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Power Quality Monitor Allocation Based on Singular Value Decomposition and Genetic Algorithm

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Abstract

This paper proposed a novel method for allocating power quality meters with the main objective of ensuring a completely observable power distribution system. The method was designed to establish the quantity, location and type of measurement to be performed (voltage and/or current) for a given distribution system by employing genetic algorithms and the principles of state estimation based on the singular value decomposition. Moreover, a limitation in the number of current measuring channels was inserted in the mathematical formulation as an alternative for reducing costs. The method has been validated by running a three-phase harmonic state estimation using the IEEE 34 and 37 bus distribution test feeders. The results demonstrated the effectiveness of the method for designing power quality monitoring systems in distribution grids, ensuring full observability for state estimation purposes.

Keywords Distribution system · Meter placement · State estimation · Genetic algorithms · Singular value decomposition

1 Introduction

In practice, the installation of power quality meters (PQMs) in distribution systems (DSs) is directly related to consumers' complaints or to measurement campaigns performed by the utility. PQMs are allocated by experts according to general guidelines, power quality (PQ) knowledge and DS topology. Main or express feeders or even specific customer venues (when required) are generally chosen as good locations for a meter. However, following such recommendations are difficult in practice, as continuous and real-time monitoring of distribution systems is increasingly required in the context of smart grids (Chung et al. 2007).

Smart grids have been growing in several countries worldwide, such as in Australia, the USA, Canada, China, European Union, Republic of Korea and India (Selvam et al. 2016; Stedman 2016). In this sense, the perspective for smart grids provides an increasing number of permanent and integrated monitoring spots in distribution systems. But even with such perception, it is still technically and economically prohibitive to install meters at all nodes in the system. Thus, it is highly desirable to develop advanced methods to allocate meters, so that from a reduced number of meters it is possible to estimate the state of the whole system and to monitor relevant PQ disturbances. Therefore, minimizing the quantity of PQ meters under an optimized allocation perspective, making the DS completely observable, is greatly relevant in economic terms. Remark that the cost of this operation is strongly linked to the number of meters to be installed, and in technical terms, the installation at some nodes of the system may present technical difficulties (Weng and Zhang 2008).

Also, regarding the three-phase voltage estimation of all distribution systems nodes, currently only a limited number of utilities have adopted this estimation process (Lubkeman et al. 2000; Simendic et al. 2005; Katic et al. 2013; Atanackovic and Dabic 2013). However, the tests in real systems indicate that this is feasible and sufficiently accurate for the purpose of real-time monitoring (Simendic et al. 2005; Katic et al. 2013; Melo et al. 2019).

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Regarding the allocation of meters, it can be observed that, initially, the great majority of the works was focused on symmetrical and balanced transmission systems (Marín et al. 2003; Eldery et al. 2006; Reis et al. 2008; Almeida and Kagan 2011a; b; Ketabi et al. 2012; Kazemi et al. 2013; Wong et al. 2014). More recently, some works are focused on DSs (Melo et al. 2019; Kouzelis et al. 2015; Bottura et al. 2019; Lucimario et al. 2016; Shaaban et al. 2019; Dehnavi et al. 2019; Kempner et al. 2014; Gomes et al. 2016). In addition, most of the researches consider the allocation only for monitoring short time voltage variations (Eldery et al. 2006; Reis et al. 2008; Almeida and Kagan 2011b; Ketabi et al. 2012; Kazemi et al. 2013; Wong et al. 2014; Kempner et al. 2014; Gomes et al. 2016; Ibrahim et al. 2014; Martins et al. 2019) which results in a low number of PQM to be installed, insufficient to make the grid completely observable during normal operation. Moreover, it is assumed that the measuring equipment has a sufficient number of channels to measure all current branches connected to a specified bus (Eldery et al. 2006; Reis et al. 2008; Ketabi et al. 2012), requiring expensive meters (with more than one three-phase current measuring channel).

Among the techniques used for PQM allocation in the above-referenced papers, methods based on linear programing (Eldery et al. 2006; Reis et al. 2008; Almeida and Kagan 2011a; Kempner et al. 2014), as well as optimization methods, such as the application of evolutionary algorithm techniques (Wong et al. 2014; Ibrahim et al. 2014), were developed. The PQM allocation problem has a combinatorial nature. Thus, a simple genetic algorithm (GA) was chosen to solve the problem in this paper. GA was also employed in Marín et al. (2003), Almeida and Kagan (2011b), Kazemi et al. (2013) and Gomes et al. (2016). The proposed method takes advantage of the properties of the singular value decomposition (SVD) technique applied in a harmonic state estimation (HSE) method presented in Breda et al. (2016), it has the capability to indicate the nodes that need to be monitored to make the system completely observable.

In this context, the main contribution of this paper is to propose a method for PQM allocation (PQMA) capable of defining the quantity, location and type of measurement to be performed for a given system so that it becomes completely observable. This PQMA method will be applied for distribution systems and will allow all bus to have their three-phase voltages for fundamental frequency and for different harmonic orders be estimated accurately, and its formulation considers reduced line current measurements. Still, the utilities can use this method in the system planning stages or programed measurement campaigns.

This paper is divided in five sections besides this introduction. Section 2 presents the fundamentals of the proposed method, which are based on the concepts about three-phase state estimation and on the properties of the SVD technique. Section 3 shows the results obtained by the developed method and Sect. 4 shows the validation of the approach by using three-phase harmonic state estimation. Finally, Sect. 5 presents the conclusions.

2 Fundamentals of the Proposed Method

The PQMA method proposed in this work is based on the principles of three-phase harmonic state estimation for DSs using t SVD technique, proposed in Breda et al. (2016). The main ideas of the state estimation method are briefly presented below.

2.1 Three-Phase State Estimation

Based on the system topology, a state estimator is formulated by using the three-phase admittance matrix of the system and the location of the meters. The formulation presented in Breda et al. (2016) uses voltage measurements available in the nodes and line currents to estimate the state of the system. It can also use the measurements of current injections in the nodes, as in Eldery et al. (2006), Reis et al. (2008) and Ketabi et al. (2012).

Considering the nodal voltages as the system state variables, the estimated voltages ($\boldsymbol{v}$), the measurements vector ($\boldsymbol{a}$) and the errors vector ($\boldsymbol{\varepsilon}$) are as follows (Madtharad et al. 2003):

$$\begin{bmatrix} a_v \\ a_i \end{bmatrix} = \begin{bmatrix} I & 0 \\ Y_{IM} & Y_{IC} \end{bmatrix} \begin{bmatrix} v_M \\ v_C \end{bmatrix} + \begin{bmatrix} \varepsilon_v \\ \varepsilon_i \end{bmatrix} \tag{1}$$

in which $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{0}$ is null matrix, $\boldsymbol{a_v}$ and $\boldsymbol{a_i}$ are the vectors of voltage and current injection (and/or line current), respectively; $\boldsymbol{Y_{IM}}$ and $\boldsymbol{Y_{IC}}$ are the elements of the admittance matrix for the nodes with measured and calculated voltages related to $\boldsymbol{a_i}$, respectively; $\boldsymbol{v_M}$ and $\boldsymbol{v_C}$ are vectors of the measured and calculated nodal voltages, respectively; $\boldsymbol{\varepsilon_v}$ and $\boldsymbol{\varepsilon_i}$ are vectors of errors of the voltage measurements and current injections, respectively.

Thus, a measurement matrix $\boldsymbol{H}$ can be defined as:

$$H = \begin{bmatrix} I & 0 \\ Y_{IM} & Y_{IC} \end{bmatrix} \tag{2}$$

Because $\boldsymbol{H}$ is numerically very close to a singular matrix, the solution method chosen for this system is the SVD technique (Breda et al. 2016; Madtharad et al. 2003). By using the S, the matrix $\boldsymbol{H}$ ($m \times n$) can be decomposed as the product of three matrices (3), where m is the number of measurement points and n is the number of state variables:

$$H = UWV^T \tag{3}$$

In (3), $\boldsymbol{W}$ is a diagonal matrix $(n \times n)$ with positive or zero elements, which are the singular values of $\boldsymbol{H}$. Matrices $\boldsymbol{U}$ and $\boldsymbol{V^T}$ are orthogonal, where $\boldsymbol{U}$ is an orthogonal column matrix $(m \times n)$, and $\boldsymbol{V^T}$ is the matrix transposed from the orthogonal matrix $(n \times n)$. However, as the systems considered in this work are unbalanced three-phase, it is necessary to adapt this formulation. Thus, matrix $\boldsymbol{H}$ will have order $3\ m \times 3n$, matrix $\boldsymbol{W}$ will have order $3n \times 3n$, matrix $\boldsymbol{U}$ will have order $3\ m \times 3n$ and, finally, matrix $\boldsymbol{V^T}$ will have order $3n \times 3n$.

The advantage of using SVD for power system state estimation is that a previous observability analysis is not required, which is opposite to the classic methods of state estimation (Melo et al. 2019; Eldery et al. 2006; Reis et al. 2008; Almeida and Kagan 2011a, b). Thus, for a given measurements set, there will always be a solution and, if the power system is not completely observable, the SVD-based method indicates candidate nodes for placing meters in order to make it completely observable. This is done by analyzing the matrices of (3), as explained below (Breda et al. 2016):

- After running the SVD algorithm, the null singular values (zeros on the main diagonal) of matrix $\boldsymbol{W}$ are found;
- If there is no null singular value, the system is completely observable, and the process is completed. Otherwise, the positions of the $\boldsymbol{W}$ columns, in which the null singular values are located, are stored;
- Finally, the $\boldsymbol{V}$ columns corresponding to the positions previously stored in the previous step are checked. In these columns, rows containing nonzero values indicate the unobservable nodes that need to be monitored.

Therefore, this characteristic of the SVD technique in indicating the nodes to be monitored to obtain the complete observability of the power system can be explored to propose a PQMA method in distribution systems. The details are presented in the next section.

More information about SVD applied to the state estimation in partially observable systems is found in Yu and Watson (2004).

2.2 PQMA Formulation

The general formulation, modeling and solution of the proposed PQMA will be presented below.

2.2.1 General Formulation

The main idea of the proposed method can be summarized in the following items:

- When the distribution system topology is known, it is possible to formulate a three-phase state estimation problem using the concepts of Sect. 2.1 (Eqs. (1) and (3)), detailed in Breda et al. (2016), whose focus is on the three-phase harmonic state estimation. However, the PQMA proposed in this paper uses only the fundamental frequency, without the need to employ other harmonic frequencies;
- An initial voltage and current meters set are established, where the quantity and position must be defined, considering any criteria. Using the load flow calculation and considering any loading scenario, the values measured by these meters are calculated, which are taken as known measurements for the state estimation process. It is important to mention that the load flow calculation is executed for the fundamental frequency only, simplifying the method;
- With the measurements obtained by a load flow calculation and considering deviations $\boldsymbol{\varepsilon_v}$. and $\boldsymbol{\varepsilon_i}$ from (1) as null, the three-phase state estimation based on SVD is performed and matrix $\boldsymbol{H}$ is analyzed in order to identify if there are unobservable nodes. If so, meters are allocated on these nodes to make the system completely observable.

The challenge of the procedure previously outlined is to minimize the number of meters and (or) measurement channels in order to reduce costs. The results obtained in Breda et al. (2016) showed that the same number of meters, if properly allocated, could increase the number of observable nodes. Thus, based on this finding, the problem of meters allocation proposed in this work employs genetic algorithms (GAs), which is an exciting and simple alternative when it concerns a high number of possibilities to be considered.

It is worth noting that the results of the proposed PQ meter allocation method supports both fundamental and harmonic state estimation. Therefore, to meet the IEC 61000-4-30 and IEEE *Std* 519-2014 requirements the meters to be installed must be able to perform measurements up to, at least, the 40th harmonic order.

The PQMA implemented can be summarized in the block diagram of Fig. 1.

2.2.2 GA Modeling and Solution

In order to apply GA to solve the problem as mentioned above, each individual from the population refers to a chromosome (all possible measurement points), represented by a vector, in which each element (gene) represents an information set (presence or absence of measurements) that must be manipulated in search of the best solution.

Initial Population In this work, the chromosome is an existence vector X, defined as a binary vector of n elements, where n is the number of the system nodes (n_b) plus twice the number of lines capable of receiving meters $(2n_l)$, as both lines end may have meters installed. Figure 2 shows the chromosome structure and its respective genes (elements).

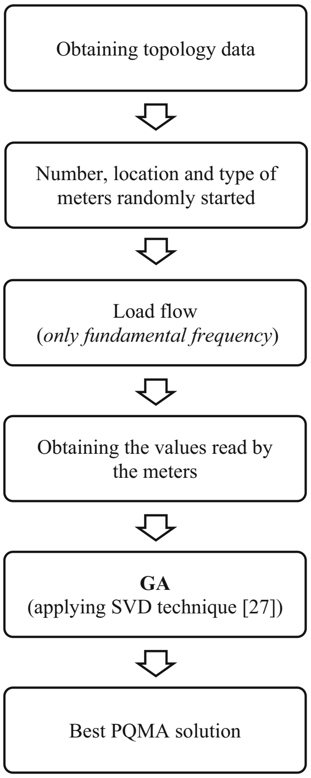


Fig. 1 Block diagram of the PQMA implemented

Thus:

$$\text{From } j = 1 \text{ to } n_b:\quad x(j) = \begin{cases} 1, & \text{Meter installed in the bus } j \\ 0, & \text{Meter not installed in the bus } j \end{cases}$$

$$\text{From } j = n_{b+1} \text{ to } n:\quad x(j) = \begin{cases} 1, & \text{Meter installed in the line } (j - n_b) \\ 0, & \text{Meter not installed in the line } (j - n_b) \end{cases} \tag{4}$$

Consequently, its dimension is $(n \times 1)$, as follows:

$$X = [x(1)x(2)x(3)\ldots x(n_b)x(n_b+1)\ldots x(n)]^T \tag{5}$$

where the elements from $\boldsymbol{x(1)}$ to $\boldsymbol{x(n_b)}$ relate to the voltage meters installed in the bus, and the elements from $\boldsymbol{x(n_b+1)}$ to $\boldsymbol{x(n)}$ are related to the current meters installed in the lines.

In addition to the chromosome, it is also necessary to define, before the initial generation, a cost vector $\boldsymbol{C}$ $(1 \times n)$ that represents the cost of installing a meter at each possible location. That way, the internal product of this vector with vector $\boldsymbol{X}$ results in the total costs related to the set of meters. The cost vector is defined as:

$$\begin{aligned} &\text{From } j = 1 \text{ to } n_b: \\ &\quad c(j) = \{\text{installation cost in the bus } j\} \\ &\text{From } j = n_{b+1} \text{ to } n \\ &\quad c(j) = \{\text{installation cost in the line} (j - n_b)\} \end{aligned} \tag{6}$$

With j ranging from 1 to n, resulting in:

$$C = [c(1)c(2)c(3)\ldots c(n_b)c(n_{b+1})\ldots c(n)] \tag{7}$$

where the elements from $\boldsymbol{c(1)}$ to $\boldsymbol{c(n_b)}$ relate to the installation cost of meters in the bus, and the elements from $\boldsymbol{x(n_b+1)}$ to $\boldsymbol{x(n)}$ are to the installation cost of meters in the lines.

Finally, in order to obtain feasible solutions for system monitoring, a population with 1000 chromosomes was chosen. This population size was empirically chosen in order to ensure a better coverage of the problem domain compared to smaller populations. The values of each gene from each chromosome of this population were randomly generated.

Evaluation Each individual (chromosome) will go through this process summarized by the block diagram of Fig. 3. This diagram illustrates how the actions of the algorithm developed from the beginning of the process with the HSE application until the final calculation of the fitness function of each chromosome during the GA evaluation step.

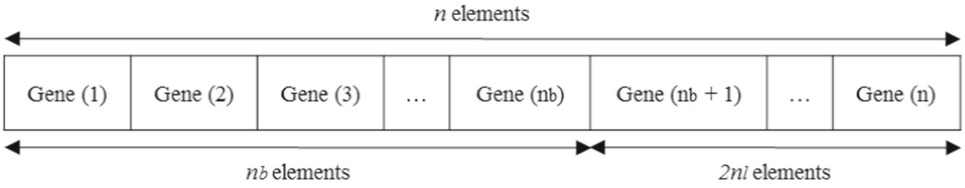
The objective function and constraints are presented below.

- *Objective function*: The objective of this problem is to minimize the total cost of the measurement system for a complete DS monitoring, as shown by (8).

$$\min f(x) = \sum_{i=0}^{n} c_i x_i = C \cdot X \tag{8}$$

- *General constraint:* The general constraint imposed to all cases addressed in this work was to ensure the complete observability of the system, that is, all state variables (complex voltages in the nodes) will be obtained from the estimation. Thus, chromosomes with unobservable nodes will be discarded. In fact, for each individual of each

Fig. 2 Chromosome structure and its respective genes (elements)



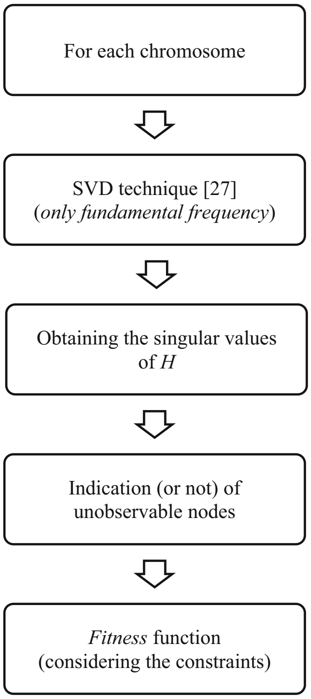


Fig. 3 Block diagram of the evaluation method for each individual

population, the SVD technique is only applied for the fundamental frequency and it is verified if the singular values of matrix $\boldsymbol{H}$ (diagonal values of matrix $\boldsymbol{W}$) are not zero, following a tolerance threshold of 1×10^{-9} p.u.. This procedure is performed for all three phases of the system. Thus, r is defined as the scalar value related to this general constraint, as defined by (9).

$$r = \begin{cases} 1, & \text{Singular values} < 1 \times 10^{-9}\,\text{pu} \\ 1 \times 10^{3}, & \text{Singular values} > 1 \times 10^{-9}\,\text{pu} \end{cases} \tag{9}$$

Thus, if the value of any singular value for any phase obtained by the SVD technique is not zero, the r value for this chromosome will be 1×10^{3}.

- *Constraint of the number of current channels:* the meters are modeled with a limitation regarding the number of current measuring channels. In this work, in order to reduce costs, we proposed a constraint that limits only one three-phase current measuring channel per meter. Thus, defining s as the scalar value related to this constraint, one has:

$$s = \begin{cases} 1, & \text{Current measuring channels associated to one meter} \leq 1 \\ 1 \times 10^{3}, & \text{Current measuring channels associated to one meter} > 1 \end{cases} \tag{10}$$

In general, during the solution process, if the number of current measuring channels associated to one meter is greater than 1, the value of s for this solution will be $1\text{x}10^{3}$. So, it will be automatically discarded by the GA.

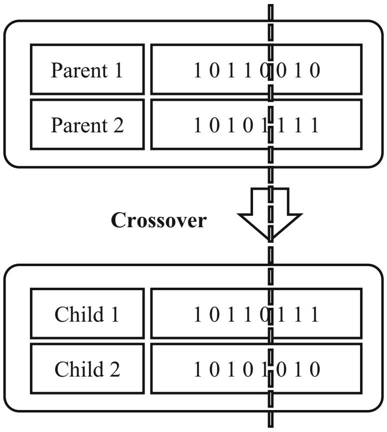


Fig. 4 Crossover operation

- *Fitness function:* To choose the best configuration of each generation, a fitness function (*fitness*) is calculated from the internal product of the existence vector with the cost vector and the constraint functions, as seen in (11).

$$fitness = C \cdot X \cdot r \cdot s \tag{11}$$

The best configuration chosen (strongest individual) is the one with the lowest value of the *fitness* function.

Selection After the evaluation of the fitness function, the selection step occurs. This step, basically, consists of selecting stronger individuals (with the lowest values of the *fitness* function), but not neglecting the weaker ones completely (with higher values of the *fitness* function). This strategy was used because weak individuals may also have characteristics that are favorable to the creation of another individual with good characteristics.

One method that presents the mentioned requirements is the addicted roulette method, which consists in creating a virtual roulette, in which each individual receives a "piece," in this case inversely proportional to its value of the *fitness* function. The roulette is virtually rotated and the individual upon which it stops will be the one selected. For this work, in particular, two parents are selected at each iteration, i.e., a pair of chromosomes.

Crossover Figure 4 illustrates the crossover operation. In this work, the single crossover point was applied, using the method of roulette with rate equal to 80%. This value is very close to the values adopted in Almeida and Kagan (2011a, b), Kazemi et al. (2013), Gomes et al. (2016) and Bahabadi et al. (2011).

Mutation After the crossover, the mutation step occurs. During the mutation stage, changes in the genes can occur as

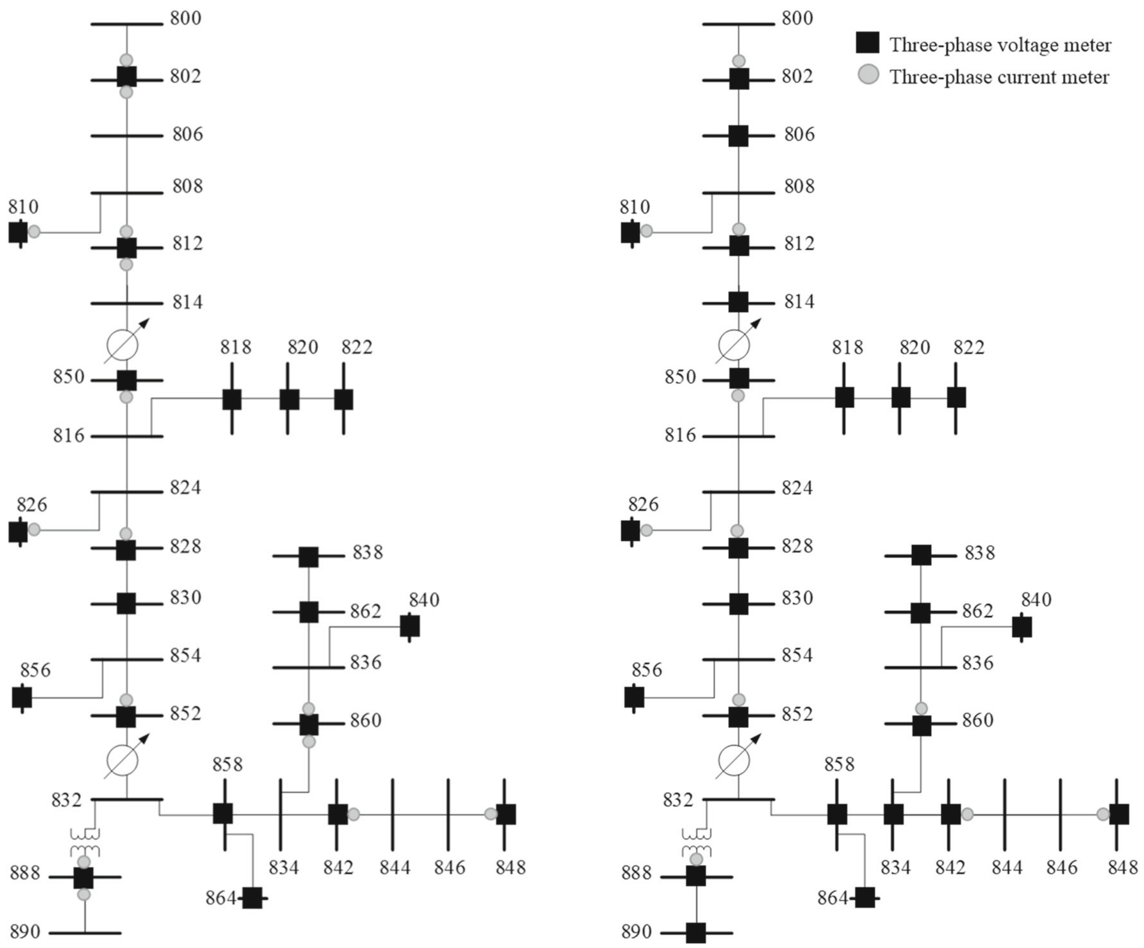


Fig. 5 PQMA result for IEEE 34-bus system (Cases 1 and 2)

follows: a number between 0 and 1 is drawn, also using the roulette method. If this number is lower than a predetermined probability (which for this work was 1%), the mutation operator acts by changing the gene value. This value is also very close to the values adopted by other works, such as Almeida and Kagan (2011a, b), Kazemi et al. (2013), Gomes et al. (2016) and Bahabadi et al. (2011).

Elitism After the mutation step, the implemented GA uses elitism. After each iteration, elitism maintains in the population an individual of "elite" (with the lowest value of the fitness function found so far). This consideration is necessary, because, despite a high number of possible combinations for the formation of individuals, the search space is very restricted, due to limitations imposed by constraints. Thus, the elite individual cannot be discarded from the population while remaining an elite individual. An elite individual ceases to be so when an individual more apt than himself arises in the population. Therefore, the main role of elitism in this work is to keep the individual with the lowest value of the fitness function of a generation, replacing the highest value of the new generation's fitness function, as long as it is still considered the strongest individual.

Stop Criteria In this work, during the GA execution, populations of individuals are generated randomly at each iteration, where each population is related to a set of possible solutions of the problem studied. In addition, at each iteration, each possible population is evaluated in order to verify how capable it is to be the best solution to the problem. If the solution does not meet any constraint, the algorithm sharply penalizes it. Also, in order to avoid a local optimum, as described throughout the text, the roulette method was used in three different steps: selection, crossover and mutation.

Finally, after all the steps, the stop criteria adopted in this work are based on the objective function value. Thus, if the value of this function does not change after 50 generations, the algorithm assumes that the process converged. The best result found in all generations is then considered the best solution to the problem. Otherwise, the number of generations is updated and the process returns to the evaluation block. It is worth noting that the number of 50 generations was chosen because several tests have pointed out that it is sufficient to ensure the algorithm convergence.

3 Application of the Proposed Method

The load flow results were obtained through the DIgSILENT PowerFactory program (DIgSILENT 2010), and the GA itself was elaborated using the MATLAB program. The method was run on a PC INTEL Core i7 2.67 GHz with 6 GB RAM.

The costs of all the PQM were considered equal, that is, the cost vector C consists of only unitary values. This strategy was adopted to eliminate the influence of the costs in the results presented in this section, so that the allocation could be analyzed without any bias. Of course, when the method is applied to real cases, utilities are recommended to insert costs associated to the meters acquisition and installation, especially if there are locations difficult to reach or install. In these, the costs must be very high to discourage PQ meter placement.

The validation of the PQMA algorithm was performed by simulations using the IEEE 34- and 37-bus test feeders (Kersting 2001), considering that all the loads are modeled as constant power loads. Despite both systems have similar number of nodes, they present different topologies (the 37-bus test feeder, for example, has more lateral branches), which is one of the inputs for the allocation algorithm.

For this, two cases were evaluated for each system:

- *Case 1:* The constraint about the number of current measuring channels (constrain (10)) is neglected;
- *Case 2:* The constraint (10) is considered.

3.1 Results Obtained for the IEEE 34-Bus Test Feeder

Figure 5a and b show the results obtained by PQMA implemented for Cases 1 and 2, respectively, for the IEEE 34-bus test feeder.

For Case 1, the number of voltage meters required for complete observability of the system is 21. In addition, 15 three-phase current measuring channels are also required. For Case 2, the number of voltage meters increases to 25, and as each voltage meter has only one three-phase current channel, this quantity was reduced to 11, in comparison with Case 1.

Traditionally, nodal current injection is considered in the distribution three-phase state estimation (Eldery et al. 2006; Reis et al. 2008; Ketabi et al. 2012). By doing this, each branch connected to a voltage meter has to be equipped with a three-phase current channel. If this strategy was applied to the results, as there are 35 branches in total connected to the 21 bus equipped with voltage meter for Case 1 and 42 branches connected in total to the 25 bus equipped with voltage meter for Case 2, it would result in 35 current channels for Case 1 and 42 current channels for Case 2. Thus, the approach proposed in this paper reduced those numbers significantly, according to the results: 15 current measuring channels for Case 1 and 11 current measuring channels for Case 2.

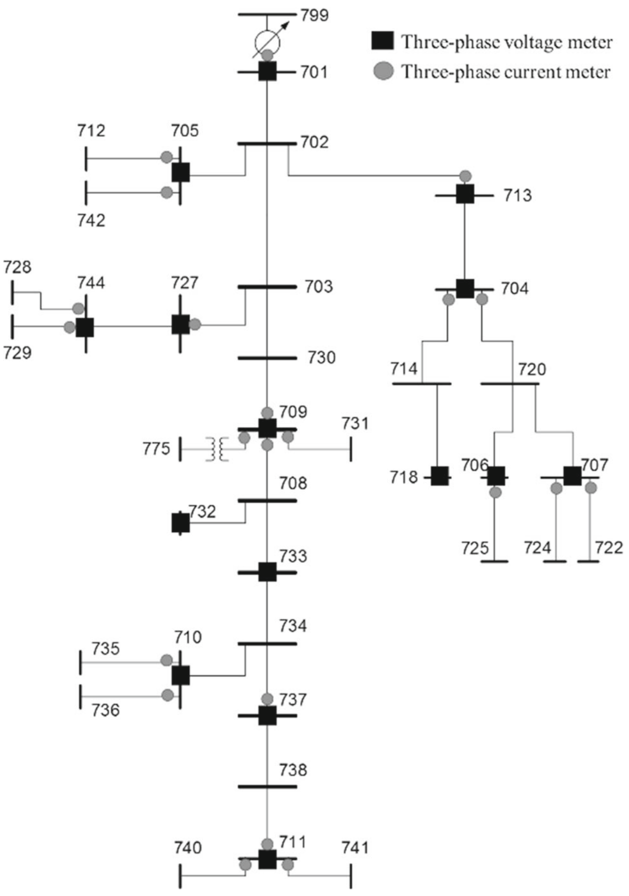


Fig. 6 PQMA result for IEEE 37-bus system (Case 1)

Also, due to the installation of voltage meters in single or two-phase nodes, there is also a saving in the number of single-phase current meters in the 34-bus system. In cases 1 and 2, the current measurement on lines 810–808 and 826–824 is done in only two phases, i.e., the other single-phase channel of each meter is not necessary.

3.2 Results Obtained for the IEEE 37-Bus Test Feeder

Figures 6 and 7 illustrate the results obtained for cases 1 and 2, respectively, for the 37-bus system.

For Case 1, the number of voltage meters required for complete observability of the system is 15, and 22 current measurement channels are also required. For Case 2, the number of voltage meters increases to 24, and since each meter has a three-phase current measurement channel, the number of current channels has decreased to 13.

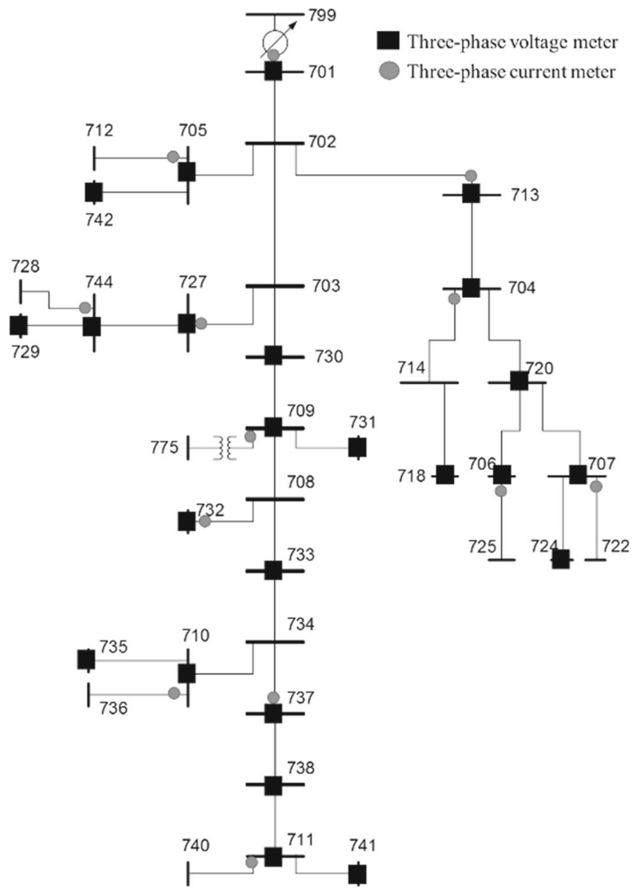


Fig. 7 PQMA result for IEEE 37-bus system (Case 2)

Also, for the IEEE 37-bus test feeder, the proposed approach resulted in a reduced number of current channels in comparison with employing the current injection as input. For example, as there are 36 branches in total connected to the 15 bus equipped with voltage meter for Case 1 and 49 branches connected in total to the 24 bus equipped with voltage meter for Case 2, however, the results obtained by the proposed method indicated that only 22 and 13 current channels were necessary for cases 1 and 2, respectively.

One interesting outcome of the proposed method is that, by comparing cases 1 and 2 of both systems, it can be observed that the number of voltage meters increases if the number of current channels constraint is considered. Thus, a financial analysis would be required to check if it is necessary to invest in increasing the number of equipment (voltage meters), or increasing the number of current measuring channels of existing meters.

4 Validation of the Proposed Method

To validate the results obtained by the PQMA, the meter allocation will be used to estimate the harmonic state of the IEEE 34- and 37-bus test feeders, by using the HSE proposed in Breda et al. (2016). Thus, a single harmonic current profile was adopted for all loads of the systems, as shown in Table 1. Equivalent harmonic current sources represent all loads modeled. This current profile was presented in Pires (2006), which comprises measurements of a Brazilian power distribution system.

In addition, a harmonic state estimation comparison will be considered based on the meters allocation recommended by Branco et al. (2018), where the authors developed a multi-objective technique for the allocation of PQ meters in order to make the system completely observable for short-term voltage variations. It must be emphasized that the intention of using the solutions presented in Branco et al. (2018) was to assess how the results of a voltage sag-driven meter allocation method would perform for harmonic state estimation. In addition, the method presented in Branco et al. (2018) was developed within our research group, so it was interesting to assess to what extent it could be applied to reach a completely observable grid.

4.1 Method Validation for IEEE Test Feeders

Figures 8, 9, 10 and 11 show the results of the three-phase state estimator for the fundamental and fifth harmonic frequencies. These frequencies are the most present in the frequency spectrum of the currents shown in Table 1, using as input the measurement locations pointed out by PQMA for Case 1 and Case 2 of the 34- and 37-bus test feeders (see Sects. 3.1 and 3.2).

It is important to comment that for this step of validation, the HSE developed in Breda et al. (2016) is used to estimate harmonic voltages, in addition to fundamental voltage, whereas the PQ meter allocation method is based on the fundamental voltages and currents.

As the results of the HSE found for Cases 1 and 2 were the same, only one figure for each system will be used to represent the two cases.

For 34-bus system, the results refer to phase *A*. Exceptionally, nodes 810, 826, 838 and 856 considered phase *B*. This is done because these are single-phase or two-phase bus bars that do not have phase *A*. For the 37-bus system, the results presented are associated with the fundamental frequency and phase *A*. For the 37-bus system, the results presented are associated to the fundamental frequency and phase *A*.

Also, regarding Figs. 8, 9, 10 and 11, the bus numbers marked with an "*" indicate the presence of voltage meters. The bars represent the estimated values, while the lines refer to the actual values (obtained through harmonic load flow).

From the results obtained for both systems, it is noted that the estimated values are equal to the respective actual values. That is, there is no presence of any unobservable island, as the algorithm was able to successfully estimate all values

Table 1 Harmonic current profile per phase

Order Harm.	Phase A		Phase B		Phase C	
	Mag. (%)	Angle (º)	Mag. (%)	Angle (º)	Mag. (%)	Angle (º)
1	100.00	– 30.96	100.00	– 152.64	100.00	78.90
3	10.77	168.17	9.74	– 130.28	8.01	163.46
5	6.45	15.65	5.66	– 145.27	4.09	– 89.52
7	2.16	– 170.42	1.27	– 133.33	0.85	– 2.75
9	0.56	– 33.20	1.02	– 51.65	0.94	178.79
11	0.62	26.26	0.33	– 58.45	0.82	– 143.17

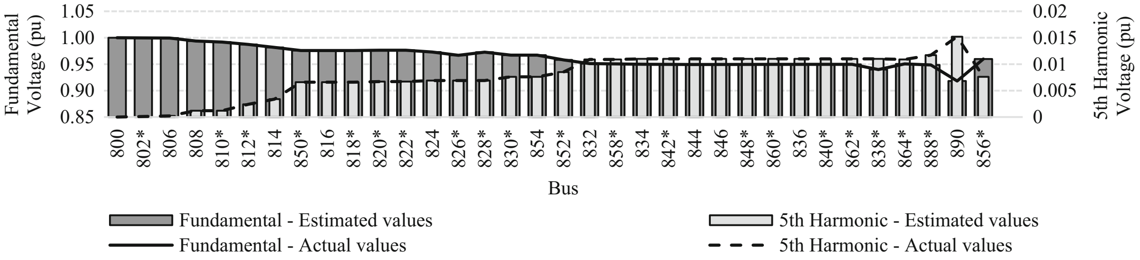


Fig. 8 Results for the voltages in each bus of the IEEE 34-bus system for Cases 1 and 2 (Fundamental frequency and 5th harmonic component—Magnitudes)

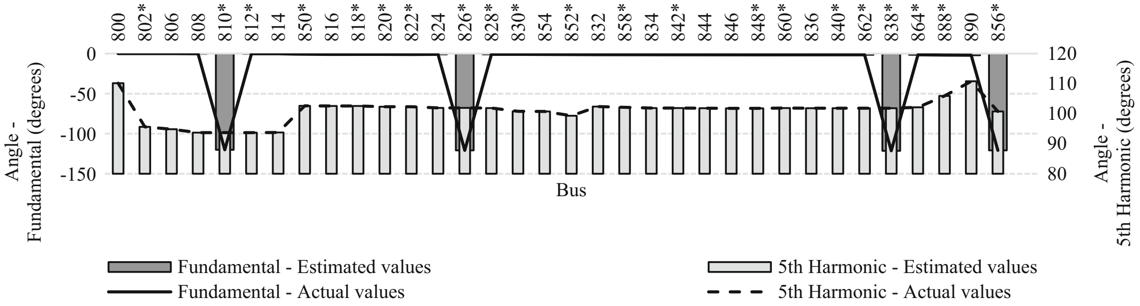


Fig. 9 Results for the voltages in each bus of the IEEE 34-bus system for Cases 1 and 2 (Fundamental frequency and 5th harmonic component—Phases)

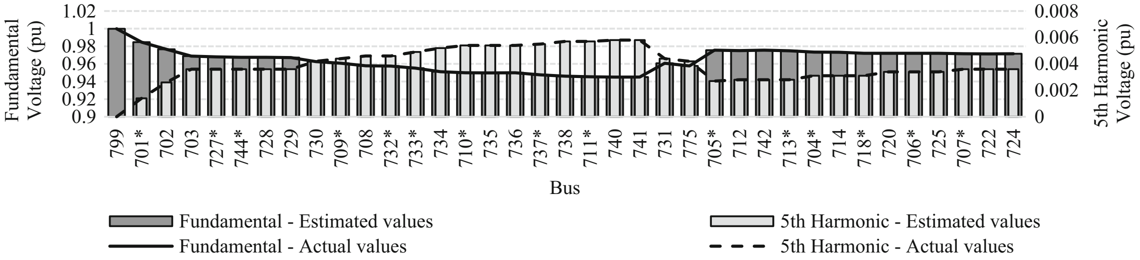


Fig. 10 Results for the voltages in each bus of the IEEE 37-bus system for Cases 1 and 2 (Fundamental frequency and 5th harmonic component—Magnitudes)

of the system state variables for the fundamental frequency and all other harmonic orders. Since no errors of any kind were considered in the measurements, when the estimation is reached using the SVD technique, the relative error of estimation is 0%. Therefore, it is observed that the PQMA was efficient in estimating the harmonic state of both systems.

4.2 Comparison with the Method Proposed in Branco et al. (2018)

For the 37-bus system, a meter allocation scenario suggested by Branco et al. (2018) considering one of the solutions with the highest number of meters was chosen. This scenario was

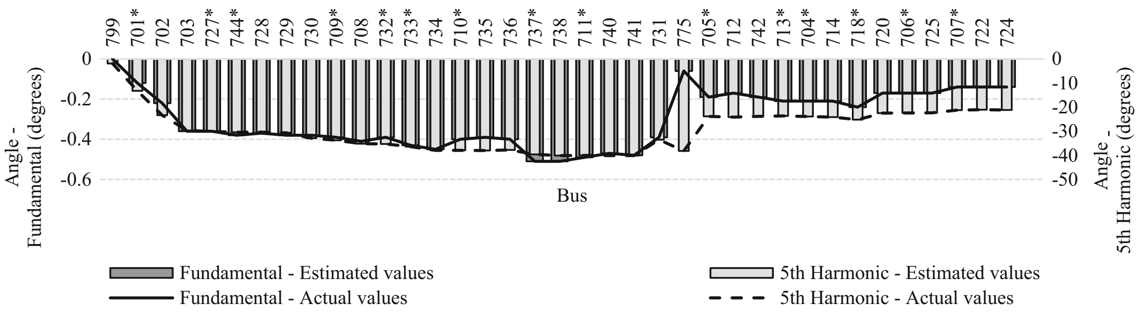


Fig. 11 Results for the voltages in each bus of the IEEE 37-bus system for Cases 1 and 2 (Fundamental frequency and 5th harmonic component—Phases)

efficient for voltage sag monitoring and it was chosen in an attempt to ensure a complete observability of the grid.

The considered scenario presents voltage meters installed at nodes 701, 727, 744, 728, 729, 730, 709, 708, 732, 733, 734, 735, 736, 737, 738, 740, 731, 712, 742, 704, 718, 720, 725 and 722. As the suggested locations do not concern line currents, it is assumed that all current branches connected to a node with voltage measurement are also being monitored. In this way, the number of nodes with voltage measurement is equal to 24 and the number of three-phase current measuring channels is equal to 43 (total number of current branches connected to each of the 24 nodes in which there is voltage measurement).

The results provided by the estimator show that, from this suggested configuration, 12 nodes have their voltage values correctly estimated, while node 741 does not have its estimated phasor voltage values. Thus, if it is desired to make the system completely observable, it is necessary to install another meter at this location. In other words, despite the voltage meters in almost two-thirds of the system nodes, it would still be necessary to invest in at least one more measuring equipment to ensure a complete observability using the scenario pointed out by Branco et al. (2018).

This number of 24 meters is greater than the result obtained by PQMA, in Case 1 for the 37-bus system, where only 15 meters are required for a complete observability of the system. Thus, even though work (Branco et al. 2018) focus for the monitoring of short-term voltage variations, whose expectation is a lower cost for monitoring, the authors presented a more costly solution than the method proposed by the PQMA, in this paper.

Thus, the importance of developing specific allocation methods for each type of analysis is evident. Because in Branco et al. (2018), the allocation was developed only to voltage sag monitoring, it became clear that it is not suitable for estimating harmonic.

5 Conclusion

The PQMA method developed in this work aimed at three-phase state estimation in order to make the system utterly observable without applying an exhaustive search process to obtain the best solution. The utilities can use this method in the system planning stages or programed measurement campaigns. Two approaches validated the algorithm: one considering no limitation in the number of current measuring channels and the other considering this limitation.

Regarding the results obtained by the method, what can be noticed when comparing the cases with different constraints imposed is that, with the constraint in the number of current channels, a greater investment in the number of equipment is necessary. Thus, a financial analysis would be necessary to verify to what extent it is interesting to invest in increasing the number of equipment, or increasing the number of current measuring channels of existing equipment in the utility. This would be a recommendation for researching continuity.

Moreover, the importance of taking account line currents in the formulation, and not only current injections, is observed. As in the case which the same bus was allocating meters, a higher number of current meters are necessary if only are considered current injections. In this sense, all lines connected to the bus would need a current meter.

Finally, the results obtained by the PQMA were validated using the three-phase state estimator, and for all cases it is observed that there is no unobservable island in the system. Therefore, one important finding of this paper was that even using the fundamental frequency in the proposed allocation method, the optimal number of meters and optimal placement work properly for both fundamental and harmonic state estimation. However, the method presented does not take into account redundancy of measurements, which may be the subject of future works.

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