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Optimal location of Power Quality Monitors in distribution grids based on MRA methodology

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Abstract. Distribution grids currently face news paradigms where Power Quality (PQ) has become one of the most important aspects for distribution system operators (DSO) and consumers. To ensure a PQ within the limits defined by international standards, there is a permanent need to monitor all parameters associated with the distributed voltage by the grid. This task is carried out using the installation of Power Quality Monitors (PQM) at strategic points of the grid. The main aim of this paper is to define a methodology to optimize the best location for the PQM installation. To achieve this target the Monitor Reach Area (MRA) matrix is calculated and an Integer Linear Programming (ILP) optimization model was used to find the best solution. Two case studies were carried out, in which residual voltage values were observed when three-phase short circuits are applied to all nodes. The results obtained show the good effectiveness of the developed method, presenting solutions that allow the total monitoring of the studied networks, using the smallest possible number of PQMs. In this way, it is possible for the DSO to keep the network monitored in real-time with huge efficiency gains.

Keywords. Integer linear programming, Monitor reach area, Power quality monitor, Sag severity index.

1. Introduction

Nowadays, it is increasingly important to ensure the PQ that is supplied. Several disturbances affect the distributed PQ in a distribution grid. Some of these disturbances are caused by factors external to the electrical system, such as lightning strikes, fires, etc. For the study of internal grid, it is important to refer to standards such as EN50160 regarding the characteristics of the supply voltage in power distribution grids [1]. This standard addresses several parameters voltage-related, such as frequency variations and harmonic distortion rates. These parameters are important when one intends to study the PQ in an electrical grid. However, this standard has some limitations. It only applies under normal conditions, not considering external situations that may occur, such as power supply failure, exceptional weather conditions or third party actions. Therefore, the parameters presented in this standard are mandatory since they are contemplated in the quality of service regulation [2]. Some of the internal disturbances in an electrical grid refer to voltage fluctuations that correspond to variations in the effective voltage values and are possible to observe with the naked eye through the flicker effect [3]. A distribution grid can experience deformations of voltage and current waves relative to the sinusoidal shape, which are related to harmonics and inter-harmonics. The grid can also suffer from long-duration voltage variations consisting of voltage dips in the grid, which are responsible for the largest number of losses in power distribution grids, as noted in [4], [5]. Due to this type of problem, several works have been developed over the years to study power distribution grids to monitor their quality. Thus, this work aims to explore various methods that can be used to optimize the monitoring of PQ in a distribution grid using strategically placed power quality meters. For this purpose, two case studies will be analyzed to achieve the optimal solutions for the problem.

This topic has been studied over the past few years by several researchers. According to [6], there are four main methods used for the placement of Power Quality Monitor (PQM) being, Monitor Reach Area (MRA), Cover and Packing, Graph Theory and Multivariable Regression Method. A method called Fault Position was introduced in [7], which simulates short circuits on each of the buses present in the grid to understand how the grid behaves. A mathematical analysis that predicts the intensity and duration of these voltage sags in the grid is proposed in [8]. References [9] and [10] a Genetic Algorithm (GA) is used to determine the best combination of PQMs to be installed while minimizing the construction cost. The author [11] indicates that the method proposed by [12] does not guarantee quality observability and suggests simulating faults not only at the buses but also between the lines that connect these, considering the hypothesis of simulate other types of faults besides three-phase faults. The authors [9], [13] applied GA using Fuzzy Logic to guarantee the homogeneity and observability of the grid.
In [14], it is again proposed to use GA and Fuzzy Logic with the goal of determining the optimal placement of PQM. Through this model, it is possible to observe which is the best combination of PQM capable of providing the

best observability with the lowest possible cost. It is proposed in [15] the use of a Clonal Algorithm for a 63 Bus grid with the objective of being able to observe the faults in the grid, taking into account the possible symmetries that may occur using the minimum possible number of PQM. It was proposed in [16] the placement of PQM using a coverage matrix that takes into account the grid topology Topological Monitor Reach Area (TMRA), optimized through GA and able to discriminate the optimal placement of PQM through the concept Sag Severity Index (SSI). In 2016 it was proposed in [17] the optimization of a grid using the Particle Swarm Optimization Algorithm method for the purpose of monitoring a grid where several types of faults were studied, and the results of placement of PQM were summarized by relating them to the type of fault in question. These were just some of the many authors that suggested proposals in order to solve the problem of voltage dips that may arise in an electrical grid. In [3], [18] a multiobjective approach is proposed to optimize the power quality monitoring.

This paper is divided into six sections. In Section I, the topic is introduced with a summary of the state of art. Section II is divided into three sub-sections and addresses some concepts used in the implementation of the work. In Section III, the optimization model applied to the cases that will be studied is presented. Section IV comprises two sub-sections, concerning the case studies of this work to characterize each one of them and in Section V, the results obtained are analyzed. Finally, in Section VI, conclusions remarks are stated.

2. Methodology

This section discusses some concepts that will be implemented throughout the work. It is divided into three parts. The first one, Subsection II-A, addresses the methodology that allows the building of a matrix capable of storing the behaviour of a grid when affected by short circuits. Next, subsection II-B introduces a concept that enables the conversion of this matrix into another binary matrix that aims to ensure grid monitoring. Finally, Subsection II-C introduces a concept to improve the one addressed in Sub-section II-B.

A. Fault Position Methodology

The fault position method was proposed in [7] in order to calculate the voltage drops in transmission systems. It consists of individually short-circuiting each of the grid buses and then calculating the value of the residual voltages at the other buses to obtain the values of the voltage drops across the grid. A matrix with a dimension equal to the number of buses in the grid is then built with all the values obtained for each fault position. This method makes it possible to get the most vulnerable areas by the short circuits applied at each bus. The residual bus voltages are given by (1).

$$V_{ij} = 1 - \frac{Z_{ij}}{Z_{jj}} \tag{1}$$

where V_{ij} represents the residual voltage present at bus i when j is short-circuited, Z_{ij} is the short-circuit impedance of bus i upon a fault at j, and Z_{jj} is the short-circuit impedance of bus j when j is short-circuited.
This method makes it possible to build the Fault Voltage Matrix (FVM) (2), which stores all the information about the residual voltage values obtained in the grid. Assuming that the grid has n buses $i, j \in \{1, \ldots, n\}$

$$FVM = \begin{bmatrix} V_{11} & V_{12} & V_{13} & \cdots & V_{1n} \\ \vdots & & & \ddots & \vdots \\ V_{n1} & V_{n2} & V_{n3} & \cdots & V_{nn} \end{bmatrix} \tag{2}$$

where V_{ij} represents the residual voltage present at bus i when a short circuit occurs at bus j.

B. Monitor reach area

In order to study the behavior of a power grid when it experiences severe voltage dips, the MRA method was developed. As mentioned in [5], [4], short circuits are the main problem that distribution grids face. The MRA concept is defined as an area of the grid where whenever a fault occurs, it can be detected by at least one PQM. Several types of short circuits that can affect the grid in a harmful way. In this paper, it will be studied how phase to phase short circuits affect a distribution grid. After obtaining the FVM, the MRA concept is applied, which generates a binary matrix. The entries of the new MRA matrix assume values “0” or “1” depending on the residual voltage values obtained in FVM. Placing “1” at position ($i; j$) indicates that point j will have to be covered by a PQM placed on the bus i, which corresponds to a situation where the residual voltage is less than or equal to a preset value. On the other hand, the value “0” indicates that point j does not need to be covered by a PQM placed on bus the i, which corresponds to a situation where the value is higher than the preset limit, according (3).

$$MRA(i,j) = \begin{cases} 1, & V_{ij} \leq p \\ 0, & V_{ij} > p \end{cases} \tag{3}$$

Where V_{ij} represents the voltage at bus i when bus j is short-circuited and p represents the predefined threshold voltage value, given in p.u.
The MRA method proves to be effective in grids with radial topology. However, it is not a foolproof method because it is only based on a limited number of fault positions and does not take into account other faults that may arise on the grid, such as line faults, as stated in [11].

C. Topological monitor reach area

In the building process of the FVM matrix, the value “0” p.u. is obtained on the main diagonal due to the simulated short circuit. Furthermore, it is also possible to get “0” p.u. on outward of the main diagonal entries due to the relative position of the buses and the place where the short circuit occurs. For example, considering the situation presented in Fig. 1, a power grid composed of eight buses, bus 4 is short-circuited (“0” p.u.), and the values obtained at buses 5, 6 and 7 are also “0” p.u.. This type of situation can suggest, at first glance, a short circuit at 5, 6 and 7, which is proven to be false. These values of “0” p.u. outside the main diagonal are related to the grid topological changes.

A concept called TMRA referred to in [16] is introduced to overcome these changes. This concept is similar to MRA, however, with some differences. A TMRA matrix can be constructed by placing “1” at positions whose residual voltage is less or equal to the p threshold and “0” for values whose residual voltage is greater than the p threshold. However, there is one more condition to be met. The value “0” is set whenever “0” p.u. is obtained on a bus where a short circuit has not been simulated, i.e. outside the main diagonal. As a result, all buses downstream of the bus that experienced the fault will be considered unsuitable for PQM placement. Unlike the MRA concept, the TMRA concept can differentiate between a “0” p.u. obtained on the main diagonal, that is, on the bus where the short circuit was simulated, and the “0” p.u. obtained on adjacent buses that are a consequence of that same short circuit. The matrix created through the TMRA concept, Coverage Matrix (CM), is given by (4).

$$CM(i,j) = \begin{cases} 1 \quad , \quad V_{ij} \leq p \\ 0 \quad , \quad V_{ij} = 0, i \neq j \\ 0 \quad , \quad V_{ij} > p \end{cases} \tag{4}$$

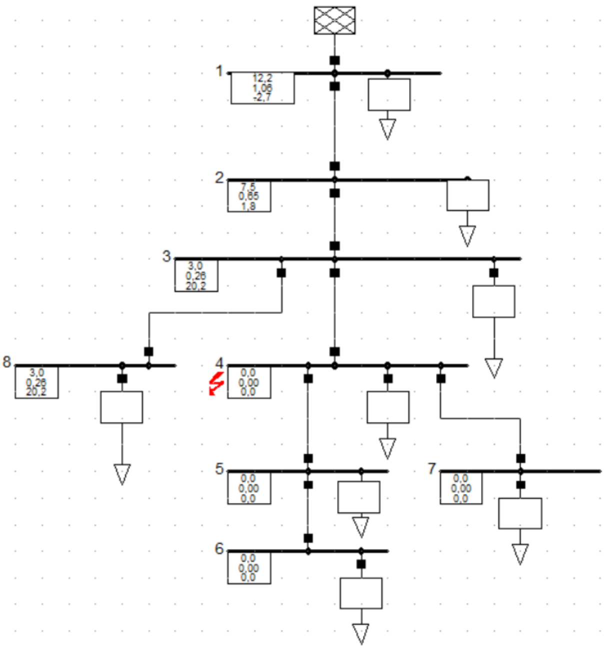

Fig. 1. Example of an 8-Bus Radial Distribution grid

3. Optimization model

This section presents the optimization model used to address the ongoing issue. The objective to be fulfilled will be to minimize the number of PQM placed on the power grid guaranteeing full observability of the grid. For this purpose, a linear programming model with binary decision variables has been constructed.

Let N={1,…, n} be the set of buses in the grid.

Consider the decision variables x_i where x_i=1 if a PQM is placed on bus $i\in N$ and 0 otherwise. The optimization model is given by:

$$minimize\ f(x) = \sum_{i\in N} x_i \tag{5}$$

$$s.t. \quad CM \times x \geq 1 \tag{6}$$

$$x_i \in \{0,1\}, i \in N \tag{7}$$

Where $x = (x_1, \ldots, x_n)$ is the vector of decision variables and 1 = (1, …, 1) is a vector of n components, (5) is the objective function where is intended to minimize the number of installed PQM. Constraint (6) guarantees that whenever a fault occurs on one of the buses, at least one PQM will be able to detect it and constraints (7) impose the sign constraints on the variables ensuring that they are binary variables.

This linear programming model was solved using the FicoXpress [19] Optimization software.

4. Case studies

This section will analyse two case studies using IEEE networks with different operating conditions and sizes.

A. IEEE 13 Bus System

The first case study is summarized on the power grid presented in Figure 2. It is a 4.16 kV 13 bus grid, studied in [3]. Values given by IEEE Power Society were implemented in order to model the grid in PowerFactory. From this grid, three-phase short circuits were simulated on all buses. Figure 3 shows the simulation of one of the tests, specifically at bus 671. Through the program PowerFactory, this process was simulated for each bus and voltage values, in p.u.. So, a 13 x3 FVM matrix was created that encompasses all the values obtained for each situation, as shown in Figure 4. Then, the methodology described in (4) is applied together with the FVM obtained in Fig. 4 to obtain the CMs for the various residual threshold limits, as shown in figures 5 and 6. After getting the CM matrix, the optimization model (5)-(7) is solved, following the process described through the flowchart presented in Fig. 7.

B. IEEE 33 Bus System

The second case study addresses a 12.66 kV grid [20]. It is a balanced grid composed of 33 Buses and 32 three-phase loads, supplied through 3.715 MVA and 2.3 MVar synchronous generators, shown in Fig. 8. By the same procedure used before, the values of the residual voltages were obtained for an MVM matrix of dimension 33×33.

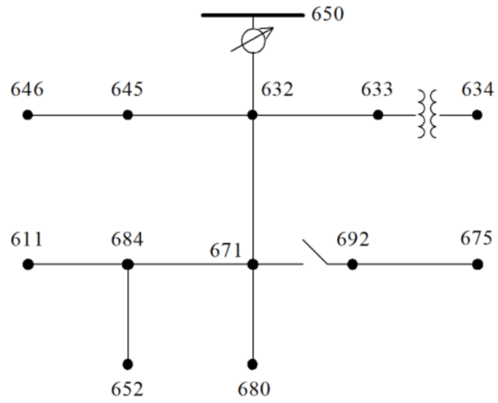

Fig. 2. Single line diagram of IEEE 13 Bus radial grid.

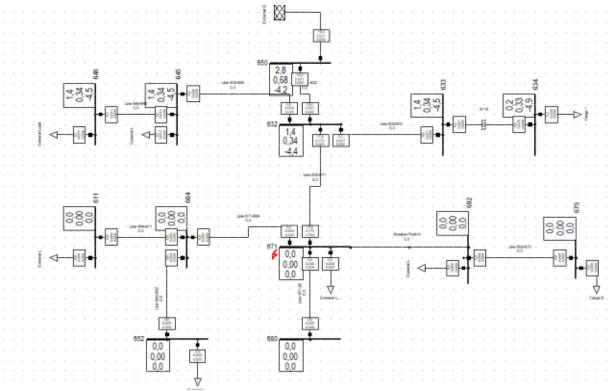

Fig. 3. IEEE 13 Bus grid simulated on PowerFactory software.

FVM	650	632	633	634	645	646	671	680	684	652	611	692	675
650	0	0	0	0	0	0	0	0	0	0	0	0	0
632	0.50	0	0	0	0	0	0	0	0	0	0	0	0
633	0.58	0.15	0	0	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14
634	0.76	0.48	0.39	0	0.48	0.48	0.45	0.45	0.45	0.45	0.45	0.45	0.45
645	0.58	0.15	0.15	0.14	0	0	0.14	0.14	0.14	0.14	0.14	0.14	0.14
646	0.62	0.22	0.22	0.21	0.08	0	0.21	0.21	0.21	0.21	0.21	0.21	0.21
671	0.68	0.34	0.34	0.33	0.34	0.34	0	0	0	0	0	0	0
680	0.73	0.43	0.43	0.43	0.43	0.43	0.14	0	0.14	0.14	0.14	0.14	0.14
684	0.71	0.38	0.38	0.37	0.38	0.38	0.06	0.06	0	0	0	0.06	0.06
652	0.73	0.42	0.41	0.41	0.41	0.41	0.12	0.12	0.07	0	0.07	0.12	0.12
611	0.72	0.40	0.40	0.39	0.40	0.40	0.09	0.09	0.03	0.03	0	0.09	0.09
692	0.68	0.34	0.34	0.33	0.34	0.34	0	0	0	0	0	0	0
675	0.71	0.38	0.38	0.37	0.38	0.38	0.07	0.07	0.07	0.07	0.07	0.07	0

Fig. 4. FVM matrix for 13 Bus system.

CM	650	632	633	634	645	646	671	680	684	652	611	692	675
650	1	0	0	0	0	0	0	0	0	0	0	0	0
632	1	1	0	0	0	0	0	0	0	0	0	0	0
633	1	1	1	0	1	1	1	1	1	1	1	1	1
634	1	1	1	1	1	1	1	1	1	1	1	1	1
645	1	1	1	1	1	0	1	1	1	1	1	1	1
646	1	1	1	1	1	1	1	1	1	1	1	1	1
671	1	1	1	1	1	1	1	0	0	0	0	0	0
680	1	1	1	1	1	1	1	1	1	1	1	1	1
684	1	1	1	1	1	1	1	1	1	0	0	1	1
652	1	1	1	1	1	1	1	1	1	1	1	1	1
611	1	1	1	1	1	1	1	1	1	1	1	1	1
692	1	1	1	1	1	1	0	0	0	0	0	**1**	0
675	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 5. CM matrix for 13 Bus system with 0.9 p.u. threshold.

CM	650	632	633	634	645	646	671	680	684	652	611	692	675
650	1	0	0	0	0	0	0	0	0	0	0	0	0
632	0	1	0	0	0	0	0	0	0	0	0	0	0
633	0	1	1	0	1	1	1	1	1	1	1	1	1
634	0	0	1	1	0	0	0	0	0	0	0	0	0
645	0	1	1	1	1	0	1	1	1	1	1	1	1
646	0	1	1	1	1	1	1	1	1	1	1	1	1
671	0	1	1	1	1	1	1	0	0	0	0	0	0
680	0	0	0	0	0	0	1	1	1	1	1	1	1
684	0	1	1	1	1	1	1	1	1	0	0	1	1
652	0	0	0	0	0	0	1	1	1	1	1	1	1
611	0	1	1	1	1	1	1	1	1	1	1	1	1
692	0	1	1	1	1	1	0	0	0	0	0	1	0
675	0	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 6. CM matrix for 13 Bus system with 0.4 p.u. threshold.

Subsequently, the CM coverage matrix was built according to the TMRA concept. This matrix was used in order to optimize the number of PQM to be placed on the grid. For the CM matrix of dimension 33×33 the same optimization model used in the study case IV-A was applied.

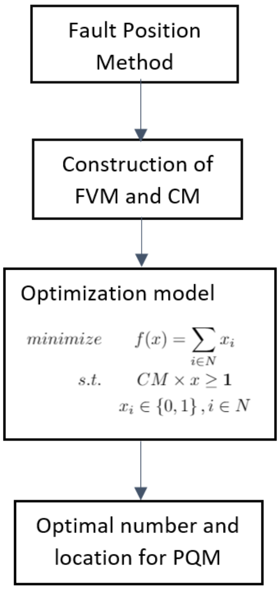

Fig. 7. Procedural Flowchart.

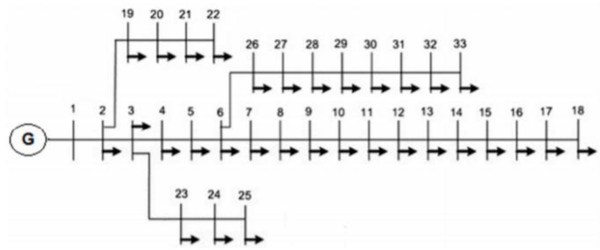

Fig. 8. Single line diagram of IEEE 33 Bus radial grid.

5. Results and discussion

The main aim of this research would be to ensure the full observability of a power grid with the placement of a minimum number of PQM. Several methods were introduced to allow the implementation and resolution of the problem. An FVM matrix has been built through the concept introduced in Sub-section II-A. The main diagonal of FVM is composed of "0" p.u.. This represents all the values of the buses when they suffer a fault. Each column of the FVM matrix stores the values obtained at a specific bus for all the short-circuit simulations performed. Each row stores the obtained values on all the buses in the grid when a specific bus is exposed to a fault.

Through the Sub-sections II-B and II-C, it is possible to understand the importance of the preset voltage limit in CM construction. In this work, two scenarios were considered as preset stress limits: p = 0.4 p.u. and p = 0.9 p.u.. Therefore, whenever a voltage value at a bus drops below the predefined p threshold limit, a PQM in the grid informs about the existence of a fault in the grid. Given the FVM matrix of the 13-bus power grid, shown in Fig. 5 with a default limit of p = 0.9 p.u., according to (4), it is possible to observe that when bus 650 is short-circuited, all buses assume the value of 0 p.u.. Those values are shown in row 650. However, it can be seen that whenever there is a short circuit bus in the grid, bus 650 always assumes a value less than 0.9 p.u., regardless of where the fault occurred. This ensures that placing a PQM on bus 650 will guarantee full observability of the grid, as obtained in the optimal solution presented in Table I.

Following the same reasoning used for the 0.9 p.u. thresholds, for a 0.4 p.u. threshold, the bus chosen by the linear programming model applied to the 13 bus grid will be those that, when exposed to a short circuit situation from another bus, will obtain residual voltage values below the pre-established threshold value. Bus 632 is chosen due to the fact that if a fault were to occur, for example, at 633, the PQM placed at 650 would not be able to detect the fault because its residual voltage would not be below 0.4 p.u. but rather at 0.58 p.u. (Row 633, Column 650) Fig. 5. For this fault to be detected, a PQM is placed on 632. So, when 633 is short-circuited, 632 has a residual voltage of 0.15 p.u. (Row 633, Column 632) and therefore will be able to detect the fault.

This methodology is applied whenever it is impossible to cover the failures with one of the previously placed PQM. The obtained results for PQM placement on the 13 and 33 Bus grids with 0.4 p.u. threshold can be seen through figures 9 and 10. The results presented in Table I show that the smaller the threshold value chosen for the construction of the coverage matrix, the larger the number of PQM to be placed in the grid. This type of result is expected since the voltage values decrease significantly in a short-circuit situation. Consequently, there will be a larger number of values below a threshold of 0.9 p.u. compared to the 0.4 p.u. threshold. As a result, constructing a CM matrix with a residual stress limit of 0.9 p.u. will have a greater number of entries at “1” when compared to a CM matrix for a limit of 0.4 p.u.. According to the optimization model, the constraint capable of guaranteeing full grid monitoring is given by (6). This constraint indicates that the product of the CM matrix by the binary vector x will guarantee PQ monitoring over the entire grid. To meet this same constraint, for a 0.4 p.u. threshold, the linear programming model needs to put a larger number of entries at “1” in the *x* vector. This, in turn, results in a greater number of PQMs being placed the lower the preset threshold is.

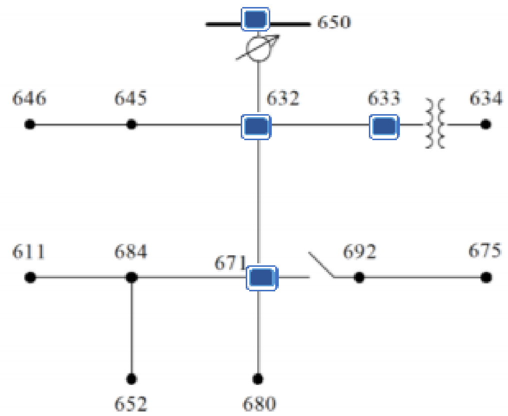

Fig. 9. Optimal PQM locations for 13 bus system with 0.4 p.u. threshold.

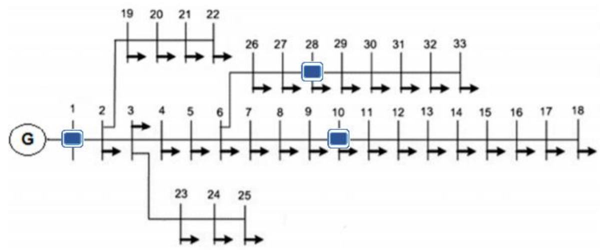

Fig. 10. Optimal PQM locations for 33 bus system with 0.4 p.u. threshold.

Table I - Optimal location for PQM placement

Case study	0.9 p.u. threshold	0.4 p.u. threshold
13 Bus	Bus 650	Buses 650, 632, 633, 671
33 Bus	Bus 1	Buses 1, 10, 28

In Fig. 11, the columns of different colors in the bar chart represent the grid behavior when subject to a short circuit in a specific bus. It can be seen that bus 650, represented by the highest bar, is, notoriously, the bus that most affects the correct operation of the grid. When this bus suffers a failure, it jeopardizes the entire grid. Hence it is necessary to place a PQM on bus 650 regardless of the pre-established limit. The buses in the *x*-axis are sorted from upstream to downstream relative to the feeding point. It can be seen, from Fig. 11 that the PQM that were suggested by the optimization model, for p=0.4 p.u. show several columns with very low residual voltage values.

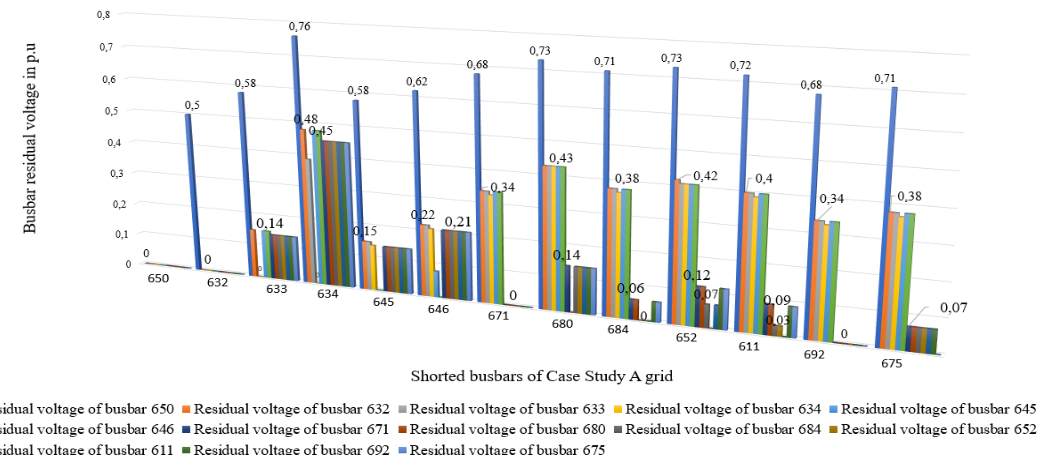

Fig. 11. Behavior of 13 Bus system when exposed to short circuits at the different Buses

Thus, whenever there is a grid failure, there will always be at least one PQM that assumes a residual voltage value below the threshold value. Consequently, it is possible to monitor the entire grid.

The approach taken in [16] becomes interesting through the Sag Severity Index (SSI) concept that consists in checking all admissible solutions through the ratio between the total number of phases of all buses that have voltage sag lower than the pre-established voltage limit (N_{SPB}) over the total number of phases of all buses in the grid (N_{TPB}). This ratio is given by (8).

$$SSI = \frac{N_{SPB}}{N_{TPB}} \tag{8}$$

An SSI close to unity indicates that the bus experience severe voltage dips and that priority should be given to installing PQM at these locations. It is a criterion that can be used to complement the choice of the best location for the PQM installation to be done.

6. Conclusion

This work shows the importance of correct monitoring of distribution networks to maintain their efficiency. Therefore, it was verified that the optimal choice of PQM location for the monitoring of distribution grids is of great importance, not only due to the operational management of the grid but also due to the economic aspects involved. An optimization model was built to determine the minimum number of PQM to be placed and their optimal location.

The used methodology, with the TMRA matrix and the integer linear programming optimization model, proved to be very effective, allowing good observability of both studied grids with a minimum number of PQM, as proposed in the objectives. Furthermore, the optimization model developed allows obtaining the optimal solution with reduced processing time, less than one second, which suggests that it is easily applicable to larger grids.

The optimization model could be easily adapted to consider the costs of placing PQM on the distribution grids, which could be useful in some cases. In future work, new methodologies could be addressed, including, for example, a multi-objective approach, trying not only to minimize the number of PQMs but also to optimize topological ambiguity by maximizing observability.

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