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A New Approach for Optimal Power Quality Monitor Placement in Power System Considering System Topology

***Abstract**. Nowadays, most of the equipment used in the industries are mainly based on semiconductor devices and microprocessors and hence these devices are very sensitive to voltage disturbances. Among power disturbances, voltage sags are considered as the most frequent types of disturbances in the field and their impact on sensitive loads is severe. However, to assess voltage sags, installation of power quality monitors (PQM) at all system buses is not economical. Thus, this study is carried out to develop a power quality monitor positioning algorithm to find the optimal number and placement of PQMs in both transmission and distribution systems. In this proposed approach, first, the concept of topological monitor reach area is introduced. Then the genetic algorithm is used in finding the optimal number of PQMs. Finally, to optimally place the identified number of PQMs, all possible combinations of those PQMs in the power system are evaluated using two novel indices namely, monitor overlapping index and sag severity index. The proposed algorithm has been implemented and tested on the IEEE 30-bus and the IEEE 34-node test systems to show effectiveness of the proposed method to both transmission and distribution systems.*

***Streszczenie.** W artykule zaprezentowano nowy algorytm oceny jakości energii mający na celu optymalizację rozmieszczenia monitorów. Do tego celu wykorzystano algorytm genetyczny. Wykorzystywane są dwa współczynniki – wzrostu napięcia i zapadu napięcia. (**Nowa metoda oceny rozmieszczenia monitorów jakości energii w systemie energetycznym z uwzględnieniem jego topologii**)*

Keywords: Power Quality Monitor, Topological Monitor Reach Area, Genetic Algorithm, Monitor Overlapping Index, Sag Severity Index.
Słowa kluczowe: monitor jakości energii, algorytm genetyczny.

Introduction

In recent years, power quality (PQ) has been treated as a prominent issue which demands utilities to deliver a good quality of electrical power to end users especially to industries having sensitive equipment. Among all power disturbances, voltage sags are the most frequent types and give severe impact on the sensitive loads [1]. It may cause failure or malfunction of sensitive equipment in industries which eventually leads to huge economic losses. This type of power disturbance is defined by IEEE standard 1159-1995 as a voltage reduction in the RMS voltage to between 0.1 and 0.9 per unit (p.u.) for duration between half of a cycle and less than 1 minute [2]. Voltage sags have attracted many researchers to perform assessment and mitigation related to such power quality disturbances [3].

To ensure high quality of electricity supplied to customers, PQ monitoring should be implemented first [4]. Ideally, in a PQ monitoring scheme, power quality monitors (PQMs) must be installed at all buses in the power network to capture every PQ event that may happen in the network. However, due to economic constraints, utilities are unable to invest heavily on PQMs and require an optimal solution to install the monitors at appropriate places in a power system. For this purpose, many researchers have recently started working on the optimal placement of PQM in power systems. The first method for optimal placement of PQM is based on density matrix concept where three constraints namely, voltage, current and connectivity are considered to evaluate monitor placement towards observability of fault occurrence [5]. In [6], to monitor voltage sags in a power system, the monitor reach area (MRA) which is based on voltage constraint is used. It is reported in the literature that by just using the MRA matrix, it is not accurate enough to identify the most appropriate locations for PQMs [6]. However, the MRA concept is widely used by many researches for optimal placement of PQM. To overcome the boundary issue of monitor's coverage, fuzzy logic has been applied [7] and detailed fault analysis has been considered to ensure whether the MRA based PQMs placement scheme can record all fault disturbances [8]. The results in [8] have shown that some of the fault occurrences along lines cannot be detected using a simple MRA based PQM placement scheme. Fuzzy logic in genetic algorithm together with a penalization function has been applied in obtaining optimal monitor placement [9]. All the above mentioned methods have been tested only on power transmission systems but not on the distribution systems. In [10], an algorithm based on graph theory was developed to find the optimal PQM placement in distribution system. Graph theory is applied to obtain the system coverage matrix and then ambiguity index is used to evaluate the best monitor placement in the system. However, this method is mainly based on expert's knowledge and experience in the monitoring program. In addition, this approach is only applicable for radial distribution system because it needs to determine rooted tree as in the graph theory where there is parent-child relationship among nodes. It may cause a problem in determining parent-child relationship in a transmission system. Therefore, an optimal PQM method that is applicable for both transmission and distribution systems is required.

The aim of this study is to develop a novel algorithm to determine optimal PQM placement in both transmission and distribution systems. In this algorithm, the topological monitor reach area (TMRA) and a monitor's coverage control parameter, α, are used to obtain an optimal solution. The monitor's coverage control parameter is defined as a voltage level in p.u. to decide either fault occurrence inside or outside of the monitor's coverage area. A PQM usually detects and captures voltage variations when the measured RMS voltage is below or equal to 0.9 p.u. However, the setting value of 0.9 p.u is not suggested in this study so as to allow some overlapping of the monitor coverage area at the boundary. This approach will help to overcome the boundary issues and non-monitored fault on line segment at the boundary.

The Concept of Topological Monitor Reach Area

In order to characterize the performance of a power system towards the possible occurrence of voltage sags, short circuit analysis is normally performed because fault is the most probable cause that leads to voltage sag. In short circuit analysis, all types of faults with zero impedance were simulated at each bus considering it as the most severe fault to the system. Simulations were carried out using the DIgSILENT power system simulation software.

The residual voltage at each bus is valuable information in the formation of the monitor reach area (MRA) [6]. Therefore, the residual voltages are necessary to be stored in a matrix form called as the Fault Voltage (FV) matrix where the matrix column relates to bus number and the matrix row relates to the simulated fault position [9]. Then, the MRA matrix can be obtained by comparing all the FV matrix elements for each phase with a coverage control parameter, α (p.u.). Each element of the MRA matrix is filled with 1 (one), when the bus residual voltage goes below or equal to α value in any phase and with 0 (zero) otherwise:

$$(1)\quad \mathrm{MRA}(j,k)=\begin{cases}1, \text{if } \mathrm{FV}(j,k)\le \alpha \text{ p.u. at any phase}\\ 0, \text{if } \mathrm{FV}(j,k)\le \alpha \text{ p.u. at all phases}\end{cases}\quad \forall j,k$$

In this study, a topological monitor reach area (TMRA) is introduced to make it applicable for both distribution and transmission systems. The TMRA matrix is a combination of MRA matrix and system topology matrix by using operator 'AND' as expressed in (2). The TMRA is constructed based on the concept of path graph theory such that a graph G = (V, E) consists of edges (lines) and vertices (nodes) and the vertices (V) are connected by edges (E). A path P = (V,E) is a sequence of vertices such that there is an edge that links its vertices from starting vertex to end vertex in the sequence [11]. During a fault, the faulted bus becomes a cut vertex which separates into several vertices of the same component as many adjacent edges. Similar to MRA and FV matrices, the T matrix column is correlated to bus number and its row is correlated to fault location. The matrix is filled with 1 (one) when there is a path from generator bus (start vertex) to a particular bus (end vertex) in the system and 0 (zero) otherwise. Thus, the TMRA matrix is given by,

$$(2)\quad \mathrm{TMRA}(j,k)=\mathrm{MRA}(j,k)\bullet \mathrm{T}(j,k)\quad \forall j,k$$

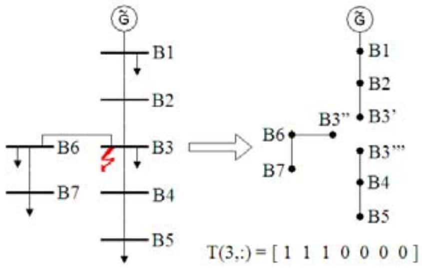
Figure 1 shows some examples of a particular row in a T matrix for a radial system with a single power source, a radial system with two power sources, and a ring system with a single power source. When fault happens at bus 3, the system can be represented in a graph with bus 3 separated into several numbers depend on number of branches connected to the bus. The T matrix column is then filled with '1' or '0' by checking connectivity between generator bus to the other bus based on criteria mentioned above. A system in Figure 1(a) has only one generator which is located at bus 1. Obviously, there is a path from generator bus (bus 1) to buses 1, 2 and 3 but not for the rest. Therefore, T matrix column is filled with '1' up to column three and '0' for the rest. It is a different situation when another generator is added to the system at bus 5 as shown in Figure 1(b). In this case, buses 4 and 5 have a link to the second generator and thus, T matrix is filled with '1' up to column 5. In other hand, a ring system as shown in Figure 1(c) gives all '1's for T matrix column because there is a path to give connection between generator bus (bus 1) to the other buses. As a result, this T matrix gives information about system topology. These examples are considered only for fault at bus 3 and it needs to be done at all buses in the system to obtain a complete T matrix.

Optimization Application on PQM Placement

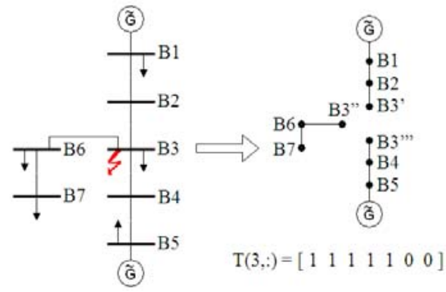
There are two steps considered in optimum placement of PQMs in a power system. The first step is to determine the minimum number of monitors while the second step involves finding the best arrangement of monitors in the system. The position of monitors in a power system is first estimated to provide an expectable solution from the optimization process which is called the Monitor Placement (MP) vector. This vector is required to evaluate the performance of installed monitor towards its observability of the system. The MP is defined as a binary decision vector towards installation of monitors at specific buses in a power system where its dimension corresponds to the number of buses in the system. The value 0 (zero) in the MP (n) indicates that no monitor is needed to be installed at bus n whereas the value 1 (one) indicates that a monitor should be installed at bus n. The MP vector can be described as follows:

$$(3)\quad \mathrm{MP}(n)=\begin{cases}1, \text{if monitor is required at bus } n\\ 0, \text{if monitor is not required at bus } n\end{cases}\quad \forall n$$

a) A radial 7-bus system with a single power



b) A system in a) with two power sources



c) A ring 6-bus system with a single source

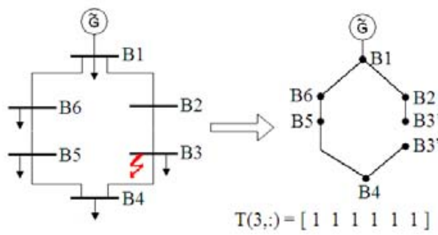


Fig. 1. Example of row 3 in T matrix for different system topologies

A. Optimal Number of Power Quality Monitors

Normally, utility company has limited financial capability to invest on PQMs. However, the investment should not be lower than that is required for the minimum feasible number of monitors for a specific power system. Therefore, the total number of the monitors should be determined as minimum possible number of PQMs while maintaining its capability to observe any fault in the whole system which may lead to voltage sag. To determine the minimum number of PQMs, genetic algorithm (GA) is applied as an optimization tool by using MATLAB software. The objective function of the optimization problem is to minimize the number of monitors which is given by summation of MP vector elements [8]. This function can be mathematically expressed in (4).

$$(4)\quad f=\min\sum_{n=1}^{N}\mathrm{MP}(n)$$

In order to evaluate the monitors to be able to observe the whole system, this search algorithm should find the optimal number of monitors under some constraints. These constraints are determined by evaluating each suggested MP vector in the GA process with TMRA matrix to show its coverage on the power system. It is important to note that the multiplication of the TMRA matrix by the transposed MP vector gives the number of monitors that can detect voltage sags due to faults at specific buses [6]. If one of the resulting matrix element is 0 (zero) then it means no monitor is capable to detect sag caused by fault at that particular bus whereas if the value is greater than 1 (one), more than one monitor has sensed a fault at the same bus. Therefore, the following constraint must be fulfilled to make sure that each fault is observed at least by one monitor:

$$(5) \quad \sum_{i=1}^{N} \mathrm{TMRA}(i,l) * \mathrm{MP}(i) \geq 1 \qquad \forall l$$

In the optimization process, the initial population of MP vector (individual) is randomly created and then the GA operators change the individual in each generation through the manipulation of bits in their strings (MP matrix elements) until a convergence criterion is achieved [9] based on the optimization problem formulated by (3) and (4).Then, the algorithm will find at least the minimum number of ‘1’ (one) in MP vector which strongly depends on the TMRA matrix. Note that, the number of monitors will increase when the coverage control parameter, α is decreased and the monitoring scheme becomes more sensitive to the occurrence of voltage sags. Thus, the selection of suitable α value depends on economic capability but the number of allocated monitors should not be lower than the suggested number of monitors. In this study, α is set to 0.85 p.u. In the simulations, it is found that by increasing the α value above 0.85 p.u, the acquired optimum numbers of monitors may not cover the whole system especially at the boundary line.

B. Optimal Placement of Power Quality Monitors

In order to find the optimal monitor arrangement in a power system, all possible monitor arrangements should be taken into account. The maximum number of possible arrangements (PA) is obtained by using a mathematical sequence combination calculation as given in (6) where N is the total number of buses for monitor installation and M is the number of monitors to be installed in the system. The M value is determined from the previous process. First, an algorithm is developed to place the M monitors, one-by-one in matrix form similar to MP vector. However, the MP vector must be tested for the constraint given in (5) and eliminate the arrangement which does not fulfill the constraint. All possible monitor arrangements are then evaluated to find the optimal placement of PQMs.

$$(6) \quad \text{Number of PA} = \frac{N!}{M!(N-M)!}$$

The placement of monitors in a power system will result in different overlapping of monitor’s coverage area for different arrangements. Here, it is important to note that these overlaps indicate the number of monitors which record the same fault occurrence in a power system. As mentioned before, multiplication of the TMRA matrix and the transposed MP vector gives overlapping information when the value is greater than 1 (one). This means that there is no overlapping of monitor’s coverage when all elements of the multiplication matrix are equal to 1 (one). Thus, monitor overlapping index (MOI) is introduced to evaluate the best monitor arrangement in a power system. The MOI can be obtained by summing all elements of multiplication of the TMRA matrix and the transposed MP vector and then dividing the sum by the total number of all fault locations for each type of faults (NFLT) as expressed in (7). A MOI value indicates a better arrangement of PQMs in the system.

$$(7) \quad \mathrm{MOI} = \frac{\sum(\mathrm{TMRA} * \mathrm{MP}^{\mathrm{T}})}{\mathrm{NFLT}}$$

However, in certain conditions, the MOI value can be the same for several possible monitor arrangements. As a result, the evaluation step of monitor placement requires the use of another index which is called the Sag Severity Index (SSI). This index defines the severity level of a specific bus towards voltage sag where any fault occurs at this bus will cause a big drop in voltage magnitude for most buses in the system. Therefore, the severity level (SL) should be determined first. The SL is the total number of phases experiencing voltage sags (NSPB) with magnitudes below t p.u. for all buses over total number of phases (NTPB) in the whole system and is given by,

$$(8) \quad \mathrm{SL}^{\mathrm{t}} = \frac{\sum \mathrm{N}_{\mathrm{SPB}}}{\sum \mathrm{N}_{\mathrm{TPB}}}$$

Then, the SSI is obtained by applying weighting factors for different severity levels where the lowest t value is assigned with the highest weighting factor and vice versa. The SSI can be expressed as,

$$(9) \quad \mathrm{SSI}^{\mathrm{F}} = \frac{1}{15}\sum_{k=1}^{5} k * \mathrm{SL}^{(1-\frac{2k-1}{10})}$$

The highest value of SSI at a particular bus implies that the bus is the most influential bus that causes voltage sag in a power system and therefore this bus needs to be given a priority in installing a PQM compared to other buses with lower SSI values. Minimum MOI yields the selection of the best monitor arrangement with the least overlapping of monitor’s coverage. However, when there are several same minimum MOI values for particular monitor arrangements, the SSI is then applied to determine the best solution for optimal PQM placement in a power system. Figure 2 shows a flow chart of the overall optimization steps in the proposed power quality monitoring scheme.

Test Results and Discussion

To validate the effectiveness of the proposed optimal PQM placement, two test power systems are considered, namely, the IEEE 34-node distribution system and the IEEE 30-bus transmission system. In both case studies, the DIgSILENT software is used for fault analysis while the optimization problem is handled by means of special codes created in the MATLAB software.

A. Case I: Test on IEEE 34-node System

The IEEE 34-node test feeder system is an unbalanced distribution system which consists of three voltage levels; 69 kV, 24.9 kV and 4.16 kV. The 69 kV is the voltage level at external grid that feeds the system by stepping down to feeder’s nominal voltage level at 24.9 kV and then the voltage is reduced by an in-line transformer to the 4.16 kV for a short section of the feeder. The system consists of 34 nodes interconected by 34 lines. In addition, there are two in-line regulators which are required to maintain a good voltage profile [12].

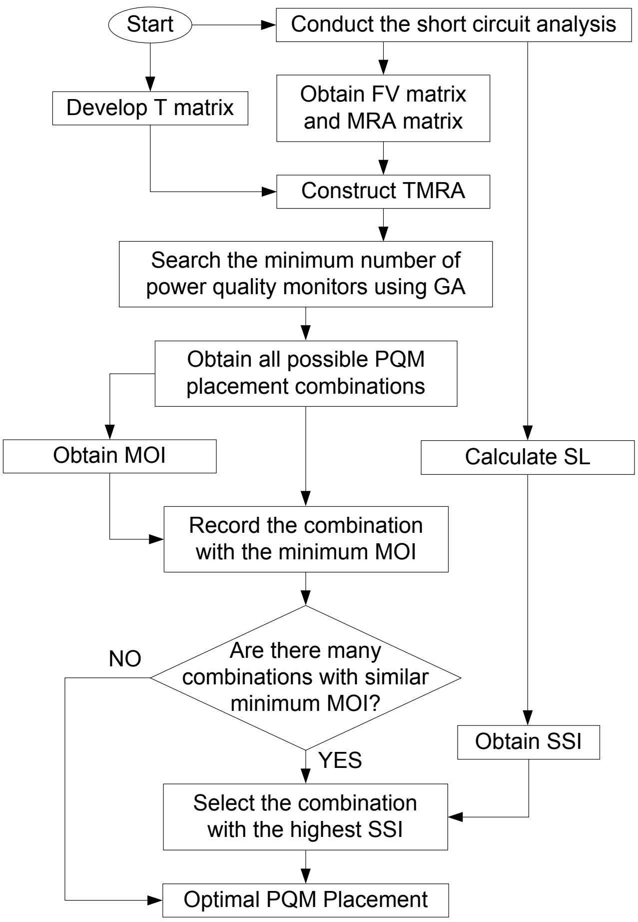


Fig. 2. The overall optimization flowchart

The optimization algorithm provides 3 PQMs as the optimum number of monitors to install for this power system when the maximum coverage control parameter, α is set to 0.85 p.u. Table 1 shows the result of the top four possible arrangements from all the 28 possible combinations of the three PQMs which fulfill the observability requirement. From Table 1, it can be seen that the combination of PQMs placed at buses 1, 4 and 20 gives the best (lowest) MOI value but the worst (lowest) in terms of SSI among the four monitor arrangements. Eventhough for the case of PQMs placed at buses 1, 4 and 15 gives the highest SSI value, the combination with the lowest MOI (buses 1, 4 and 20) is considered as the best monitor arrangement so as to avoid overlapping in the monitoring scheme recording the same event and then minimize size of data storage. Therefore, the optimal monitor placements for the 34-node test feeder system are suggested as buses 1, 4 and 20 as this combination gives the lowest MOI value. Figure 3 illustrates the monitor coverage area when the PQMs are placed at the suggested locations. This clearly illustrates that any faults that may occur in the system including faults occuring on line at the boundaries of the monitors' coverages can be captured by these monitors.

To further validate and prove the observability for the faults that may occur along the boundary line of the monitor coverage area, two boundary lines involved in this case study are simulated with single phase to ground faults at 9 different locations as a percentage of line length. These boundary lines are: line connecting bus 6 to bus 7 (line 6-7) and line connecting bus 19 to bus 20 (line 19-20). From the test results have shown that any fault along the boundary lines is completely covered by at least one of the monitors. On the other side, it has been validated in this study where the monitoring scheme could not record fault occurrence above 70% of line length when there is no overlapping part allowed by setting α value exactly at 0.9 p.u. Thus, it is proven that allowing a small coverage overlapping has provided a solution towards boundary issue and uncovered parts of the monitoring scheme.

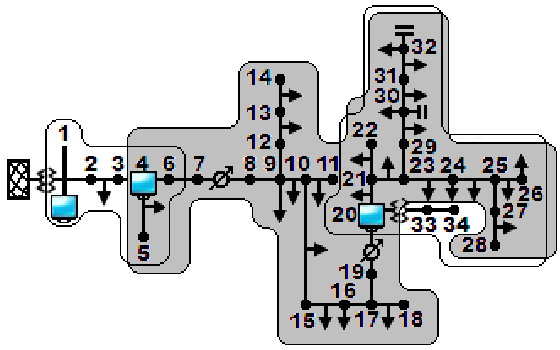


Fig. 3. Coverage area for optimal PQMs placed at buses 1, 4 and 20 for the IEEE 34-node system.

Table 1. The best 4 PQM arrangement in the IEEE 34-node system when α is set at 0.85 p.u.

PQM Placement	1,4,20	1,4,19	1,4,17	1,4,15
MOI	**1.111**	**1.147**	**1.184**	**1.258**
$SSI^{SLG(a)}$	0.845	0.861	0.893	0.920
$SSI^{SLG(b)}$	0.916	0.931	0.961	0.980
$SSI^{SLG(c)}$	0.796	0.778	0.800	0.816
$SSI^{DLG(a,b)}$	1.767	1.802	1.854	1.901
$SSI^{DLG(b,c)}$	1.683	1.716	1.761	1.796
$SSI^{DLG(c,a)}$	1.617	1.647	1.695	1.737
SSI^{LLL}	2.536	2.574	2.657	2.722
Average SSI	**1.451**	**1.473**	**1.517**	**1.553**

B. Case II: Test on IEEE 30-bus System

The IEEE 30-bus test system is a balanced transmission system which consists of two voltage levels which are 132 kV and 33 kV. There are two generating stations, three sychronous condensers in the 132 kV grid and four step-down transformers (2 two-winding transformers and 2 three-winding transformers) to supply the 33 kV grid at three stations located at buses 4, 6 and 28. The system consists of 30 buses which are interconected by 60 lines. The IEEE 30-bus test system data is provided in [13].

After applying the GA optimization algorithm, it is found that only one monitor is enough to observe the whole system when α value is set to 0.85 p.u. However, some less severe fault consisting of high impedence faults in far away locations may not be captured by this single monitor scheme. Therefore, the α value is set at 0.55 p.u. for the optimization method to be more senstive. For this α value, a minimum of 8 monitors are required for the IEEE 30-bus system. Table 2 shows the results of the top four monitor arrangements from all the 12 possible monitor combinations of these 8 PQMs which fulfill the observability requirement. According to the results, the optimal monitor placement for the IEEE 30-bus test system is suggested for PQMs to be placed at buses 4, 7, 11, 15, 17, 20, 26 and 29. In this case, all faults which cause voltage magnitude below than 0.6 p.u. at faulted locations can be observed by these monitors including faults on the line at boundaries of the monitors' coverages. This demonstrated that by reducing α value, it will increase sensitivity of monitoring scheme.

Table 2. The best 4 PQM arrangement in the IEEE 30-bus system when α is set at 0.55 p.u.

PQM Placement	4, 7, 11, 15, 17, 20, 26, 29	4, 7, 11, 15,17, 19, 26, 29	4, 7, 11, 15,17, 20, 26, 30	4, 7, 11, 15,17, 19, 26, 30
MOI	**2.057**	**2.057**	**2.057**	**2.057**
$SSI^{SLG(a)}$	0.404	0.399	0.400	0.395
$SSI^{SLG(b)}$	0.404	0.399	0.400	0.395
$SSI^{SLG(c)}$	0.404	0.399	0.400	0.395
$SSI^{DLG(a,b)}$	0.826	0.815	0.813	0.802
$SSI^{DLG(b,c)}$	0.826	0.815	0.813	0.802
$SSI^{DLG(c,a)}$	0.826	0.815	0.813	0.802
SSI^{LLL}	1.264	1.251	1.253	1.240
Average SSI	**0.708**	**0.699**	**0.698**	**0.690**

As mentioned earlier, the number of required monitors towards sensitivity of voltage sag occurrence can be varied by changing the α value. A study has been done to see relationship between optimal PQM allocation and sensitivity of the monitoring scheme based on α value. Table IV shows that the monitoring scheme becomes more sensitive on voltage sag occurrence with the increase in the number of allocated monitors for the power system. In this study, any fault occurrences which leaves less than 0.1 p.u. remaining voltage at faulted bus can be captured by 3 monitors as seen in Table 3. It is important to notice that these monitors will observe the fault occurrences when the voltage magnitude at the monitored bus reaches 0.9 p.u. However, sometimes these three monitors could not observe a fault occurrence at certain buses due to voltage magnitude at monitored bus is greater than 0.9 p.u. For example, when a less severe fault happens in a far away location causing the residual voltage magnitude at the fault location to be more than 0.1 p.u., then all the 3 monitors may not experience voltage sag and hence it may requires a higher α value to guarantee the event to be recorded. Inherently, the result gives information about the relationship between α value and voltage magnitude at fault location. Consequently, it can be used as a guideline to allocate PQM based on system requisite and then obtain an optimal PQM placement in the power system as suggested in this study.

Table 3. The optimum number of PQMs at different α values

The α value (p.u.)	The minimum required number of PQMs
0.85	1
0.75	3
0.65	6
0.55	8
0.45	11
0.35	17
0.25	19
0.15	25
0.05	29

Conclusion

This paper has presented a novel method to find an optimal number and locations of the PQMs to monitor voltage sags caused by any type of fault in power system. The proposed method is based on the use of topological monitor reach area that is obtained by utilizing commercial simulation software to calculate residual voltages originated by faults in the power system. In addition, the proposed algorithm is flexible enough to take into consideration of PQM allocation problem towards economical capability. The proposed optimal PQM placement program has been implemented on the IEEE 30-bus and the IEEE 34-node systems respectively. It has been shown that the proposed approach is applicable for both transmission and distribution systems and gives the optimal PQM placement depending on desired monitors sensitivity towards fault occurrence. Thus, the proposed methodology may help the power quality monitoring engineers to plan and budget on power quality monitoring activity especially for voltage sag detection.

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