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Multiobjective optimization for power quality monitoring allocation considering voltage sags in distribution systems

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ABSTRACT

In this research, a multiobjective optimization approach is proposed to help allocate Power Quality (PQ) monitors in Distribution Systems (DS), focusing on: minimizing the cost of monitoring; minimizing topological ambiguity; maximizing the load monitoring; maximizing the amount of monitored extensions; minimizing the amount of Voltage Sags (VS) that are not monitored and maximizing the monitoring redundancy of the VS. A Multiobjective Evolutionary Algorithm with Tables (MEAT) was used to solve the problem. Results from the IEEE test systems showed that the MEAT provided the Pareto Fronts with diversified and well-distributed solutions, which made them relevant for planning monitoring systems for PQ in DS. The proposed model enables power companies to evaluate investments needed for continuous monitoring of PQ, ensuring greater flexibility in the monitoring plan and a better analysis of the cost/benefit ratio considering the six objectives presented.

1. Introduction

Considering the current characteristics of electrical systems, with increasing quantities of non-linear loads, many efforts have been made to minimize disturbance effects arising from a lack of Power Quality (PQ) [1]. Taking this into account, constant monitoring of PQ is essential to take corrective measures and identify where the disturbances come from in the system. Thus, monitoring the system efficiently would allow for different applications, such as diagnosing the operating conditions; locating events associated with a lack of PQ; sharing information between remote locations; studying how PQ events spread; evaluating the cost of PQ; and improving preventive maintenance programs, among others [2]. It is known that the investment required for completely monitoring Electric Power Systems (EPS) is relatively high and can be technically unfeasible due to economic and practical issues.

Alternatively, only some specific points in EPS are monitored. However, this approach results in another difficulty, which is to define the best places to install the monitoring equipment. For technical and operational issues, in the context of PQ, there is no prior knowledge regarding the points where the monitors should be installed in order to provide the best overview of the situation faced by the EPS. The initial location to install a power quality monitor will be dependent on the objective of the research conducted. Furthermore, most of the events associated with Voltage Sag (VS), such as short-circuits, have a stochastic nature, which also hinders a continuous monitoring plan.

In practice, installing a PQ monitor in Distribution Systems (DS) is directly related to consumer complaints received by the utility. As described in [3], PQ monitors are allocated by experts and these professionals install them according to general guidelines, PQ knowledge and DS topology. Main or express feeders or even specific customer venues (when requested) are generally chosen as good locations for a monitor. However, the authors emphasize that for an automatic approach, these guidelines and knowledge must be clearly formulated and standardized, leading to better results.

Due to the high cost of acquiring and maintaining monitoring equipment concerning voltage sags, various studies have been carried out resulting in different methodologies for optimal monitor allocation focusing on PQ. Considering this, the methodologies presented in [4,5] should be cited, which use graph theories to express the connectivity among DS nodes to find the best allocation schemes.

In this regard, several studies suggest methodologies to optimize the allocation of PQ monitors in EPS. For instance, there are studies which aim to ensure full coverage of the VS occurrence [6–10], and other proposals focused on ensuring redundancy [9,11,12] and the topological monitor reach area [10] when monitoring these events. Another study seeks to optimize the allocation of monitors that benefits the fault location in EPS [13]. In [14], monitors are allocated in accordance with

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the importance of the load, which is considered to tackle nontechnical losses [14]. Research has also been carried out to optimize the allocation for monitoring harmonic distortion [15]. Other studies have been conducted to locate the origin of voltage fluctuations, such as flicker [16]. In another hand, there are proposals for optimal monitor placement applied to estimation of voltage unbalance [17].

Based on the existing research found, it can be seen that there are different criteria that may be considered and analyzed for an optimized monitoring plan. However, in most research, monitoring planning is optimized for a particular type of event. Another aspect found in the literature is the concern to find the monitoring system that needs the smallest investment possible to implement it. However, when minimizing the cost, there is always a cost/benefit ratio between the amount to be invested and the quality of the measurements provided by this investment. Therefore, there may be solutions that require greater investment, and which have a cost/benefit ratio equal to or better than the less expensive solution.

In this context, this paper presents a multiobjective modeling to help allocate PQ monitors in DS. Selecting monitoring points in DS, which are mostly radial, is a challenging task as it involves the topological characteristics of the system and the loads connected to it [4].

The proposed approach aims to reduce monitoring costs; minimize the topological ambiguity; maximize voltage sag monitoring coverage; maximize monitoring redundancy of sags; and maximizes load monitoring and monitored lateral branches. A Multiobjective Evolutionary Algorithm with Tables (MEAT) was used to solve the problem. The results of the distribution system models of IEEE 13, 34 and 37 bus bars [18] demonstrated that the MEAT provided the Pareto Fronts (PF) with diversified and well-distributed solutions, which made them relevant for planning monitoring distribution systems.

2. Problem modelling

DS radials can be analyzed as tree graphs. This work adopts this representation, as it is appropriate and conducive to the mathematical modeling of EPS [3].

Fig. 1(a) illustrates a generic example of a 6 bus bar (nodes) DS. Fig. 1(b) also shows the representation of a 6 DS tree.

Fig. 1(b) shows that the components (lines and loads) of the feeder circuit are the tree nodes, interconnected by arcs (oriented edges), which denotes the hierarchy between the elements. The tree representation illustrates the hierarchical relationship between the nodes. For example, node $L1$ is the tree root and is connected to nodes $L2$, $L3$ and $L4$, namely the three nodes are descendants of $L1$. Regarding node $L7$, this is considered the father of node $L12$. Following the same logic, nodes $L6$, $L9$, $L10$ and $L11$ are descendants of $L3$. In addition to the tree representation of the DS, a property and a number are assigned to each component (each node of the tree). The possible properties are the Main Feeder (MF) (or feeder trunk), Lateral Branches (Lb) or Load (Lo). A node (that may belong or not to the MF) is determined from the root among the Lb arising from a node. The nodes with the largest number of descendants from the root to a terminal node are the main nodes. After defining the path comprising the main nodes, called the MF or trunk, the derivations of the feeder including the nodes with no loads and those which do not belong to the trunk are defined as Lb. The numbering of each node of the tree is done in accordance with the node number and the position that the component has in connection with the node. Thus, component c_{ij} is the jth component connected to node i.

Afterwards, the variables and the objective function equations adopted in this research are presented, which will be used to characterize the multiobjective modeling proposed.

2.1. Monitor allocation in one component

The indication of whether a particular component c_{ij} (MF, Lb or Lo) is directly monitored or not is performed by the x_{ij} variable, where

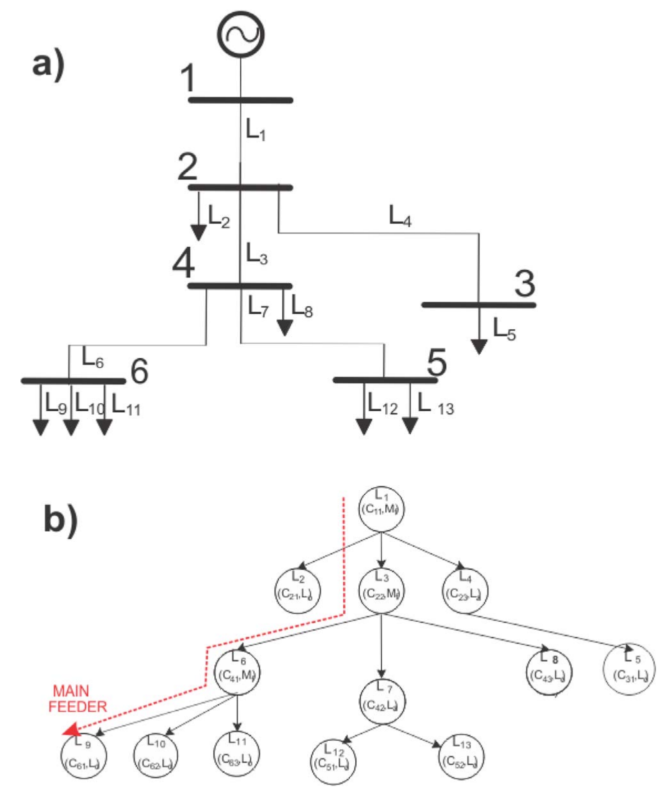

Fig. 1. A generic example of (a) DS model of 6 bus bars; and (b) its respective tree representation.

value 1 indicates that a monitor is allocated on the jth component connected to the tree node i of the DS.

$$x_{i_j} = \begin{cases} 1, & \text{if there is a monitor installed in component } c_{ij} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

2.2. The cost of DS monitoring

The cost of the monitoring system is defined by Eq. (2).

$$f_1(x) = \sum_{i=1}^{n} \sum_{j=1}^{N_i} p_{i_j}.\, x_{i_j} \tag{2}$$

where p_{ij} is the cost to monitor the jth component connected to node i of the DS tree, n is the number of nodes of the DS, and N_i is the number of components connected to node i. The cost of allocating a monitor on a node can be determined considering the cost of the equipment itself, the cost of installing and monitoring it, as well as the communication channels for accessing, retrieving and processing all the necessary information.

2.3. Load monitoring in a DS

The load amount in a component c_{ij} is designated by l_{ij}. Accordingly, the power installed in a DS, monitored by a particular arrangement of monitors, is determined by:

$$f_2(x) = \sum_{i=1}^{n} \sum_{j=1}^{N_i} l_{i_j}.\, x_{i_j} \tag{3}$$

where l_{ij} is the active power load connected to the jth component connected to node i of the DS tree, and n and N_i are defined according to Eq. (2).