Impact of the Dynamic Network Reconfiguration on Optimal Placement of Monitors for Harmonic State Estimation

Impacto de la Reconfiguración Dinámica de Red en la Localización Óptima de Monitores para la Estimación de Estado Armónico

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ABSTRACT

This paper addresses the impact of the dynamic network reconfiguration (DNR) on the observability of harmonic voltages and currents in smart distribution systems. Optimal placement of power quality monitors (PQMs) is generally applied without taking into account the DNR. Two indexes are proposed to assess the impact of the dynamic reconfiguration on harmonic observability and a test case is implemented. The results show the need for new formulations for optimal placement of PQMs, where a configuration of the PQMs is selected while the impact of the DNR is as low as possible.

Keywords: Dynamic network reconfiguration, harmonic observability, harmonic state estimation, optimal placement monitor, power quality, smart distribution system.

RESUMEN

Este trabajo tiene como objetivo evaluar el impacto de la reconfiguración dinámica de red sobre la observabilidad de tensiones y corrientes armónicas en redes inteligentes de distribución de energía eléctrica. Generalmente la localización óptima de los monitores de la calidad de la potencia eléctrica se aplica sin tener en cuenta la reconfiguración de la red. En el artículo se proponen dos índices para para medir el impacto de la reconfiguración dinámica sobre la observabilidad armónica y un caso de prueba es implementado. Los resultados muestran una necesidad por nuevas formulaciones del problema de localización óptima de monitores, donde la localización óptima se seleccione garantizando que el impacto de la reconfiguración dinámica sea el mínimo posible.

Palabras clave: Calidad de potencia, estimación de estado armónico, localización óptima de monitores, observabilidad armónica, reconfiguración dinámica de red, redes inteligentes de distribución.

Introduction

The concept of smart grid aims a high efficiency in the electrical systems and incorporates some characteristics as the use of digital control and real time technologies, distributed generation, dynamic optimization, distributed automation, and smart metering (Brown et al., 2010 and Haughton et al., 2010).

The dynamic network reconfiguration (DNR) in real time systems is part of these smart characteristics. DNR applied to smart distribution systems promotes advanced solutions due to the integrated technologies and procedures, for planning and operation of electrical distribution systems (Bernardon et al., 2012). DNR is an important tool to minimize the power losses as well as improve the reliability of the smart distribution networks.

The power quality plays an important role in the context of smart distribution networks with DNR. Due to the expected increase of nonlinear loads, the amount of harmonic currents injected into smart distribution networks is also increasing. At the same time, these harmonic voltages and currents cause different operational problems such as overheating and failure of equipment, false tripping of sensitive loads, misoperation of protective relays, among others (Kumar et al., 2005).

Currently, the power quality monitoring is essential to diagnose the power quality problems, for example, the harmonic components. However, installing power quality monitors (PQMs) in every component of the network is not feasible due to the financial constraints of the PQMs, voltage and current transformers, communication channels, besides the dimension of the distribution systems. Therefore, there is an increasing interest in efficient tools to know and assess the power quality of the network with a limited number of distributed PQMs. This problem can be stated as follows: how to find the optimal number and locations of PQMs while a set of observability constraints are satisfied? (Yuxin Wan et al., 2014), (Muscas et al, 2007), (Shafiee Rad et al., 2012).

The constraints in the optimal placement problem (OPP) of PQMs are usually related to the maximum system observability. In the case of harmonic components, the observability of all harmonics voltage and current must be guaranteed with the solution of OPP. Measurements obtained from a partial monitoring system are necessary to estimate the power quality state of

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the whole network. Thus, the estimation of the power quality levels is performed on nodes with a partial monitoring system through of the harmonic state estimation (HSE). HSE is a technique for identifying the distribution of the harmonic components in electrical systems with limited measurements.

Various methods have been presented in the literature for placement of PQMs for harmonic state estimation. (Madtharad et al., 2005) present a new technique for optimal measurement placement based on the minimum condition number of the measurement matrix with the sequential elimination to solve the problem. The main disadvantage is that the method can guarantee only near-optimal solutions.

In (Kumar et al., 2005), a method based on genetic algorithms is proposed to solve the OPP using the approach of the minimum variance. The aim is to select the measurements (from the set of all possible measurement locations) that minimize the expected value of the differences between estimated and actual state variables. When the number of PQMs or the system size increases, a method based on genetic algorithms works better than the sequential technique.

In (Muscas et al., 2007), an optimization algorithm is proposed to choose the optimal number and position of PQMs. The optimization procedure is based on the dynamic programming and takes into account the measurement uncertainty and tolerance at line parameters. (Shafiee Rad et al., 2013) proposed an algorithm that uses minimum variance criterion and a sequential method for optimal meter placement. Singular value decomposition (SVD) method is used for observability analysis and finally a weighted least square (WLS) method for harmonic estimation is applied. The minimum trace of the covariance matrix is used to find the optimal measurement location.

The mentioned works have a particular issue: The optimal placement of PQMs is performed using error of the estimated state variables as a minimization criterion. Therefore, to find a solution to the optimal placement problem of PQMs is required a previous solution of the HSE. Other works present a new approach to guarantee the harmonic observability based on the topological connections and circuital laws. This approach is more simplified because to find the optimal placement of PQMs, a solution of HSE is not required.

This is the case of (Almeida et al., 2013), which describes a methodology based on evolutionary algorithms to find a monitoring partial system in order to guarantee the full harmonic observability of the network. Harmonic observability is verified through rules based on Kirchhoff's laws; a branch and bound algorithm and a modified genetic algorithm are used to solve the optimization problem. A most efficient configuration of the monitoring system is found with this method, compared with similar methodologies. Similarly, (Yuxin Wan et al., 2014) proposes a novel model for the optimal placement of the PQMs, considering network observability and fault location constraints. The OPP is formulated as a linear integer problem by applying Ohm's law and Kirchhoff's laws to obtain relationships between voltages and currents. This method shows higher speed and high accuracy.

The methods proposed in the previous works have a common factor that is remarkable: the solution of the OPP depends on the network topology (the interconnecting of the electrical nodes). The network topology defines the harmonic observability and once a reconfiguration is applied to the power system, a new topology appears and the harmonic observability must be evaluated again.

Thus, this paper aims to study the impact of the DNR on the optimal placement of PQMs by taking into account the constraints needed for HSE in smart distribution networks. Nevertheless, the scope of this work is the impact on the observability of the harmonic state variables, but not the impact on the harmonic state estimation. It is considered also that dynamic reconfiguration is applied to minimize the power losses, i.e. the number of the supplied customers is always the same with only changes on the network topology.

The paper is organized as follows. Optimal monitor placement for harmonic state estimation is presented in section 2. The impact of the dynamic reconfiguration on harmonic observability is analyzed in 3. Section 4 shows the numerical results using the IEEE 33-node test system. Conclusions are provided in the final section.

Formulation of the Optimal Placement of PQMs to Harmonic State Estimation.

A monitoring system is optimal when the power system observability is guaranteed and its cost is minimized (Almeida et al., 2013). Therefore, the optimal placement of PQMs for harmonic state estimation must be allowed that all harmonic voltages and currents can be measured or calculated in a distribution network. This method incorporates the cost of installing a monitor in a specific location and also determines how the transducers should be connected. This method is taken as reference for assessing the impact of the dynamic network reconfiguration on the optimal placement of PQMs.

Some definitions to understand the OPP are given in (Almeida et al., 2013):

Allocation Vector (AV): this row vector defines the configuration of the monitoring system and it has a size equal to the summation of the number of sections connected at each bus i. Thus, the possible installations of the current transformers in a set of lines connected at a same bus are incorporated. AV is defined according with (1). A PQM with six channels (measurements of three-phase voltages and currents) is considered in the problem formulation.

$$av\left((v_i, i_{ij})\right) = \begin{cases} 1, & \text{if a PQM is installed at bus } \boldsymbol{i} \text{ and the line section } \boldsymbol{ij} \\ 0, & \text{if a PQM is NOT installed at bus } \boldsymbol{i} \text{ and the line section } \boldsymbol{ij} \end{cases} \quad (1)$$

Cost Vector: It is a row vector taking into account the cost of installing a PQM at a specific node y line section. The sizes of CV and *AV* are the same. So, the total cost for a specific configuration can be calculated as shown in (2).

$$Total\ cost\ (TC) = AV * CV^t \quad (2)$$

Optimization problem: this problem is presented in (3).

$$\begin{aligned} &Minimize\ \ TC = AV * CV^t \\ &s.t.:\ ov_i \geq 1, \quad i = 1,2,3,\dots,N_n, N_n+1,\dots,(N_n + N_b) \end{aligned} \quad (3)$$

where N_b is the number of branches and N_n is the number of nodes of the power system. The constraints are reduced to an observability vector (*OV*), which will be explained below.

Problem's constraints: Constraints are detailed in (Almeida et al., 2013). Nevertheless, a new method to derive these constraints is proposed in this work and it is explained below. The observability vector (*OV*) is constructed from other vectors defined in (Almeida et al., 2013). To formulate a systematic approach using the problem´s structure, we propose a method to derive the constraints using only the definition of the topological incidence matrix of a distribution system.

The proposed method in this work is described below.

- Incidence matrix (*Ain*): it is constructed using the rule shown in (4). The number of rows is the number of branches (electrical lines) and the columns is the number of nodes.

$$Ain_{ij} = \begin{cases} 1 & \text{if branch } \boldsymbol{i} \text{ starts at node } \boldsymbol{j} \\ -1 & \text{if branch } \boldsymbol{i} \text{ ends at node } \boldsymbol{j} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

  where $i = 1,2, \dots, N_b$ and $j = 1,2, \dots, N_n$.

- Possible locations of PQMs: L is defined as the total locations to install the PQMs and found from the incidence matrix, as shown in (5). A vector $\mathcal{L}$ of length $1 \times L$ also is defined and each element corresponds to measure the voltage i and the current of the branch j (end of the line connected at node i).

$$L = \sum |Ain_{ij}|, \quad \forall\, i, j$$

$$\mathcal{L}_k = |Ain_{ij}|, \ \forall\, |Ain_{ij}| > 0, k = 1, \dots, L \quad (5)$$

$$\mathcal{L}_k = \begin{cases} \text{voltages measured at node } \boldsymbol{i} \\ \text{currents measured at branch } \boldsymbol{j} \end{cases}$$

- Connectivity matrix (*CnM*): it is based on Kirchhoff's voltage law. Each row corresponds to a voltage or current and each column to a $\mathcal{L}_k$ (possible location of a *PQM*). Connectivity matrix is constructed as shown in (6). Two submatrices are constructed: one is CnM_V that is created from the transposed rows of Ain; the second, CnM_I is created from the values of Ain.

$$CnM = \begin{bmatrix} [CnM_V]_{N_n \times L} \\ \hline [CnM_I]_{N_b \times L} \end{bmatrix}$$

$$CnM_{V_{colum}} = \left|Ain_{i,\forall j}{}^t\right|; \forall i \in \mathcal{L}_k \quad (6)$$

$$CnM_{I_{ik}} = \begin{cases} 1 & \forall i \in \mathcal{L}_k \\ 0 & otherwise \end{cases} ; k = 1, \dots, L$$

- Connectivity vector (*CnV*): In the optimization problem, allocation vector *AV* represents the set of possible locations of PQMs. Thus, *CnV* is obtained from (7).

$$AV = [x_1\ x_2 \dots x_L]$$

$$CnV = CnM \times AV^t \quad (7)$$

- Redundancy-From-Vector (*RFV*) and Redundancy-To-Vector (RTV): two redundancy matrices (RFM and RTM) are formulated to calculate two redundancy vectors, as shown in (8) and (9). These vectors are used to identify when the state variables of voltage at the end nodes from a branch would be simultaneously calculated. A unique redundancy vector (RV) is calculated, as shown in (10).

$$RFM = \begin{bmatrix} [0]_{N_n \times L} \\ \hline [RFM_I]_{N_b \times L} \end{bmatrix} \quad RTM = \begin{bmatrix} [0]_{N_n \times L} \\ \hline [RTM_I]_{N_b \times L} \end{bmatrix}$$

$$RFM_{I_{row-i}} = CnM_{V_{row-i}}, \ \forall i, j : \ Ain_{ij} = 1 \quad (8)$$

$$RTM_{I_{row-i}} = CnM_{V_{row-j}}, \ \forall i, j : \ Ain_{ij} = -1$$

$$RFV = RFM \times AV^t$$

$$RTV = RTM \times AV^t \quad (9)$$

$$RV_{m,1} = RFV_{m,1} \times RTV_{m,1}, \ \ m = 1, \dots, (N_n + N_b) \quad (10)$$

- Co-connectivity vector (*CcV*): it allows determining which voltages may be calculated using the voltage values already measured or calculated. *CcV* is calculated as shown in (11).

$$CcV = \begin{bmatrix} [CV]_{N_n \times 1} \\ \hline [0]_{N_b \times 1} \end{bmatrix}$$

$$CV_j = \prod CnV_k, \ \ \forall\, m \neq j \colon |Ain_{im}| = \left|Ain_{ij}\right| = 1 \quad (11)$$

- Pre-Observability vector (P*OV*): this vector determines if a state variable will be observable and it is calculated as shown in (12).

$$POV = CnV + RV + CcV \quad (12)$$

- Observability vector (*OV*): due to the dependence between *CcV* and *CnV*, *OV* is constructed as shown in (13). *OV* incorporates the possibility to calculate the line current of a branch when the voltages in its terminals are known.

$$OV = \begin{bmatrix} [POV]_{N_n \times 1} \\ [POV_M]_{N_b \times 1} \end{bmatrix}$$

$$POV_{M_{k,1}} = \prod POV_{j,1}, \ \ \forall j \colon \left|Ain_{kj}\right| = 1 \quad (13)$$

Finally, *OV* is used as the set of constraints for the optimization problem in (3). This method to determine the constraints is applied to a test case in this work.

Impact of the Network Reconfiguration on Optimal placement of Power Quality Monitors.

Smart Grid concepts in electrical distribution systems allow notable advantages regarding to the efficient operation of the networks. Automatic network reconfiguration is one of these smart concepts and it is essential for the operation in smart distribution systems. DNR usually must be resolved taking into account the network modeling, changes in the network topology, load flow calculations and the constraints (radial network, current and voltage limits, among others). All this information must be taken into account in the optimization problem to find the best network configuration according to these constraints. This paper considers that dynamic reconfiguration is applied to minimize the power losses, while the number of the supplied customers is always the same, with only changes in the network topology.

When the DNR problem is solved, the results are applied and the network topology is changed. It is clear that *OV*, in equation (13), changes when the network topology is modified, this due to that incidence matrix changes too. Therefore, the problem of optimal placement of PQMs must be formulated and solved again. Thus, the optimal monitoring system found in a specific case cannot be optimal for different network topologies which are obtained from the DNR.

This work aims to estimate the impact of the dynamic network reconfiguration on the harmonic observability. The authors propose two indexes for quantifying the observability of the harmonic state variables from a partial monitoring system. It is important to highlight that the scope of this work is only to estimate the impact on the observability of the harmonic state variables, but not the impact on the harmonic state estimation.

The first percentage index is called Harmonic Observability Rate (*HOR*) and it is presented in (14). A value of HOR near to 100% is better because indicates a full harmonic observability.

$$HOR_{nt_i} = \left(\frac{(\#rows\ OV_j \geq 1)|_{AV^*_{nt_b}}}{(N_n + N_b)}\right) \times 100\% \qquad (14)$$

HOR_{nt_i} is calculated for each network topology nt_i and evaluates the harmonic observability in an optimal configuration of PQMs $AV^*_{nt_b}$,which was calculated previously.

In addition, the hours of operation for each nt_i can be taken into account. This allows weighting the set of observability values for each network reconfiguration and a unique index to evaluate the harmonic observability can be obtained according (5). HOR_T weighs the harmonic observability from an optimal location of PQMs $AV^*_{nt_b}$, according to the hours of operation with a particular network topology.

$$HOR_T = \frac{\sum_{i=1}^{NT_t}\left(HOR_{nt_i} \times Noh_{nt_i}\right)}{Noh_t} \qquad (15)$$

where NT_t is the total number of all network topologies generated from the DNR. A value of HOR_T near to 100% means that the harmonic observability is very good in the different network topologies generated from the dynamic reconfiguration.

Figure 1 shows the proposed method to construct the optimization problem and the procedure to evaluate the two proposed indexes.

Numerical examples and discussion

The 33-node test system is used to test the proposed indexes performance. In (Abdelsalam et al., 2014), the 33-node test system was used for optimally locating the PMUs with different network configurations and some renewable sources: Photovoltaic (PV) and Wind Power (WP). In this work, IEEE 33-node test system is analyzed in five network configurations.

Table 1 presents the network configuration cases that were taken into account in this work. In each case, there are five line sections opened to ensure the radial topology operation while the same number of customers is supplied. The operation hours in each case are determinate by the renewable sources and formulated based on a total 24 hours of the day.

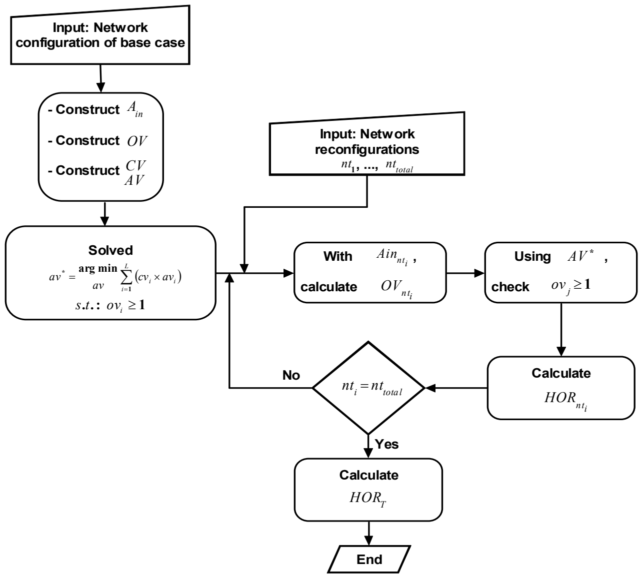


Figure 1. Proposed method to evaluate the impact of the DNR on optimal placement of PQMs

Table 1. Topologies studied and their characteristics

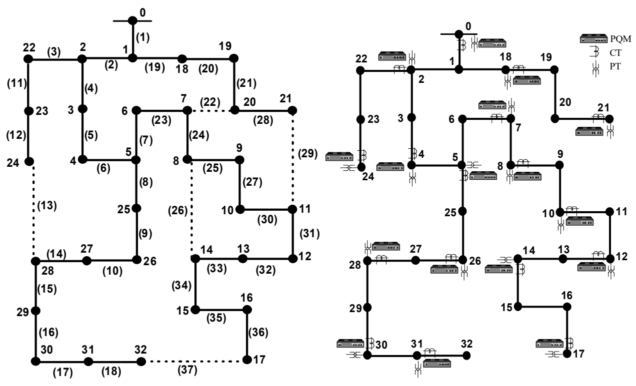
Network configuration	Open line sections	Distributed generation	Operation hours
Base case	13 22 26 29 37	Without PV and WP	---
RC.1	14 22 25 33 36	Low PV and high WP	5
RC.2	13 18 23 25 33	High PV and low WP	7
RC.3	10 22 25 33 37	Low PV and high WP	7
RC.4	14 18 23 25 33	Only WP	5

The OPP of PQMs is applied to case base shown in Figure 2.a and described in Table 1. The dotted lines represent the tie switches. Optimal placement of PQMs to guarantee the full harmonic observability is found using the proposed method and the results are presented in Table 2. For the solution of the OPP, the cost vector CV contains ones in all positions, i.e. the cost of installing a PQM is the same in any node of the distribution system.

Table 2. Results of the optimal placement of the PQMs for the base case

PQM	Measurements		PQM	Measurements	
	Voltage (node)	Current (branch)		Voltage (node)	Current (branch)
1	0	1	10	17	36
2	2	3	11	18	20
3	4	5	12	21	28
4	5	8	13	24	12
5	7	23	14	26	10
6	8	25	15	28	14
7	10	30	16	30	16
8	12	32	17	31	18
9	14	34			

Figure 2.b shows the placement of the PQMs and highlights the locations of the voltage and current transducers.



a) Base case

b)Optimal placement of the PQMs for the base case

Figure 2. Base case of operation of the IEEE 33 Node test feeder and the optimal placement of the PQMs

Indexes calculation: indexes to evaluate the impact of the DNR on harmonic observability are calculated according with the proposed method presented in Figure 1. The placement of the PMQs has already been defined in Figure 2.b and the next step is to evaluate the harmonic observability for all reconfiguration cases. The results are shown in Table 3.

Table 3. Results of the indexes to evaluate the harmonic observability with optimal placement of PQMs for the base case

Network Reconfiguration cases	HOR %	HOR_T %
RC.1	100	96.15
RC.2	92.3	
RC.3	100	
RC.4	92.3	

The results show that for RC.2 and RC.4 network reconfigurations, the harmonic observability is impacted due to a 7.7 % of the system is not observable. During the operation time in this reconfiguration case is not possible to estimate all harmonic voltages and currents. However, the index HOR_T shows that when the harmonic observability is weighted in all operation time, the observability loss is less than in the worst cases. This index can be used by electrical utilities to assess the efficiency of the monitoring system installed. In addition, the electricity market regulators would require minimum standards of harmonic observability based on the proposed indexes to monitoring the harmonic components in the distribution systems.

Proposed solution to get the full harmonic observability: A modification of the objective function used in the OPP may guarantee the full harmonic observability.

The results of the OPP in the previous section were obtained using the *CV* with ones in all its positions. This means that the possible locations of PQMs are not penalized in the optimization problem. The proposal is to penalize the locations where a current measurement is on a line section that can be open in a reconfiguration case. Thus, it is required to know all reconfiguration cases and which line sections could be opened. The locations of PQMs in these line sections are penalized to avoid the observability loss due to PQMs without current measurements when a network reconfiguration is presented in the distribution system.

Table 4 shows the line sections identified and which must be penalized in the optimization problem.

Table 4. Penalty of the line sections

Line section	10	14	18	25	33	36
Cost vector value	100	100	100	100	100	100

The results of the OPP are shown in Table 5 and the new results of the indexes are shown in Table 6 using this optimal placement of the PQMs. The new optimal placement of the PQMs guarantees the full harmonic observability in the different network reconfiguration cases. It is highlighted that one additional monitor is necessary, compared to the base case without penalization, to guarantee the full harmonic observability.

Table 5. New results of the optimal placement of the PQMs for the base case

PQM	Measurements		PQM	Measurements	
	Voltage (node)	Current (branch)		Voltage (node)	Current (branch)
1	1	0	10	17	36
2	2	3	11	19	20
3	3	5	12	21	28
4	6	7	13	22	11
5	8	24	14	23	12
6	10	27	15	25	9
7	11	31	16	27	14
8	12	32	17	29	16
9	14	34	18	31	18

Table 6. Results of the Indexes to evaluate the harmonic components observability

Reconfiguration cases	HOR %	HOR_T %
RC.1	100	100
RC.2	100	
RC.3	100	
RC.4	100	

Conclusions

Optimal placement of PQMs becomes an important method to be applied in smart electric networks. However, conventional methods do not take into account the dynamic network reconfiguration in the solution of the optimal placement problem. This work presents a method to estimate the impact of the dynamic reconfiguration on harmonic observability and the results shows its good performance. When the information of the reconfiguration cases was incorporated in the optimization problem, it is possible to guarantee the full harmonic observability.

In addition, the authors suggest new perspectives to solve in future works related with optimal monitor placement, such as: incorporation of the observability indexes into the optimization problem; a proposal for a multi-objective optimization problem including all network reconfiguration cases or proposals for the optimal monitoring systems based on the detection of different kinds of power quality disturbances.

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