BI-OBJECTIVE APPROACH FOR POWER QUALITY MONITORS ALLOCATION PROBLEM

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Abstract— This paper aims to choose power quality monitors optimum locations for monitoring short-duration voltage variations. Besides reduce the monitoring system cost and ensure the coverage of the whole system, this research explores the potential of the monitors arrangement for fault location purpose. It proposes a multi-objective approach with two objectives: minimization of power quality monitors quantity and maximization of identified events. The Algorithm for Bicriteria Discrete Optimization finds all non-dominated solutions for the optimization model applied to the IEEE 13 bus test feeder. The results analysis showed the method functionality and proved its applicability to power distribution systems.

Keywords— Voltage Sags Monitors, Optimization, Electric Faults, Voltage Sags and Swells

1 Introduction

The Power Quality (PQ) is becoming a reason of concern for utilities and end users of electric power systems (Dugan et al., 2012). Among the disturbances that affect the PQ, the Short-Duration Voltage Variations (SDVVs) deserve to be highlighted. According to (Dugan et al., 2012), SDVVs are variations in the Root Mean Square (RMS) voltage value which can last from half cycle to 1 min and can be subdivided according to the residual voltage value, being: sags (dips), if the voltage value remains between 0.1 and 0.9 per unit (p.u.); swells, if the residual voltage is an increase to between 1.1 and 1.8 p.u.; and interruptions, if it decrease to last than 0.1 p.u. (Dugan et al., 2012).

From these SDVVs types, sags are the most frequent, and they may cause a malfunction in equipments that are sensitive to voltage level (industrial consumers), which can interrupt an entire industrial process (Zambrano et al., 2017). Due to the economic losses that the SDVVs can cause and the increase in the demand of regulatory agencies regarding the PQ provided, it is important for the utilities to monitor these events in their networks, aiming to verify the quality of their product and to solve possible conflicts with customers (Eldery et al., 2006).

The short-circuits are the phenomena that most cause SDVVs and occur randomly in the electrical power system, as a result of the wind, snow, trees, lightning strikes, burning, flooding, landslides or accidents of any nature (Kindermann, 1997). In reason of the short-circuits unpredictability, an efficient monitoring must have a significant duration. The equipment must stay a long time (maybe years) connected to the grid, in order to record SDVVs (Dugan et al., 2012).

Therefore, the utilities have the interest in permanent monitoring these events, being necessary besides the installation of Power Quality Monitors (PQMs), the installation of measurement transformers, and the setting of an automatic collection system of information about the recorded events, with a desired comunication channels connecting to a central of treatment and management of data (Eldery et al., 2006). Thus, the decision of installing more than one measurement point in the monitoring system corresponds to many expenses, being desired to utilize the minor number possible, guaranteeing the monitoring of all possible events in the electrical network.

Many efforts have been made to deal with the problem of choosing the best locations to install PQMs, aiming at the monitoring of SDVVs occurring in the electrical power system and minimizing the PQMs quantity. Some papers have studied this problem in electrical power transmission systems (Eldery et al., 2006; Olguin et al., 2006; Espinosa-Juárez et al., 2009; Almeida and Kagan, 2010; Martins and Guerra, 2016a; Martins and Guerra, 2016b). Others approached the problem in distribution systems (Won and Moon, 2008; Gomes et al., 2016; Kempner et al., 2017).

The utilities have interest in storing a chronology of SDVVs, but also use the recorded data in the moment of the event to determine with accuracy the disturbance source. From this ideia, in cases of permanent short-circuits, the time of repair and restoration of the system is reduced, which implies in an improvement to the quality of the service, as well as the evaluation indices of the utilities by the regulatory agency (Dzafic et al., 2018).

Although several studies have been carried out about the PQMs allocation problem, a few papers treated so far the application in the distribution systems, but not yet considering the fault location problem during the PQMs allocation. Martins and Guerra (2016b) mentioned the same issue considered in this paper, but not included it in their optimization model. This paper proposes a multi-objetive approach, based on the methodology of (Olguin et al., 2006) and, differently from (Martins and Guerra, 2016b), the fault location issue is handled as one of the objectives of the optimization problem.

2 Description and Modeling of the Problem

Not being possible to simulate all possible short-circuits, it must be interesting to apply short-circuits in a way to obtain a SDVVs representative database.

Considering the modified 13 bus IEEE system presented in Fig. 1, the performance of the system was assessed under occurrence of single-phase A-to-ground faults. Fig. 2, 3 and 4 show, by means of color scale matrices, the response of the system to every possible faults occurring at network buses. Short-circuits at buses 4 and 5 were not simulated (these buses only contain B and C phase branches), and either at bus 10 (only C phase is observed). Besides, only three-phase buses in medium voltage were considered as candidate points to the PQM's placement, i.e., buses 1, 2, 6, 7, and 11 (Fig. 1). Being so, as only single-phase A-to-ground faults were considered, a PQM installed in one bus will record voltage sags in phase A and voltage swells in phases B and C.

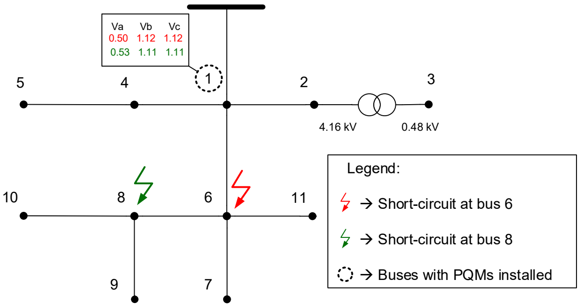


Figure 1: Example of symmetry condition in the modified 13 bus IEEE system considering only solid single-phase A-to-ground faults.

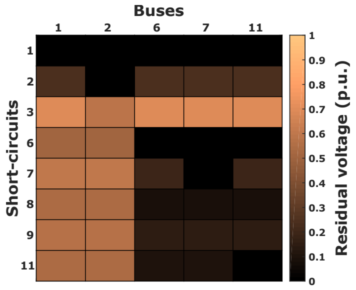


Figure 2: DFVM in phase A during the occurrence of solid single-phase A-to-ground faults.

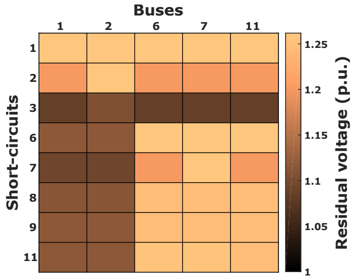


Figure 3: DFVM in phase B during the occurrence of solid single-phase A-to-ground faults.

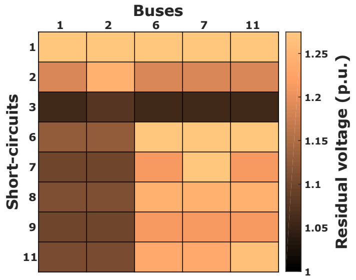


Figure 4: DFVM in phase C during the occurrence of solid single-phase A-to-ground faults.

In Fig. 2, 3, and 4, the rows of the matrix represent a short-circuit applied at bus corresponding to the row index, and the columns represent the residual RMS voltage (in p.u.) at buses indicated. Hence, for example, row 4 contains the voltage values at buses 1, 2, 6, 7, and 11 during a phase A-to-ground fault at bus 6. The matrices represented in Fig. 2, 3, and 4, are known as During Fault Voltage Matrices (DFVM) (Kempner et al., 2017). Considering a threshold of 0.6 p.u. to a PQM start to record a voltage sag, it is possible from DFVM of Fig. 2 to know in which buses one PQM will be sensitized for each short-circuit occurrence. In literature the binary matrix that stores this information is known as Monitor Reach Area (MRA) (Olguin et al., 2006), Observability Matrix (OM) (Almeida and Kagan, 2010), or Binary Observability Matrix (BOM) (Kempner et al., 2017).

Based on DFVM of Fig. 2, a binary parameter is defined for each be element of the matrix. Thus, the observability information of the event of row e from bus which is monitoring the short-circuit (column b) is stored. This parameter, here called λ_{be}, assumes 1 if residual voltage at bus b due to event e is lesser or equal to the threshold, and 0 otherwise.

Monitoring systems with fewer PQMs are desired, but all fault conditions must be observed by at least one PQM. Based on Table 1 notation, this can be represented mathematically by means of Expressions 1-3.

$$\min \sum_{b \in B} x_b \tag{1}$$

$$\text{s.t.:} \quad \sum_{b \in B} \lambda_{be} x_b \geq 1 \qquad \forall e \in E \tag{2}$$

$$x_b \in \{0, 1\} \quad \forall b \in B \tag{3}$$

This is the same model of discrete linear programming proposed by (Eldery et al., 2006; Olguin et al., 2006; Kempner et al., 2017). However, these papers were concerned only at the observability of the system to the SDVVs.

One other concern is about what can be defined as symmetry between events related to one measurement point. This symmetry occurs when one PQM records the same (or almost the same) voltage value for two totally different fault positions (Martins and Guerra, 2016b). From the point of view of the PQM it is impossible to determine which of the two fault conditions occurred in the system. Therefore, this phenomenon makes the problem of fault location difficult, and this paper proposes an optimization model aiming to reduce the multiple estimation of the location in function of the process of PQM's allocation.

In order to define numerically a symmetry condition, an interval must be stipulated around a measured voltage value, due to uncertainty during measurement. For example, considering one uncertainty of ± 0.05 p.u., the short-circuit conditions 6 and 8 (Fig. 2, 3, and 4) are symmetrical related to one PQM installed at bus 1. This symmetry condition is illustrated in Fig. 1. One solution to this symmetry problem is to add another PQM in such a way that it can differentiate events 6 and 8. Thus, looking at the monitoring system as a whole, this symmetry will no longer exist.

The installation of a PQM at bus 7, for example, is enough to solve this problem of symmetry, since this bus can differentiate these two faults (events 6 and 8) that may occur in the system (Fig. 5). It is important to note that two fault conditions are considered symmetric only if the RMS voltage values of the three phases are within the stipulated range. In the situation represented in Fig. 5, although the values of phases B and C are within the tolerance, measuring at bus 7, phase A is not. Therefore, there is no more symmetry. The PQM installed at bus 7 can differentiate events 6 and 8.

This information about symmetrical conditions on the system is represented by binary parameter $\sigma_b^{e,\bar{e}}$ (Table 1).

Fig. 6 represents all parameters $\sigma_2^{e,\bar{e}}$, i.e., for all combinations of events e and $\bar{e}$ with a measuring point installed at bus 2. The elements in blue represent symmetrical conditions ($\sigma_2^{e,\bar{e}} = 0$), and in white color, events that are not symmetric ($\sigma_2^{e,\bar{e}} = 1$). For example, events 3 and 7 are symmetrical with respect to bus 2, and events 3 and 8 are not symmetrical with respect to bus 2. Assuming that a given event is symmetrical to itself, the diagonal of this matrix will always be in blue color. Besides, this matrix is symmetrical with respect to the main diagonal, since parameters $\sigma_2^{2,1}$ and $\sigma_2^{1,2}$ represent the same situation in the electrical system. Then, for this system with 5 positions for allocation of PQMs and considering 8 events, there will be $8 \times 8 \times 5 = 320$ sigmas, which can be represented in 5 matrices, as Fig. 6.

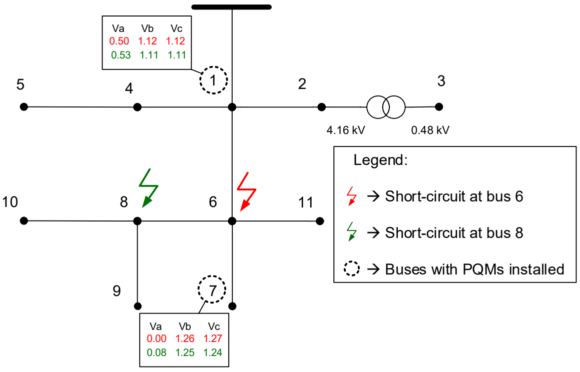
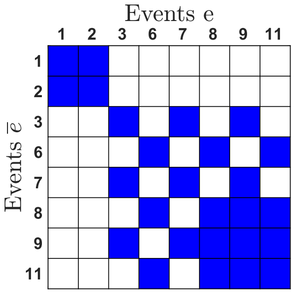


Figure 5: Example of a monitoring system capable of diferentiate the single-phase A-to-ground fault conditions at buses 6 and 8 of the modified 13 bus IEEE system.

Table 1: Mathematical notation used on the discrete linear programming optimization problem.

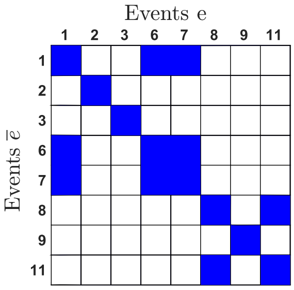
Sets	B	Set of buses of the test system.
	E	Set of the simulated events (fault conditions).
Parameters	λ_{be}	Binary parameter that indicates if event $e \in E$ is observed by a PQM installed on bus $b \in B$ (1 if observed and 0 otherwise).
	$\sigma_b^{e,\bar{e}}$	Binary parameter that indicates if events $e,\ \bar{e} \in E$ are symmetrical related to the bus $b \in B$ (0 for symmetrical and 1 for unsymmetrical events).
Decision variables	x_b	Binary variable that indicates if there is a PQM installed on bus $b \in B$ (1 if there is a PQM installed and 0 otherwise).
	y_e	Binary variable that indicates if event $e \in E$ is identifiable (1 in case of identifiable and 0 otherwise).

In Fig. 7 and 8 are shown the sigmas for PQMs at buses 7 and 11, respectively.



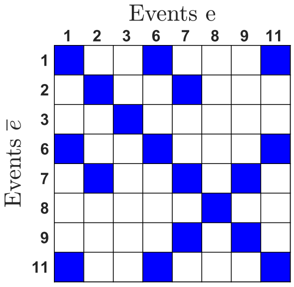
	Events e							
Events $\bar{e}$	1	2	3	6	7	8	9	11
1	■	■						
2	■	■						
3			■		■		■	
6				■		■		■
7			■		■		■	
8				■		■	■	■
9			■		■	■	■	■
11				■		■	■	■

Figure 6: Matrix with the parameters $\sigma_2^{e,\bar{e}}$ for the case of single-phase A-to-ground faults.



	Events e							
Events $\bar{e}$	1	2	3	6	7	8	9	11
1	■			■	■			
2		■						
3			■					
6	■			■	■			
7	■			■	■			
8						■		■
9							■	
11						■		■

Figure 7: Matrix with the parameters $\sigma_7^{e,\bar{e}}$ for the case of single-phase A-to-ground faults.



	Events e							
Events $\bar{e}$	1	2	3	6	7	8	9	11
1	■			■				■
2		■			■			
3			■					
6	■			■				■
7		■			■		■	
8						■		
9					■		■	
11	■			■				■

Figure 8: Matrix with the parameters $\sigma_{11}^{e,\bar{e}}$ for the case of single-phase A-to-ground faults.

In this context, an important concept can be defined as: an event is said to be identifiable if and only if the set of installed PQMs is able to differentiate the SDVVs caused by that event from all other events. Thus, a binary variable is defined for each event (y_e) and it is intended to maximize the number of identifiable events. Expression 4 represent this objective, and the contraints represented by Expressions 5 and 6 complete the proposed model.

$$\max \sum_{e \in E} y_e \tag{4}$$

$$\text{s.t.:} \quad \sum_{b \in B} \sigma_b^{e,\bar{e}} x_b \geq y_e \qquad \forall e, \bar{e} \in E, e \neq \bar{e} \tag{5}$$

$$y_e \in \{0,1\} \quad \forall e \in E \tag{6}$$

Therefore, this paper proposes a multi-objective model, represented by Expressions 1-6, where it is intended not only to minimize the number of PQMs, but also to maximize the unique identification of events. This identification is made through the addition of PQMs in strategic positions in order to differentiate the events between them.

The proposed model was solved through the Algorithm for Bicriteria Discrete Optimization (ABCDO) (Sayin and Kouvelis, 2005). This algorithm is applicable to discrete optimization with two objectives and can obtain all the solutions of the Pareto Frontier (PF), as proved by the authors.

3 Results and Discussion

The ABCDO was implemented in Python 2.7, and the discrete optimization subproblems were solved using Cplex 12.6 (CPLEX, IBM-ILOG, 2014), through an Application Programming Interface (API) for Python. Cplex uses a generic Branch & Cut algorithm to solve integer linear optimization problems, that is an exact implicit enumeration method. The optimization algorithm was run on the Microsoft Windows 10 operating system installed on an Intel® Core™ 2 Quad CPU @ 2.40 GHz computer with 6 GB of RAM.

The proposed methodology was assessed in the 13 bus distribution test system of IEEE (Kersting, 2001). This network was slightly modified to meet the purposes of the problem studied, being the switch in the original system disregarded and all buses renumbered, considering the substation bus as reference (Fig. 1).

Since single-phase faults are the most frequent in real distribution systems (about 63 % of occurrences (Kindermann, 1997)), was considered a scenario in which the system is under the occurrence of single-phase A-to-ground faults.

Solid faults were applied to all nodes where the presence of phase A was identified in the test system (nodes 1, 2, 3, 6, 7, 8, 9, and 11). The DFVMs for the three phases were obtained, and all the parameters necessary to solve the optimization problem were determined. A threshold of 0.6 p.u. for the PQMs to record the voltage sags and a range of ± 0.05 p.u. to determine symmetric events were considered. In order to simulate the short-circuits and to obtain the DFVMs, it was an option not using electrical network simulation software. Instead off, all the process was done analytically according to the methodology presented in (Kempner et al., 2017), and implemented by means of scripts coded using the MATLAB® 2015.

An optimum pareto set was obtained containing three solutions, after ABCDO ran during 0.455 seconds, where the monitoring systems have 1, 2, and 3 PQMs. The algorithm starts with 1 single PQM in the first solution failing to identify any of the simulated fault conditions, and by increasing the number of PQMs, with 3 PQMs, the monitoring system can identify all fault conditions. The pareto diagram obtained is shown in Fig. 9 and highlight this observation. The 3 solutions of this PF are also represented graphically in Fig. 10, 11, and 12.

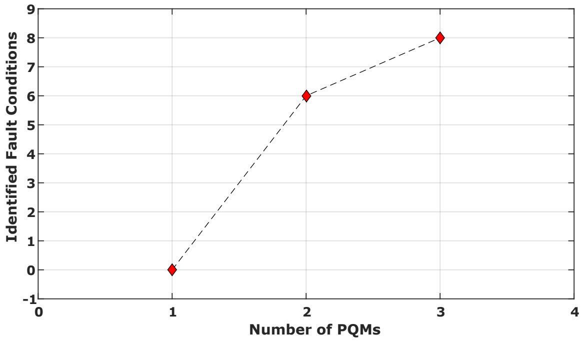


Figure 9: Optimum pareto solutions considering the occurrence of single-phase A-to-ground faults.

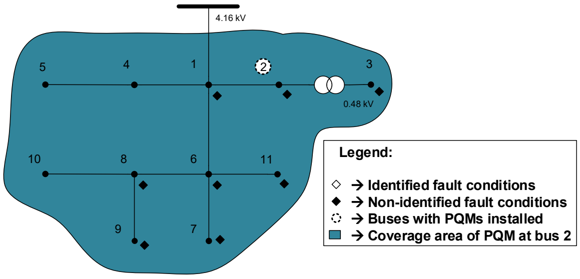


Figure 10: First solution of the PF considering single-phase A-to-ground faults.

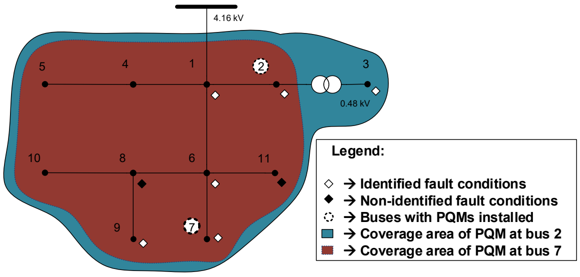


Figure 11: Second solution of the PF considering single-phase A-to-ground faults.

The first solution consists of 1 PQM installed at bus 2 (Fig. 10) and only with it is possible to observe all 8 simulated fault conditions. The shaded area in Fig. 10 includes all events that sensitize this PQM. This same information can be confirmed directly from the DFVM for phase A (Fig. 2), looking at the second column and verifying that all elements of it reflect at voltages below 0.6 p.u.. There can not be a solution with some unobserved event, since this violates one of the constraints of the optimization model (Expression 2), making this solution infeasible. Although all events are observed, none of them is identified with this solution. Since there is only one PQM, the only events that are identifiable are those that naturally have no symmetry with any other in relation to bus 2. This statement is sustained by looking again at Fig. 6 and realizing that there are no rows/columns that are wholly white (disregarding the elements of the main diagonal).

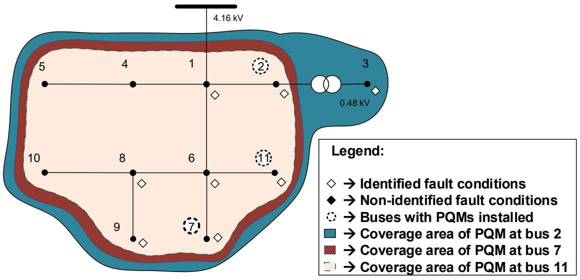


Figure 12: Third solution of the PF considering single-phase A-to-ground faults.

By adding a second PQM at bus 7 (Fig. 11); events 1, 2, 3, 6, 7, and 9 can now be distinguished by combining the two PQMs (the events that are symmetric with respect to one of the PQMs are not symmetric in relation to the other). In fact, when looking at columns 1 and 2 of the matrix of Fig. 6, it can see that events 1 and 2 are only symmetrical with each other. The PQM at bus 7 can already eliminate this symmetry (Fig. 7). Thus, with 2 PQMs it is possible to identify 6 of all 8 single-phase fault conditions. Since the system was already completely observable only with the PQM 2, the addition of the second PQM, despite raising the cost of the monitoring system, increased its reliability, since there is now a redundancy in the measurement.

The third solution adds one third PQM at bus 11 (Fig. 12). By adding it, the events 8 and 11 are identifiable, because $\sigma_{11}^{8,11} = 1$, thus eliminating the symmetry between these two events. Fig. 12 ilustrates the identification and observability of the events. Because the coverage areas of PQMs 7 and 11 are the same, the system becomes more reliable, since there are now 7 events being observed by 3 PQMs.

4 Conclusions

This paper presented a multi-objective approach to the allocation of PQMs problem, in distribution systems.

The problem was modeled through integer linear programming, with two objectives: to minimize the number of PQMs and to maximize the unique identification of events. In this way, besides of guarantee the observability of voltage sags in the electric network, the monitoring system maximized the identification of the events, facilitating the posterior fault location.

The test system was analyzed under the occurrence of single-phase A-to-ground faults and three monitoring system options were obtained. Thus, it is up to the utility to make the decision about which PQMs install on their network, according to their own interest and availability of resources. A solution with a small number of PQMs is adequate for the case where the cost is an aggravating factor in decision making. If this is not the case, the option of a system with a larger number of PQMs can improve the identification of events that may occur in the power grid. Besides, increasing the number of PQMs raises the reliability of the monitoring system, since there is an increase in the measurement redundancy, which can improve the voltage estimation in unmonitored buses.

As a continuation of this study the authors intend to apply this methodology in other distribution networks, as well as to consider other types of electrical faults. Another possibility of continuation is the analysis of the allocation of PQMs in networks with the presence of distributed generators, aiming to observe the influence of these in the system under short-circuits. It is also of interest to incorporate more objectives into the optimization model, such as the measurement redundancy mentioned in this paper.

Acknowledgment

The authors would like to acknowledge the Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of São Paulo (Brazil), for the research facilities provided to conduct this project. Our thanks also extend to the financial support received from CAPES and CNPq (Governmental Brazilian Institutions).

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