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# A Review of Power Quality Monitor Placement Methods in Transmission and Distribution Systems

***Abstract****. In today's modern world, customers require a high level of power quality than ever before because of the increasing availability of semiconductor devices and microprocessors that are more sensitive against power system disturbances. One of the most frequently occurring types of power quality disturbances are voltage sags, which are considered to likely have a severe impact on sensitive load. Thus, power quality monitors (PQM) are required to be installed in many buses in a power system to assess disturbances such as voltage sags. However, the installation of PQMs at all buses considered in the system is uneconomical. Generally, PQM placement comprises four main methods, namely, monitor reach area, covering and packing, graph theory, and multivariable regression. This paper presents a comprehensive review of articles that deal with various methods of PQM placement. The concepts as well as the advantages and disadvantages of these methods are discussed and tabulated for an all-exclusive review. Although this paper does not show a comparison of numerical performance, most of the research publications on the subject of PQM placement methods are sorted and appended for easy reference. This work may be considered as an important guide for researchers who are interested in knowing and developing better PQM placement methods.*

***Streszczenie.*** *W artykule przedstawiono przegląd dotychczasowych prac dotyczących określenia lokalizacji montażu urządzeń do monitoringu jakości energii w sieci. Omówiono idee działania, wady i zalety każdej z metod. Nie dokonano porównania złożoności obliczeniowej. Niniejsza praca stanowi przewodnik dla badaczy pracujących z tego typu urządzeniami. (****Przegląd sposobów lokalizacji punktów monitorowania jakości energii w systemach przesyłu i wytwarzania energii elektrycznej****).*

**Keywords:** Power Quality Monitor Placement, Monitor Reach Area, Covering and Packing, Theory Graph, Multivariable Regression.
**Słowa kluczowe:** lokalizacja urządzenia PQM, zasięg obserwacji, teoria grafów, regresja wielozmienna.

## Introduction

Power quality (PQ) has been defined as the ability of electric utilities to provide pure electric power without interruption [1]. In the world today, different electronic devices and microprocessor-based industrial processes that require high-quality power supply are widely applied. For this reason, PQ has become an important concern for customers as well as for utilities [2]. PQ problems, such as sag, swell, harmonic distortion, imbalance, transient, and flicker, can impact customer operations, causing malfunction costs on lost production and downtime [3-6]. Hence, PQ monitoring systems are the first step in power quality assessment and mitigation.

One of the main steps in obtaining information about voltage sag disturbances is implementing PQ monitoring in the power supply networks [7]. Ideally, the whole power system should be monitored by power quality monitors (PQMs) at each bus, then all the monitors should be integrated in a communication facility [8-12]. However, such a method is not cost effective and not economically justifiable because of the huge amount of redundant data generated. Therefore, methods for selecting the number and the location of the monitored sites must be developed to minimize the number of monitors without missing any optimum essential voltage sag information and to reduce the cost of monitoring [13, 14].

In recent years, several studies have been presented to solve the PQM placement problem by determining the optimal number and location of PQMs. A primary requisite in selecting the location of monitors is that the location must guarantee observability of the entire system and must ensure that any voltage sag event is captured by at least one PQM [15]. In accordance with this criteria, PQM placement methods can be classified into four main methods, namely, monitor reach area (MRA), covering and packing (CP), graph theory (GT), and multivariable regression (MVR). A few optimization techniques have been applied for determining the optimal number and location of PQMs in power systems. In 2003, a new concept known as MRA was introduced for the optimal location of PQMs [16]. The MRA is defined as the area of the network that can be observed from a given monitor position. An improved optimal monitoring program was introduced in [17, 18]. It uses a new optimization problem formula and a genetic algorithm (GA) to identify the optimal locations of meters. In [17], integer programming and fuzzy logic were applied to determine the optimal placement of PQMs in a large transmission network for assessing voltage sags. In 2009, an approach was presented based on the monitor reach matrix (MRM) obtained from the solution of the analytical expressions for the optimal location of voltage sag monitors [18]. Another optimal PQM placement method considered the use of severity index, MRA matrix, and genetic algorithm [2]. A different concept called the CP was developed to determine the optimum number and location of PQMs. It was based on minimizing the cost of PQMs using the integer linear programming (ILP) technique [7]. A monitor positioning algorithm was selected to determine the optimal number and location of PQMs for a given distribution system [19]. In this algorithm, the GT is applied, and system topology is considered to form the coverage matrix. A relatively new PQM placement method was proposed in [20] using the MVR model and the *Cp* statistical index. In this MVR method, the voltage sag sensitive buses are initially identified using correlation coefficients that provide the relationship between buses during voltage sags. The voltages of the sensitive buses are then treated as independent variables in the MVR model [21] to estimate the other bus voltages. The optimal number and location of PQMs are determined based on the lowest value of the *Cp* statistical index.

The main objective of this paper is to provide a comprehensive review of the PQM placement methods in power systems. Accordingly, the concepts as well as the advantages and disadvantages of these methods are discussed and tabulated for an all-exclusive review.

## PQM placement

To accurately identify the fault location, the PQMs must be installed on all buses for PQ analysis and diagnosis, which is very costly. Hence, developing methods for selecting the optimum number and location of the monitored sites is necessary to minimize the number of monitors without missing any essential voltage sag information.

The following section provides an overview of the existing methods in the placement of PQMs. These methods use MRA, CP, GT, and MVR. The development of these methods is arranged chronologically in Fig. 1.

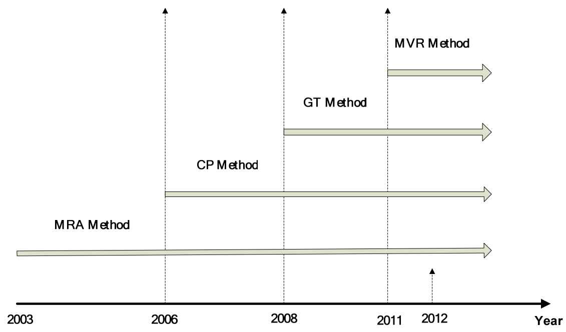


Fig. 1. The development of the PQM placement methods.

**Monitor Reach Area (MRA) Method**

In 2003, Olguin et al. proposed a method based on the MRA concept which gives the area of the network that can be observed from a given meter position [16]. According to this definition, if a fault is inside the MRA, then the event will trigger the sag meter, while faults outside the MRA, it will not [22]. Thus, the MRAs of all possible locations are determined to establish and to formulate the optimization problem that is solved using the branch and bound search [23, 24]. By knowing the bus impedance matrix Z, the dip voltage of any given bus per unit can be obtained by

(1) $$V_{dip} = Ones - Z.Inv(Diag.(Z)) \ ,$$

where $V_{dip}$ is the dip matrix that contains the residual voltage of all the buses, *Diag.(Z)* is the diagonal matrix of *Z*, and Ones is a matrix with all its elements equal to one. According to (1) and to the definition of MRA, $MRA_p$ can be obtained as

(2) $$MRA_p = MRA_{ij} \begin{cases} 1 \rightarrow if v_{ij} \leq p \\ 0 \rightarrow if v_{ij} \geq p \end{cases} ,$$

where all the MRAs use a binary matrix in which "1" in (i , j) indicates that node j belongs to the MRA of a meter located at bus i with a voltage threshold p. In addition, in [16], the concept of monitor observability is used to find the optimal placement of PQMs in transmission systems. The proposed approach cannot assure complete observability because its formulation is based on a limited number of fault positions and is applied to a single type of fault. Moreover, it is not suitable for radial distribution networks [25].

In [26], an improved optimal monitoring program that identifies the optimal location of meters using a GA is introduced. Moreover, a new algorithm is presented in [17] for the optimal placement of monitors based on GA and combined with fuzzy logic. Comparing this technique with MRA, the fuzzy boundary concept allows better arrangement of monitors and improves the observation index, as presented in [17]. In 2009, an approach based on the MRM obtained from the solution to analytical expressions was presented for the optimal location of voltage sag monitors [18]. This approach can ensure complete observability of the power system for any type of fault (balanced or unbalanced). Another algorithm was presented based on the concept of the MRA and the sag severity index for the placement of PQMs [2]. This paper used GA to solve the optimization problem. Moreover, the researcher developed an algorithm based on particle swarm optimization (PSO) to solve the optimal PQM placement in both transmission and distribution systems [27]. In 2010, a technique was presented based on the MRA and the fault location observability analysis (FLOA). It solved the two issues of determining the monitor placement sequence of optimal monitoring programmers and of evaluating the effectiveness of sub-optimal monitoring programs[28]. In [29], the researchers used the MRA and the MRM to determine the optimization problem, which was solved using the PSO algorithm. Table 1 shows the MRA methods used by researchers from 2003 to 2010.

Table 1. MRA methods used by researchers from 2003 to 2010

| Researcher | Year | MRA | GA | Fuzzy | PSO | FLOA | Transmission | Radial | Faults |
|---|---|---|---|---|---|---|---|---|---|
| Olguin | 2003 | ● | - | - | - | - | ● | --- | Balanced |
| Mazlumi | 2007 | ● | ● | --- | --- | --- | ● | --- | Balanced and Unbalanced |
| Haghbin | 2009 | ● | ● | ● | --- | --- | ● | --- | Balanced |
| Espinosa | 2009 | ● | --- | --- | --- | --- | ● | --- | Balanced and Unbalanced |
| Ibrahim | 2010 | ● | ● | --- | ● | --- | ● | ● | Balanced and Unbalanced |
| Moraa | 2010 | ● | --- | --- | --- | ● | ● | --- | Balanced and Unbalanced |
| Wei | 2010 | ● | --- | --- | ● | --- | ● | --- | Balanced and Unbalanced |

**Covering and Packing (CP) Method**

The CP method is presented to determine the optimum number and location of PQMs [7]. It is based on minimizing the cost of PQMs when formulated as a CP problem using the ILP technique [30]. The objective function is defined as

(3) $$f(x) = C_1 x_1 + C_2 x_2 + ... + C_n x_n \quad f(x) = \sum_{j=1}^{n} C_j x_j \quad ,$$

where x is the optimization variable, C is the cost of each variable, and n is the bus number.

The constraints of this objective function are used to ensure the observability of the state variables (i.e., voltages and currents). The observability of a system depends on its state equations. These equations can be written based on Kirchof's voltage and the current law. One limitation of the CP method is its use of Kirchhoff's current law and Ohm's law to obtain the whole picture of the system's connectivity to evaluate the observability of monitors in the system. Moreover, the constraints of the optimization problem formulation in the CP method are based on steady state information rather than on actual voltage sag information. In [31], a new algorithm was presented for optimizing PQMs based on the CP method. This method improved the CP method for multivoltage level power systems, whereas the method in [7] was only tested on a system with one voltage level.

**Graph Theory (GT) Method**

In 2008, Dong and Seung presented a new algorithm to monitor the voltage sag in a power system based on the GT [19]. The power system network was represented by a simple graph and then converted into the corresponding incidence matrix to obtain a network matrix. Hence, the methodology is suitable for showing the relationship between the elements and the real nodes in power networks [32]. Moreover, the concepts of rooted tree [33], up/down area [34-36], coverage matrix [34], and weighting factors [37] are used to determine the optimal number of PQMs. The optimization routine for finding the optimal number and location of the monitors can be formulated. The objective function and its constraints are formulated in (4) as follows [21]:

(4) $$\min F(X) = \min_{x_{ij}} \left[ \sum_{i=1}^{n} \left\{ \alpha_i \cdot \sum_{j=1}^{N_i} (\beta_{ij} \cdot \gamma_{ij} \cdot x_{ij}) \right\} \right]$$

subject to $NM_{\min} \le \sum_{i=1}^{n} N_i - \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} < NM_{\max} + 1$

where $\alpha_i, \beta_{ij}, \gamma_{ij}$ are the weighting factors, *i* is the bus number, *j* is the component number, *n* is the total number of buses, $N_i$ is the number of components at bus i, $NM_{\min}$ and $NM_{Max}$ are the minimum and maximum numbers of monitors, respectively, and $x_{ij}$ is "0" (if $c_{ij}$ is monitored) or "1" (if component $c_{ij}$ is not monitored). The results in this paper show that the method is suitable only for radial power networks, and that the number of PQMs increases with the number of buses in the network.

**Multivariable Regression (MVR) Method**

In 2011, a new method was presented based on the MVR model [21]. Cp and Rp statistical indices were used in the placement of PQMs [20]. First, all data on single phase to ground (LG), double phase to ground (LLG), and triple phase to ground (LLL) faults in each bus are collected. Then, the correlation coefficient (CC), which shows the relationship among buses during system disturbances, is calculated. The two buses with the highest CC values are identified next. These buses are considered as the more sensitive buses in the system. The identified bus voltages are then considered as independent variables in the developed MVR model to estimate the other bus voltages [38].

(5) $$B = (X'X)^{-1} X'Y, \quad \widetilde{V} = B_0 + \sum_{j=1}^{k} B_j V_{ij}, i = 1,...,n$$
$$E = V - \widetilde{V},$$

where B, X, Y, E, V, and $\widetilde{V}$ are the regression coefficient, independent variable, dependent variable, error, and the observed and estimated voltages, respectively.

Finally, two or three buses that have maximum and minimum frequencies of the CC are selected. The $C_p$ and $R_p$ statistical indices are calculated using the sum of square error of the estimator and the mean square error. The appropriate number and placement of PQMs are then determined based on the lowest value of the $C_p$ and on the suitable value of the $R_p$ [39, 40]. The $C_p$ statistic and the $R_p$ are given by

(6) $$C_p = \frac{SSE(p)}{MSE(p)} - n + 2p,$$

(7) $$R_p = 1 - \frac{SSE(p)}{Syy(p)},$$

where *SSE* is the residual sum of square error, *MSE* is the total mean square error, *Syy* is the total sum of square, *n* is the number of observations; and *p* is the number of variables. To validate the proposed placement of the PQM method, the IEEE 6, IEEE 9, and IEEE 30 bus test systems are used as the transmission network, and the 69 bus test system is used as the radial distribution network.

Table 2 shows the review survey results of all methods used in PQM placement. According to the table, the GT method have limitation if utilized at a transmission network. Morover,the number of PQMs increases with the number of buses in a power system as with the CP and GT methods. There are some limitations in the MRA method, but improvement has been made by researchers in 2003 to 2010. Comparing the four methods shown in Table 2, it is noted that MRA and MVR methods are suitable for determining optimal placement of PQMs because the constraints of the optimization problem formulation are based on actual voltage sag information and also both methods can be applied for distribution and transmission systems.

Table 2. Review of the survey results on all methods for PQM placement

| Methods | Index | Symmetric | Asymmetric | Radial | Transmission | Limitation |
|---|---|---|---|---|---|---|
| **MRA** | MRA matrix and X vector | ✓ | ✓ | ✓ | ✓ | The limitations were improved by researchers in 2003 to 2010. |
| **CP** | Observablity vector, co-connectivity matrix and data redundancy factor (DRF) | ✓ | ✓ | ✓ | ✓ | The number of PQMs is more than that of the other methods. The constraints of the optimization problem formulation are based on steady state information rather than on actual voltage sag information. |
| **GT** | Coverage matrix and wighting factors | ✓ | ✓ | ✓ | × | The number of PQMs increases with the number of buses. System topology elements must be determined. |
| **MVR** | The CC, Cp statistic and Rp | ✓ | ✓ | ✓ | ✓ | The number of monitors is limited to the choice of two minimum and maximum CC buses. |

## Conclusion

This paper presents a literature review of PQM placement methods in power systems. The compared methods include the MRA, CP, GT, and the MVR methods. The concepts that these methods are based on are considered, and their advantages and limitations are highlighted. The paper also provides a general literature survey and a list of published references on the topic to provide essential guidelines on this active research area. The comparison of the four methods show that the MRA and MVR methods are suitable for determining optimal placement of PQMs because the constraints of the optimization problem formulation are based on actual voltage sag information and also both methods can be applied for distribution and transmission systems.

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