bus MV network. Finally, in Section 'Application of the DOE method to a 28-bus radial MV grid', the collected results are exposed and discussed.

The experimental design method

The DOE method involves only two types of variable, the response of interest (y) and the k predictor variables ($\xi_1, \xi_2, \ldots, \xi_k$) or factors which are supposed to influence the response. The purpose of the method is to establish a description of the system of the form [17]:

$$y = f(\xi_1, \xi_2, \ldots, \xi_k) + e \tag{1}$$

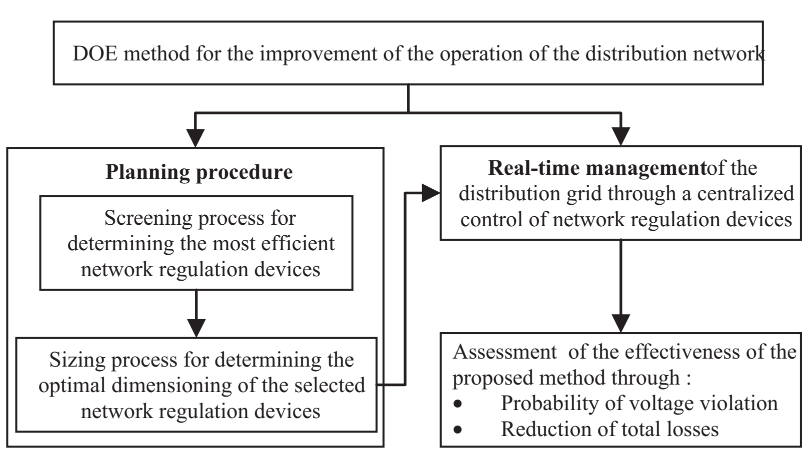

Fig. 1. Structure of the proposed method for the improvement of the operation of the MV distribution grid.