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Power quality monitor placement in power systems considering channel limits and estimation error at unobservable buses using a bi-level approach

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ABSTRACT

The aim of this paper is to propose a new method for locating power quality monitors (PQMs) in a power system at different depths of unobservability. In this method, the placement problem is solved in two levels, taking into account the limitation on the number of measuring channels of these devices. At the first level of this method, different combinations of connecting lines are selected, while the second level determines the best location of monitors for each combination, at different unobservability depths. In addition, the second level also identifies the critical buses and considers their effects on the number and location of monitors. The proposed method also minimizes the voltage phasor estimation error at unobservable buses as well as the cost of these devices as the main objectives. Therefore, this method will find the best location for installing monitors and the minimum number of channels required by these devices to make all power quality parameters, i.e. voltage and current phasors, observable. The results of applying the new method on IEEE 14-bus and IEEE 30-bus power systems and the Iranian south east regional grid (ISERG) demonstrates the performance of proposed method.

1. Introduction

Nowadays, accessibility and reliability as well as quality of electrical power is highly crucial. The power quality disturbances such as overvoltage, undervoltage, harmonics, transient phenomena etc. could affect the consumers. In fact, the equipment inserted today in electrical installations are so sensitive that power delivery with poor quality can lead to malfunction of the equipment as well as technical/economic issues [1]. Therefore, power consumers, particularly the industrial sector, require that power quality be delivered at a reliable and appropriate level. However, the first step in evaluation of power quality is monitoring.

The task of monitoring in power grids is not a new subject matter, but the issue of monitoring power quality phenomena in transmission systems has been discussed only over the recent decade. Knowledge about the chain of events that led to an interruption or blackout is important for preventing future events. Power quality monitoring is the process of gathering, analyzing and interpreting raw measurement data into useful information. The monitoring devices enable the engineers and the network operators to analyze the network for certain quality attributes that can have major effects on the system [2]. In this regard, two type of power quality monitors (PQMs), i.e. portable and permanent PQMs, are used. However, the portable type is suitable for analyzing harmonics and other phenomena in distribution systems. In the other hand, the data obtained from permanent monitors can be used to analyze the system events that led to an interruption or blackout. Even though disturbance recorders have been installed by transmission operators for this purpose, power quality monitors may give important additional information. The monitoring process could be an online monitoring process whereby the system will be monitored continuously for any interference or failure that might occur. Then there could be an alarm indicator for the system operator to take the required action. It could also be a long-term monitoring process whereby the measurements of the various quality characteristics and attributes are being stored into databases for generating periodic reports that will help in improving the overall system, make future enhancements or take prevention actions [3]. There are a number of power quality phenomena that cannot intrinsically be detected through routine monitoring equipment due to the lack of observability in some buses. Ideally, it is essential to monitor all power quality parameters, i.e. voltage and current phasors, in all buses to achieve full observability of a transmission system. However, it is not cost-effective to install power quality monitors at all buses. Therefore, there have been numerous methods proposed so far to determine the optimum number and location of power quality monitors in a transmission system. In general, the PQM placement methods can be divided into four categories.

In the first category, which was first introduced in 2003 [4], a monitor reach area-based (MRA) method was introduced to determine

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the optimum location of monitors. MRA represents an area of grid visible from the position of a monitor. According to this definition, the measurement device will record the fault if it occurs inside the MRA; otherwise, it will not be recorded [4–7]. The studies in the second category present algorithms based on graph theory (GT) to monitor voltage sags in power systems [8]. In these methods, the power system is displayed by a simple graph and then the grid coverage matrix is achieved. Moreover, it is essential to specify weight factors for all circuit elements. Therefore, this method is ideal for displaying the relationship between elements and real points in a power grid [9]. In addition, the graph theory needs to determine a rooted tree where there is a parent-child relationship. Since there might be error in determining this relationship in transmission grids, the GT-based methods are suitable only for radial distribution systems [10]. In the third category, which is based on a multivariable regression model (MVR), all data related to single phase to ground, double phase to ground and three phase to ground faults are collected on each bus [11]. Then, the correlation coefficient is calculated to indicate the relationship between buses during the disturbances. At the next stage, the two buses with the highest correlation values are detected as the most sensitive buses across the grid. The voltages of the two buses are considered as an independent variable in the MVR model developed to estimate the voltages of other buses [12–15]. Finally, the fourth category includes papers that use methods based on the covering and packaging (CP) concept in which the constraints of the problem ensure that all state variables (bus voltages and line currents) are observable at least by one monitor [16,17]. In [17], a new multi-objective method is presented for PQM placement. In this method, the optimization problem is solved using a density matrix, which is formed based on connections between buses. Furthermore, the placement problem is solved through a branch-and-bound algorithm, where the cost of installation is specified according to the number of lines passing each bus. Similarly, [18] employed the multiobjective evolutionary algorithm with tables (MEAT) to minimize the costs of installing monitors and maximize the redundancy factor. Ref. [19] proposed a method for monitoring power quality in distribution systems based on the p-median model. This model involves a limitation in dealing with localization of monitors based on importance of loads.

In most relevant, the placement problem has been explored from the perspective of grid topology serving to improve the solution. However, there are several factors and constraints affecting the number and location of monitors. One of the factors potentially contributing to placement of power quality monitors is the number of measurement channels of each monitor. Channel limitation is considered in a few number of Refs. [20,21]. Ref. [20] has presented a methodology based on evolutionary algorithms (EAs) which defines the configuration required for monitoring system, in order to monitor voltage and current state variables. Besides the number of meters and the installation sites, this methodology defined how the meters should be connected to a power network. In [21] a modified algorithm based on integer linear programming (ILP) model for the optimal placement of phasor measurement units considering the limitations on the number of measuring channels is presented. This study investigated the effect of channel capacity of measurement devices on their optimal placement for optimal power system observability. Since the number of measurement channels in each device is effective on the marginal cost of purchase and installation of PQMs, the involvement of the above parameters can lead to more practical solutions than conventional methods. The zero injection buses (ZIBs) can be another factor contributing to find optimum locations for installing monitors. In a power system, some buses are not connected to any generator, compensator or load. Therefore, in such buses, which are called as ZIBs, current flow is nearly equal to zero. Since the Kirchhoff's current law (KCL) applies to these buses, they can be integrated with their neighboring buses, which will be helpful in reducing the number of required PQMS and in turn reducing the final cost. In addition, there are a number of buses in the system, which their voltage variables should be measured directly by monitoring devices to have a better estimation for the variables at unobservable buses. In these buses the estimation error is more than an acceptable value, hence it is necessary to install a monitor in such buses to achieve their data with high accuracy. Therefore, these buses known as critical buses should be included in the PQM placement problem.

This paper proposes a new multi-objective bi-level method for finding the optimum number and location of power quality monitors in a power transmission system, while minimizing the error in voltage estimation at unobservable buses. Moreover, the new method considers the effects of zero injection buses and the number of measurement channels in each device. In the proposed method, the first objective is to minimize the installation cost, which includes a fixed cost for each PQM and a variable cost related to the used and unused channels of these devices. The second objective is to minimize the error in estimating voltage phasor of unobservable buses, which is necessary for achieving accurate monitoring of power quality disturbances. To achieve these goals, this method consists of two levels, where each level has its own optimization problem. Therefore, the final solution of proposed method will determine the number of PQMs, the locations for these devises to be installed, their type from the point of number of available channels and, the transmission lines that their currents should be measured to reach full observability of power system. Moreover, in this method, state estimation is used to determine the critical buses at different depths of unobservability.

2. PQM placement problem

The problem of locating PQMs can be formulated as a classic combinatorial optimization problem. In [16], the CP-based method for finding the optimum location of PQMs in a transmission system has been introduced. This method involves a binary optimization problem, where the equations are as follows.

$$\min f(x) = \sum_{i=1}^{N_B} c_i x_i = C^t.\, X \tag{1}$$

$$\textit{Subject to:}\quad DX \geqslant b \tag{2}$$

In (1), C is a $1 \times N_B$ matrix and represents the installation cost of PQM at each bus, where N_B is the number of buses in the system. X is also an $N_B \times 1$ binary integer matrix. After solving the above problem, the elements of X will be only zero and unity, where zero elements represent that there is no need to install PQM at the corresponding buses, while unity elements show the buses that their data is required for achieving full observability of the system. Eq. (2) provides assurance that each required parameter, i.e. bus voltage and line current, are directly or indirectly observable at least by one monitor. In (2), b is a matrix whose elements are all unity and D is a density matrix [16]. The density matrix can be formed by obtaining the matrix A of the system with dimensions of $m \times N_B$, where m represents the number of state variables. In A, column k indicates the kth bus and row r represents the rth state variable (bus voltage or line current). Each member of matrix A is defined as follows:

$$A(r,k) = \begin{cases} 1, & \textit{if } r \textit{ is observed by PQM } k \\ 0, & \textit{otherwise} \end{cases} \tag{3}$$

In fact, a bus voltage becomes observable when a monitor is installed at that bus or at one of the adjacent buses. Moreover, a line current becomes observable when a monitor is installed at each bus on both sides of the line. Therefore, A can be divided into two sub-matrices, one of which is related to the observability of bus voltages (A_v) while the other one relates to the observability of line currents (A_i) as follows.

$$A = \begin{bmatrix} A_v \\ A_i \end{bmatrix} \tag{4}$$