Optimal Placement of Voltage Sag Monitors in Smart Distribution Systems: Impact of the Dynamic Network Reconfiguration

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***Abstract*—This paper addresses the impact of the dynamic network reconfiguration (DNR) on the voltage sag observability in smart distribution systems. Optimal placement of voltage sag monitors is generally applied without taking into account the DNR and we show that the voltage sag observability is modified with the network reconfiguration. We also propose two indexes to assess the impact of the dynamic reconfiguration on voltage sag observability. A test case is implemented and the results show the need for new formulations for optimal placement problem, where the DNR should be included to guarantee the full voltage sag observability.**

***Index Terms*—Dynamic network reconfiguration, optimal placement monitors, power quality, smart distribution system, voltage sag observability.**

I. Introduction

Smart grid technology aims to improve the efficiency of the distribution systems through of applications such as: dynamic optimization, real-time information, demand side management, integration of distributed generation, smart metering, distribution automation, smart appliances and customer devices [1], [2].

An issue of the dynamic optimization field is the dynamic network reconfiguration (DNR) which plays an important role due to the power loss minimization in smart distribution systems. Moreover, power quality disturbances should be assessed in the smart grids by installing power quality monitors to record and store the disturbances in the electrical network [3]. Nevertheless, these monitors are usually installed only in few nodes in the distribution system due to the high costs of the meters, transducers and communication platforms [4], [5], [6].

The optimal placement problem (OPP) of the voltage sag monitors aims to find the optimal number and location of monitors when a set of observability constraints is satisfied. This problem is defined according to the disturbance type. For instance, the OPP for voltage sags detection and for harmonic state estimation are the most widely known and studied approaches [4], [5], [7], [8], [9].

This paper addresses the optimal placement of the monitors to minimize the acquisition and installation cost and the same time to guarantee of voltage sag observability. Information about the network topology (the interconnecting of the electrical nodes) and electrical parameters are used to formulate the OPP. Thus if the network topology does not change then the voltage sag observability would be ensured, while if the DNR is applied then the voltage sag observability would be change.

Therefore, the main goal of this paper is to study the impact of the DNR on the voltage sag observability. The OPP of the voltage sag monitors is solved through a method based on the monitor reach area (MRA) and topologic monitor reach area (TMRA) concepts which are reported with satisfactory results in the literature. Results or the DNR problem reported in previous works are used in the analyses (solution methods of the DNR problem are not in the scope of this paper).

The paper is organized as follows: Methods for optimal placement of voltage sag monitors are presented in section II. Impact of the DNR on voltage sag observability is given in III. Numerical results using the IEEE 33-node test system are presented in Section IV. Conclusions are given in the final section.

II. Procedures for Optimal Placement of PQMs in Distribution Systems

Some methods to solve the OPP of voltage sag monitors are reported in the literature. A brief summary of these methods is presented below.

A. Methods for optimal placement of voltage sag monitors

A meter placement method based on integer programming to choose the locations of the voltage sag monitors is presented in [10]. Monitor Reach Area (MRA) concept is used to construct a binary matrix and derive the constraints; branch-and-bound algorithm is used to solve the optimization problem. MRA is defined as the area of the electrical network that can be observed from a given meter position which is able to capture voltage drops. Some recommendations for future works are: realize non-symmetrical faults to define the MRA matrix; also, construct the MRA matrix through of network faults located along of the electrical lines.

A new method based on in MRA concept is presented in [11]. The proposed approach uses analytical expressions to design the MRA matrices (one for each type of fault). The main advantages are that these analytical expressions are valid for any fault location and this method provides the optimal placement of voltage sags monitors considering balanced and unbalanced faults.

The concept of Topological Monitor Reach Area (TMRA) is introduced in [12]. TMRA matrix is determined using a combination of the MRA matrix and the network topology information. The TMRA matrix is based on the concept of paths in graph theory. A multi-objective optimization problem is formulated through two functions: one based on monitor overlapping index and the other on the sag severity index. Three optimization techniques were used to compare the performance of these techniques to solve the OPP: genetic algorithm (GA), binary particle swarm optimization (BPSO) and quantum-inspired particle swarm optimization (QBPSO). This latter technique is the one that provides a better optimal solution than the others.

A new monitor placement method is developed in [5] to overcome the limitations of previous methods. The work concludes that the shortcomings of the voltage sag monitoring systems are the influence of the load and the fault resistance. The main contribution is a method create as a combination of others two: one for fault location and the other one for voltage sag detection.

B. MRA-TMRA concepts applied to optimal placement of voltage sag monitors

MRA and TMRA concepts are used in many applications related to voltage sags assessment [5], [13], [14], [12]. Therefore, in this work these concepts are selected to solve the OPP of the voltage sag monitors. *MRA* is represented with a binary matrix as shown in (1). It is important to note that a short circuit analysis is needed for the construction of the binary matrix. Three phase faults are usually simulated in all nodes of the electrical system and the residual voltages are compared with a predetermined threshold.

$$MRA_{(i,k)} = \begin{cases} 1, & \text{if } \; v_{ik} \leq v_{thr} \; \text{ at any phase} \\ 0, & \text{if } \; v_{ik} > v_{thr} \; \text{ at all phases} \end{cases} \tag{1}$$

In (1), i is the node where the monitor is installed, k is the node where the network fault is located and v_{thr} is the voltage threshold, generally equal to 0.9 per unit for voltage sag detection.

The network topology can be included in the OPP of the voltage sag monitors. TMRA concept was introduced in [7] and allows that the MRA method to be applied in distribution systems. TMRA formulation is presented in (2).

$$TMRA_{(i,k)} = \begin{cases} 1, & \text{if } \; v_{ik} \leq v_{thr} \; \text{ at any phase} \\ 0 & \text{if } \; v_{ik} = 0 \; \text{ for } i \neq k \\ 0, & \text{if } \; v_{ik} > v_{thr} \; \text{ at all phases} \end{cases} \tag{2}$$

In adittion, a decision binary column vector is defined by (3), where if the value x_i is equal to 1, then a voltage sag monitor is installed at the bus i. Otherwise a value zero means the absence of a monitor.

$$x_i = \begin{cases} 1, & \text{if a monitor is installed at bus } i \\ 0, & \text{if a monitor is not installed at bus } i \end{cases} \tag{3}$$

Finally, the optimization problem aims to minimize the cost of a set of the voltage sag monitors installed on the electrical network and guarantee the full observability of voltage sags on entire system, as shown in (4).

$$\begin{aligned} x^* = & \underset{x}{argmin} \; \sum_{i=1}^{N} (c_i * x_i) \\ s.t.: & \; \sum_{i=1}^{N} TMRA_{(i,k)} \times x_i \geq 1, \; k = 1, 2, ..., FN_t \end{aligned} \tag{4}$$

In (4), c_i is the monitor installation cost in the bus i, N is the total number of buses and FN_t is the total number of fault locations selected in the short circuit analysis which is performed through simulation platforms as ATP-EMTP, Neplan, Digsilent, among others.

III. Impact of the Network Reconfiguration on Voltage Sag Observability

Smart grid technologies allow notable advantages regarding to the efficient operation of the electrical networks. DNR is a tool widely applied in the electrical networks due to benefits such as: reduction of power losses, load balancing, improve of voltage profile, reliability and power quality improvement [15]. The network modeling, the network topology changes and the load flow calculations are need for the DNR application.

Moreover, a set of constraints (radial network, current and voltage limits, among others) can be incorporated into the optimization problem of the DNR. This paper considers that DNR is applied to minimize the power losses when the number of the supplied customers is always the same, i.e., there are only changes in the network topology.

The results of the DNR problem carry to network topology changes. If the optimal placement of voltage sag monitor has been calculated based on other network topology, then the voltage sag observability could be decreased. It is due to the voltage sags obtained of the short circuit analysis are not the same for different network topologies.

This work wants to assess the impact of the DNR on the voltage sag observability when an optimal placement or voltage sag monitor has been already defined. Balanced and unbalanced network faults are taking into account to construct the MRA and TMRA matrices, besides of the fault resistances. The authors propose two indexes for quantifying the changes of the observability when the DNR is applied. The first index is called Voltage Sag Observability Rate (VSOR) and it is presented in(5).

$$VSOR_{nt_j} = \left(\frac{(\#\, rows(MRA_{nt_j} \times X^*_{opt}))<1}{FN_t} \right) \times 100\,\% \quad \forall j \;\epsilon[1, 2, ..., \text{nt}_{\text{total}}] \tag{5}$$

VSOR is applied for each network topology (nt_i) and evaluates the voltage sag observability from a specific optimal placement of the monitors $\left(X^*_{opt}\right)$ in the electrical network. X^*_{opt} is obtained through the method presented in (2), (3), (4). A second index called Voltage Sag Observability Rate Total $VSOR_T$ is formulated in (6), which includes the number of operating hours for each nt_i. $VSOR_T$ weighs the voltage sags observability from a set of monitors installed $\left(X^*_{opt}\right)$ according to operation hours in each network topology $\left(Noh_{nt_j}\right)$.

$$VSOR_T = \frac{\sum_{j=1}^{nt_{total}} \left(VSOR_{nt_j} \times Noh_{nt_j}\right)}{Noh_{total}} \tag{6}$$

nt_{total} is the number of all network topologies generated by the solution of the DNR problem and Noh is the number of operation hours. A $VSOR_T$ equal to 100% means full voltage sag observability in the different network configurations, which will be the desired case.

The flowchart in the Figure 1 presents the method to assess the impact of the DNR on the OPP of the voltage sag monitors.

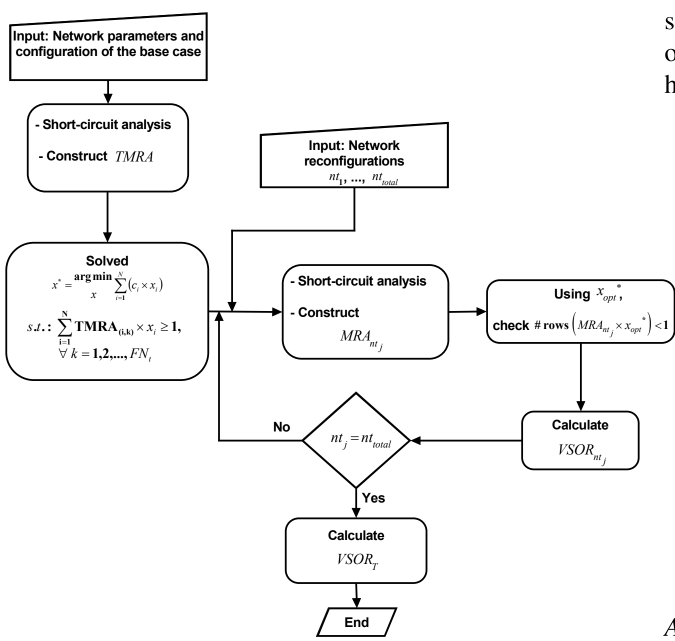

Figure 1. Proposed method to assess the impact of the DNR on the OPP of voltage sag monitors

According to Figure 1, the next steps are required for the proposed method application.

1) The network parameters and the network topologies are the input data. The information of the network reconfigurations are taken from the results of DNR problem.
2) A network configuration is selected as the base case to apply the OPP of the voltage sag monitors. A short circuit analysis is performed with five fault types (line-to-ground, line-to-line, line-line-to-ground, three-lines and three-lines-to-ground) in all buses of the network. A threshold for voltage sag detection is selected, which is generally 0.9 per unit. These results are used to construct the $TMRA$ matrix.
3) The optimization problem in (4) is solved through a genetic algorithm in Matlab. A vector X^*_{opt} indicates the optimal placement of the voltage sag monitors for the base case.
4) A new MRA_{nt_i} is calculated with the information of the new network configuration and a short circuit analysis is realized.
5) A new observability vector is calculated as $MRA_{nt_i} \times X^*_{opt}$. $VSOR_{nt_j}$ index is determined from this observability vector.
6) The steps 4 and 5 are repeated until the total number of network reconfigurations is analyzed.

IV. Numerical Examples and Discussion

The 33-node test system is used to test the proposed method. In [15], the 33-node test system was used for optimal placement of PMUs with network reconfigurations and renewable sources: Photovoltaic (PV) and Wind Power (WP). Table I shows the results of the DNR in [15]. The open line sections of each reconfiguration case (RC) are shown and the operation hours are formulated based on a total 24 hours of the day.

Table I
Simulation Cases

Network configuration	Open line sections	Distributed generation	Operation hours
Base case	13 22 26 29 37	Without PV and WP	–
RC.1	14 22 25 33 36	Low PV and high WP	5
RC.2	13 18 23 25 33	High PV and low WP	7
RC.3	10 22 25 33 37	Low PV and high WP	7
RC.4	14 18 23 25 33	Only WP	5

A. Results of the case studies

Evolutionary computation techniques are growing in solving optimization problems. The genetic algorithms show the robustness and efficiency in the solution of the optimization multidimensional problems. Therefore, in this paper the optimization problem in (4) is solved using a genetic algorithm in Matlab.

Short circuit analyses are performed through ATP-EMTP software. One-line diagram of the distribution system is shown in Figure 2.a. A total of 1600 network faults (line-to-ground, line-to-line, line-line-to-ground, three-lines and three-lines-to-ground) are realized in each network configuration. A threshold for voltage sag detection equal a 0.9 per unit is selected.

Table II shows the results of the OPP solution for each of the reconfiguration cases. These results reveal the influence of the network topology on the optimal placement of the voltage sag monitors. Figure 2.b presents the optimal placement of voltage sag monitors in the base case. The optimal placement vector X^*_{opt} calculated to the base case defines the placement of the monitors that will be the same in the remaining cases when the DNR is applied.

Table II
RESULTS OF THE OPTIMAL PLACEMENT PROBLEM

Case for the optimal placement	Location of voltage sag monitors (nodes)
Base case	1 17 28
RC.1	1 13 16 31
RC.2	1 9 24 30
RC.3	1 6 11 32
RC.4	1 6 10 27 31

The proposed method in Figure 1 is applied to assess the impact of the DNR on voltage sag observability according to the steps presented in the section II. Table III shows the results for the cases analyzed.

Table III
RESULTS OF THE VOLTAGE SAG OBSERVABILITY

	Voltage Sag Observability Index *VSOR* (%)					
Case selected for the optimal placement	Base case	RC.1	RC.2	RC.3	RC.4	$VSOR_T$ (%)
Base case	100	89.13	98.13	83.48	95.61	91.45
RC.1	99.74	100	99.29	99.74	98.96	99.5
RC.2	99.74	97.42	100	96.72	98.96	98.3
RC.3	99.74	100	95.88	100	90.20	96.7
RC.4	99.74	100	99.74	99.74	100	99,8

The principal diagonal of Table III has values which are equal to 100% due to the voltage sag observability is assessed in the same case where the optimal placement of monitors was done. In other cases, $VSOR$ proves that the network reconfiguration impacts on voltage sag observability of the optimal monitoring system. For instance, $VSOR_{Total}$ equal to 91.45 % shows that the optimal monitor placement not guaranteed the full voltage sag observability in all network topologies. Although this value is not so small, if the unobservable nodes have a high probability of failure, then many network faults cannot be detected. When the OPP was solved in the RC.4 case, the total voltage sags observability is the best, but the number of monitors is the higher.

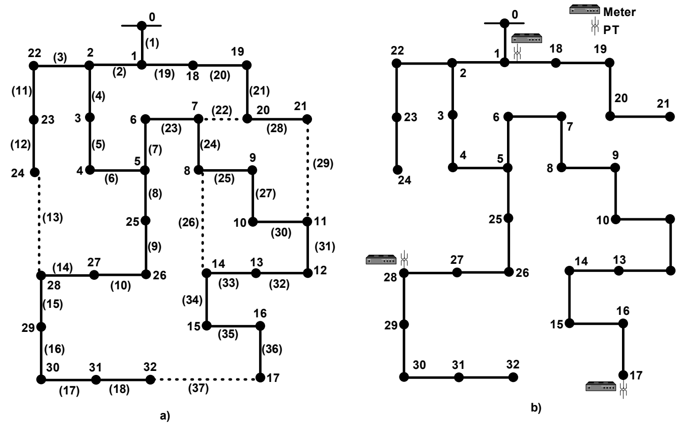

Figure 2. a) One-line diagram, b) Optimal placement of voltage sag monitors

B. Future scope

The following future scopes can be mentioned.

1) Multi-objective optimization including the voltage sag observability indices: The cost to guarantee the full observability of voltage sags can be very large when the DNR is considered. However, a voltage sag observability threshold may be formulated, which is accepted both by customers and electrical utilities. This approach may be incorporated into a future regulatory framework of power quality.

2) An optimal monitoring system to detect some power quality disturbance types: The OPP may be applied to different types of power quality disturbances. However, if a monitoring system is installed, then many disturbances should be detected. Thus, a monitoring system with high operating features should be taken into account the different types of disturbances and the DNR, at the same time.

V. CONCLUSIONS

Optimal placement of voltage sag monitors becomes an important method to be applied in a smart electric network. However, conventional methods do not take into account the DNR in the solution of the OPP. The results of this work show a considerable impact of the DNR on voltage sag observability. Balanced and unbalanced network faults, fault resistances and effects of the load are considered to construct the OPP. These considerations allow a better and reliable assessment of the DNR impact. Some reconfiguration cases showed that the voltage sag observability can be reduced, which it is due to the changes in the network topology and thus the voltage sag monitors do not detect all network faults, unbalanced with fault resistance mainly.

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