Optimal Number and Location of Measurement Instruments in Distributed Systems for Harmonic State Estimation

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Summary: **The recent studies about the attribution of the responsibilities for harmonic distortion in electric distribution systems show that the most promising approaches are based on measurement data acquired simultaneously in different nodes of the network. Therefore, distributed measurement systems are needed. For economic reasons, only a small part of network nodes can be equipped with measurement instruments, whereas the information about the overall status of the electric system has to be evaluated by means of suitable Harmonic State Estimation (HSE) techniques. This paper deals with the problem of choosing the optimal number and position of measurement devices, in order to ensure that the HSE algorithms can provide, at the lowest possible cost, results having a prefixed level of accuracy. An optimization algorithm based on the techniques of the dynamic programming is proposed and the way to take into account the uncertainty introduced by all the elements of the measurement system is discussed. Simulation results on a benchmark distribution network show the validity of the proposed approach.**

1. INTRODUCTION

The liberalized energy market makes it more and more important the task of attributing to the different subjects that interact in the electric system the responsibilities for the disturbances that degrade the power quality. The "contracts for the quality", introduced for instance by the Italian Authority for Electricity and Gas, are a clear evidence of such a need. As a consequence, it is necessary to define advanced measurement methodologies for the identification of power quality disturbances and for the localization of their sources. Some solutions have been proposed, especially for harmonic disturbances [1–5], and the debate about the choice of the most suited procedures is open, also with reference to their sensitivity with respect to the uncertainties existing in the measurement system [6].

For the practical implementation of some methodologies that require the knowledge of quantities measured simultaneously in different points of the network [3–5] it can be helpful the use of suitable Harmonic State Estimation (HSE) procedures [7–10].

For the above issues to be faced it is therefore necessary resorting to distributed measurement systems aimed at providing a "picture" of the electric network. The closeness of this picture to the actual situation (i.e. its accuracy) will increase for increasing number of measuring instruments installed in the network. This consideration obviously contrasts with both the economic requirement of reducing the costs and the present situation, according to which in medium voltage distribution systems the number of the available measurements is generally much smaller than the number of the variables to be evaluated in the HSE problem, which in turn depends on the number of nodes in the network.

Two needs therefore arise: from one side it is necessary to define suitable reliable procedures to estimate the network harmonic status starting from a limited number of measured data, from the other one it is of fundamental importance to establish the optimal number and position of the measurement stations needed for the monitoring, by both ensuring the minimal cost and complying with the accuracy constraints.

The first problem consists of defining reliable HSE algorithms that allow an accurate picture of the system to be obtained with few real measurements. From this point of view, HSE techniques based on Singular Value Decomposition (SVD) have been used to increase solvability for partially observable systems and eliminate the need of observability analysis prior to state estimation [9, 10].

The second aspect, which is fundamental for an economically correct management of the system, refers to the planning of the optimal number and position of the measurement stations [11], so that the above mentioned HSE algorithms can be successfully implemented in the cheapest way. This problem cannot be solved by means of combinatorial techniques, which would require a computational burden unacceptable also for small size networks. Suitable optimization algorithms should be therefore adopted, so that valid solutions could be achieved in a reasonable computation time. The approach proposed in this paper exploits the techniques of the dynamic programming, based on the Bellman's optimality principle.

Furthermore, differently from most of the limited proposals existing in the Literature about this subject, where the real measurements are often considered as "free of uncertainty", in this work the right attention will be given to the topics related to the measurement accuracy. Indeed, the accuracy can significantly affect both the quality of the obtainable estimates and the costs, given that using less accurate instruments can require a larger number of measurement stations to be installed, and vice-versa. To this purpose, Monte Carlo procedures for the estimation of uncertainty propagation will be introduced in the optimization algorithms to verify the validity of the state estimation in the presence of uncertainty on the input quantities.

2. HARMONIC STATE ESTIMATION IN UNDER-DETERMINED SYSTEMS

HSE was introduced in the late 80s to identify and correct harmonic related problems in power systems by exploiting the measurement of synchronized waveforms in different nodes of the network [7].

A general mathematical formulation of the HSE problem at the h-th harmonic order can be given by the following expression:

$$Y(h) = H(h)X(h) + U_{meas}(h) \qquad (1)$$

where $Y(h)$ is the vector of the measured quantities, $H(h)$ is the measurement (or gain) matrix relating state variables to measurements, $X(h)$ is the vector of state variables and $U_{meas}(h)$ is the measurement uncertainty. All the elements of the above matrices and vectors are complex quantities. For the sake of simplicity, in the following the harmonic order h will not be explicitly mentioned in the equations. Let us consider a p-bus system provided with q-measurements contained in vector Y, which is related to the p-dimensional state vector X. The possibility to solve (1) is linked to the availability of measurements in the system, because the observability of the system is assured if $q \geq p$.

Since the measurement uncertainty U_{meas} in (1) does not affect the solvability of HSE, it may be ignored in this first approach to the problem. However, the accuracy of the measurement system plays a fundamental role in the quality of the obtained estimates and thus it will be suitably taken into account in the optimization algorithm, as it will be shown in section 3.4.

The main difference of the HSE problem with respect to the State Estimation procedures applied to power systems is that, due to both the size of the networks and the relatively high costs of the instruments suitable to measure harmonics, usually a limited number of measured data is available. As a consequence, the number of independent measurement equations is usually less than the number of state variables, thus leading to an under-determined problem, for which an infinite number of solutions exist.

Therefore, approaches were proposed to provide harmonic estimation without the need for the system to be completely observable. Rather, observable islands can be determined, and observability analysis is needed to decide which estimates are meaningful [8].

On the other hand, Singular Value Decomposition (SVD) has been successfully applied to face this problem, since this mathematical tool allows observable and unobservable islands within the system to be revealed, thus eliminating the need to perform specific observability analysis [9–11].

The SVD method decomposes the matrix H into three matrices:

$$H = UWV^T \qquad (2)$$

where W is a diagonal matrix with positive or zero elements, which are the singular values of H. U and V^T are orthogonal matrices.

From (1) and (2), the following expression of X is obtained:

$$X = VW^{-1}U^T Y \qquad (3)$$

where $VW^{-1}U^T$ is the pseudo-inverse of H.

When SVD with pseudo-inverse is applied to solve HSE, if all the singular values of H are nonzero, then the power system is fully observable and all node voltages can be correctly estimated. Otherwise, in the case of under-determined systems, infinite solutions are possible and SVD will provide a minimal norm least square solution and will identify both the observable and the unobservable variables.

More details about the theoretical implications and the practical implementation of such technique can be found in the referenced papers [9–11].

In the case at hand, we can assume that the state variables to be estimated are the n nodal harmonic currents. Once these quantities are known then the harmonic status in the whole network can be calculated [9]. In particular, all the line harmonic currents can be evaluated.

Hence, the elements of the matrix H have to be calculated according to the measured quantities that compose vector Y.

Under the assumption that m nodal currents $\bar{I}$, r nodal voltages $\bar{V}$ and b line currents $\bar{I}_l$ are directly measured, the system can be defined by means of the following matrices:

$$
\begin{bmatrix}
\bar{I}_1 \\ \vdots \\ \vdots \\ \bar{I}_m \\ \bar{V}_1 \\ \vdots \\ \vdots \\ \bar{V}_r \\ \bar{I}_{l1} \\ \vdots \\ \vdots \\ \bar{I}_{lb}
\end{bmatrix}
=
\begin{bmatrix}
1 & 0 & \cdots & 0 & 0 & \cdots & \cdots & 0 \\
0 & \ddots & & \vdots & \vdots & \ddots & & \vdots \\
\vdots & & \ddots & 0 & \vdots & & \ddots & \vdots \\
0 & \cdots & 0 & 1 & 0 & \cdots & \cdots & 0 \\
\dot{z}_{11} & \cdots & \cdots & \dot{z}_{1m} & \dot{z}_{1(m+1)} & \cdots & \cdots & \dot{z}_{1n} \\
\vdots & \ddots & & \vdots & \vdots & \ddots & & \vdots \\
\vdots & & \ddots & \vdots & \vdots & & \ddots & \vdots \\
\dot{z}_{r1} & \cdots & \cdots & \dot{z}_{rm} & \dot{z}_{r(m+1)} & \cdots & \cdots & \dot{z}_{rn} \\
\dot{a}_{11} & \cdots & \cdots & \dot{a}_{1m} & \dot{a}_{1(m+1)} & \cdots & \cdots & \dot{a}_{1n} \\
\vdots & \ddots & & \vdots & \vdots & \ddots & & \vdots \\
\vdots & & \ddots & \vdots & \vdots & & \ddots & \vdots \\
\dot{a}_{b1} & \cdots & \cdots & \dot{a}_{bm} & \dot{a}_{b(m+1)} & \cdots & \cdots & \dot{a}_{bn}
\end{bmatrix}
\cdot
\begin{bmatrix}
\bar{I}_1 \\ \vdots \\ \vdots \\ \bar{I}_m \\ \bar{I}_{m+1} \\ \vdots \\ \vdots \\ \bar{I}_n
\end{bmatrix}
\qquad (4)
$$

where $\dot{z}_{ij}$ are elements of the network impedance matrix, whereas it is $\dot{a}_{ij} = \left(\dot{z}_{pj} - \dot{z}_{qj} \right) / \dot{z}_{pq}$, being p and q the nodes connected by means of branch i.

Usually, in distribution systems, HSE problem dimensions result $(m+r+b)<n$, thus leading to under-determined systems.

3. OPTIMIZATION ALGORITHM

3.1. Problem statement

The main goal of the optimal placement technique is to establish number, position and type of the measurement devices to be placed on a given system to achieve the required (total or partial) observability, with established accuracy and at the minimum cost.

As for the observability, according to section 2 the monitored system is usually under-determined and thus it cannot be considered totally observable. In these cases, it

could be useful to clearly define the portions of the network where the observability has to be ensured (i.e. the minimum set of observable islands). An *a priori* analysis of the network would be therefore needed to identify the suspicious loads which have to be monitored and the nodes that do not introduce harmonics (e.g the nodes where no loads are connected), thus reducing the size of the optimization problem.

As far as the measurement devices are concerned, the measured harmonic quantities can be either nodal voltages, load currents or line currents. Measurement devices are assumed to be equipped with suitable options (e.g. GPS receivers) that allow the synchronization between them to be achieved, so that the "absolute" phase of each quantity, i.e. the phase evaluated with respect to a common time reference, can be calculated.

An important, and sometimes neglected, question refers to the accuracy of the measuring devices. Actually, whereas most of the work done in this field focuses on the observability of the system, it should be emphasized that constraints on the maximum uncertainty acceptable for the results should also be met. This means that, in each one of the nodes of the network, the standard deviation of the estimated harmonic voltage must not overcome the limit imposed for that quantity in that node. Suitable procedures should be therefore introduced in the optimization algorithm to take into account this issue, as it will be discussed in section 3.4.

From a mathematical point of view, the search for an optimal placement of the measurement devices is a non-linear combinatorial optimization problem. Given that a complete enumeration of all the possible combinations of measurement devices placement would be unacceptable also for small size networks, a different approach must be followed to reduce the computational burden.

In [11] the problem of the optimal placement is faced by using a criterion based on the minimum condition number of the measurement matrix H and on a sequential elimination process. This obviously strongly reduces the number of possible combinations, with respect to complete enumeration, but the sequential process does not guarantee an optimal solution to be achieved, especially in the presence of networks with a large number of nodes.

An approach based on the dynamic programming will be presented in the next subsection. The number of the examined combinations of measurement devices is larger than for the sequential process, but it is still dramatically less than for complete enumeration. On the other hand, the solution obtained through the proposed approach is optimal, or very close to the optimal one, also for large size networks.

3.2. Dynamic Programming

Dynamic Programming (DP) is an approach developed to solve multi-stage decision problems and is based on the well known Richard Bellman's Principle of Optimality: "An optimal policy has the property that no matter what the previous decisions have been, the remaining decisions must constitute an optimal policy with regard to the state resulting from these previous decisions" [12]. Actually, this approach is equally applicable for decision problems where multi-stage decision making is not in the nature of the problem but is induced only

for computational reasons, as it is the optimization problem at hand.

DP tends to break the original problem into sub-problems and finds the best solution of the sub-problems, beginning from the smaller in size. When applicable, DP dramatically reduces the runtime of some algorithms from exponential to polynomial.

DP can be successfully applied when:
— the problem can be divided into stages and a decision is required at each stage,
— a finite number of states is associated with each stage,
— the decision at one stage transforms one state into a state in the next stage,
— there exists a recursive relationship that, provided that the states at stage j–1 are known, identifies the optimal decisions to reach the states at stage j
— the recursion for determining the optimal decisions at the stage j only depends on the states at stage j–1 and not on the way these states have been reached.

The problem of the optimal allocation of the measuring devices in a distribution network may be formalized according to the aforementioned points [18]. The starting point of the procedure is constituted by measurement devices only in substations and DG sites. The following stage could be characterized from one more measurement device in respect to such starting point.

A generic stage represents the total number of devices added in the network with respect to the starting level. The states in a stage define the exact position of the measurement points in the network (by also differentiating between the possibility of measuring either voltages, line currents or load currents).

Figure 1 depicts the bottom-up approach used here to solve the optimal allocation problem according to the dynamic programming paradigm. At each decisional level D_I, D_{II}, ..., D_n, new metering devices can be added. The candidates α, β, ..., η identify the possibility of measuring a given quantity (voltage, line current or load current) in a given location (particular node or line in the network). In other words, the candidates α and β could either refer to different nodes or to the same location equipped with different measurement instruments.

In order to clarify the process let us suppose that the state β at the D_{II} has to be reached from D_I. Possible states in D_I are α, β, γ, and ...η, each one labeled with the optimal value
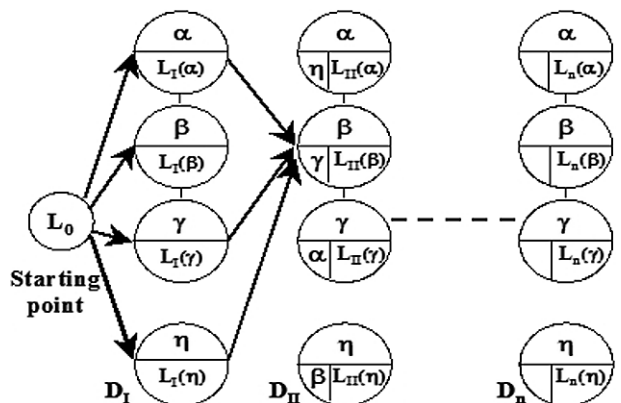

Fig. 1. Schematic flow chart of Dynamic Programming

of the objective function, L_I, calculated with a measurement device defined by candidate α, β, γ, and $\dots \eta$ respectively.

Preliminarily, all the couples formed by adding β to all the possible remaining candidates are examined, and the objective function is assessed for each couple. The state β at the level D_{II} is then labeled with the value of the function $L_{II}(\beta)$ that is the minimum value of the objective function calculated considering the couples formed with β and the remaining available candidates. By so doing, the optimal policy to reach β at level D_{II} from D_I is univocally determined (in Figure 1 the optimal path to β has been assumed through γ).

By repeating this procedure for all the states at the D_{II} stage, the optimal couple of measurement devices that minimizes the cost function is simply the one with the smallest label (e.g., if β was the state with the smallest label at level D_{II} the optimal placement of measurement devices would be in γ and β). The optimal policy corresponds to reach the state in D_{II} with the smallest label but it is worth noticing that all the states in D_{II} are reached through an optimal policy. By so doing, each policy to reach D_{III} from D_{II} will necessarily contain optimal sub-policies and the Bellman's Principle will be satisfied. In the proposed application the decision to pass from a stage the successive is based on the observability and accuracy constraints. For instance, if all the solutions at level D_{II} do not comply with the observability and accuracy constraints, the procedure is iterated by labeling the candidates at the successive stages until the goal has been reached.

A critical point of the overall procedure is the definition of both the stopping criterion and the cost function.

In the case at hand, the optimization procedure ends when at a given stage at least one solution exists for which the accuracy requirements are met on every estimates (see subsection 3.4). As for the observability of the state variables, it can be either introduced as a criterion for the acceptance of a given configuration or not, according to the goals and the specifications of the monitoring system.

As for the cost function L, it is the basis on which all decisions to move from one stage to the next one are taken. Here it has been considered a function in which the quantity used for the stopping criterion (i.e. the maximum relative deviation of the estimates) is averaged over all the harmonics and over all the N reference situations described in subsection 3.3.

3.3. Network reference conditions

The quality of the estimated quantities is evaluated against a set of reference values, obtained by applying suitable harmonic load flow procedures to the network.

Actually, the *a priori* information usually available on the loads that introduce harmonics in the network is quite poor and allows only rough knowledge of the possible situations that can occur in practice. A large uncertainty exists about the presence and/or the behavior of the harmonic sources and this means, from the circuital point of view, that the harmonic currents injected by each load can vary from zero to a maximum value I_{Lmax}.

Since the accuracy of the estimated quantities (see next subsection) can vary significantly under different network operating condition, the validity of the state estimation achievable through a given allocation of the measurement devices should be verified also in the worst cases.

In order to take into account in the optimization procedures the above considerations, a set of N reference conditions for the considered system is defined, each one characterized by different harmonic injections. The harmonic load flow is performed N times on the network conditions defined in this way, thus defining the reference values of all quantities for each of the N situations.

3.4. Measurement uncertainty

As mentioned in the previous subsections, the theoretical observability of a state variable is not sufficient to ensure that the estimate of such variable is satisfactory. Actually, the uncertainties affecting all the components of the measurement system propagate through the state estimation algorithm and make the final results uncertain too. Obviously, the larger the uncertainty on these results the greater the risk of taking incorrect decisions based on them.

It is obvious that both the metrological characteristics of the measurement devices and their placement significantly affect the accuracy of the estimates. It is therefore necessary to take into account these items, in order to guarantee that the estimated variables comply with a prefixed level of accuracy.

The evaluation of the uncertainty affecting the estimates here is faced by means of Monte Carlo procedures, which have been successfully used to solve this kind of problems in many circumstances where the analytical law of uncertainty propagation [13] is either difficult or impossible to apply. This is the case, for instance, of complex measurement algorithms, like the ones used for HSE.

Such procedures, like any other for evaluating the propagation of the uncertainties, are substantially based on two phases: formulation and calculation [14, 15]. In the former a measurement model is derived and the model inputs are quantified, while in the latter the uncertainty affecting the output(s) is evaluated by means of Monte Carlo simulations.

The first step is the most crucial, given that the uncertainty affecting the result of a measurement function can be estimated correctly only if the uncertainties affecting the input variables are properly modeled.

Therefore, suitable metrological models of both transducers and instruments should be implemented, capable of taking into account the behavior of such devices in the presence of nonsinusoidal quantities [16, 17].

The eventual lack of synchronization between the remote stations of the distributed measurement system is dealt with as a further uncertainty source affecting the evaluation of the phases. Therefore it has to be considered in the same way as the above ones.

Once the above models have been defined, a suitable probability distribution is then assigned to these uncertainty terms, which can be numerically represented by sets of random variables. A large number M of simulated tests is then performed: in each test the measured data are corrupted by different contributions, whose values are randomly extracted from the above sets, and the HSE algorithm is applied by using this set of input data. The sets of the M obtained output values, which could be considered as the probability

density function of the measurement results, are finally processed to evaluate the uncertainty of the results.

If the uncertainty affecting one of the monitored quantities, for any of the harmonic orders to be investigated, is larger than the prefixed constraint for that quantity, even in only one of the N situations defined in subsection 3.3, the solution is not considered acceptable.

It should be emphasized that the above described procedure could be easily generalized to the circumstances where the final result to be evaluated is not simply a set of voltage and/or current harmonic phasors, but consists of more or less complex quantities defined as a combination of such phasors. This is the case, for instance, of both the harmonic powers (no matter which definitions are used) and the indices defined to allocate the responsibility for harmonic pollution, like the ones discussed in [3] and [4]. Thanks to the flexibility of the Monte Carlo procedure, the criterion for establishing the configurations of measurement instruments to be accepted or rejected can be easily adapted to be based on the accuracy of such quantities.

4. APPLICATION EXAMPLE

4.1. Benchmark network

The proposed optimization algorithm has been applied to an 18 busbars balanced three-phase test network, whose scheme is shown in Figure 2, that was firstly used in [19] and then considered by several authors in order to test the validity of their approaches to different harmonic related problems [20, 21], thus becoming a sort of de-facto benchmark network. It consists of sixteen 12.5 kV busbars and two 135 kV busbars (nodes 1 and 17), whereas the sources of harmonics are two six pulse rectifiers at nodes 4 and 13. Harmonics up to the 13th order have been considered in the tests. Table 1 shows the maximum rms value of the currents ($I_{L\max}$) injected by these loads for each harmonic. Detailed data can be found in [19, 20].

4.2. Implementation

The optimization procedure has been implemented in Fortran, making it compatible with the routines of a "suite" developed at the University of Cagliari for the optimal planning of electric distribution networks in the presence of distributed generation plants [21].

The software program includes the routines that are necessary for the optimization goal to be reached:
— Harmonic load flow for the definition of N=10 reference conditions. According to subsection 3.3, in each test a value for the harmonic current injected by the two nonlinear loads is extracted randomly in the range $0 \div I_{L\max}$, whereas the phase of this current is extracted randomly in the range $\pm \pi/2$.
— HSE algorithm based on SVD and pseudo-inverse (according to section 2) for each of the considered harmonics. Nodal harmonic currents have been considered as state variables.
— Monte Carlo techniques for uncertainty estimation (according to subsection 3.4). As for the uncertainty of the measured data, a constant relative maximum deviation
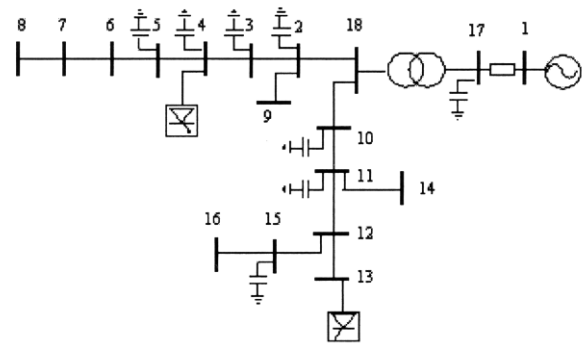

Fig. 2. Benchmark network

has been assumed for the amplitude of each harmonic voltage and current ($\pm U_{meas,a}$% around the measured value) and an absolute maximum deviation increasing with frequency for the phase angle ($\pm h U_{meas,\varphi}$, h being the harmonic order). Uniform probability distributions have been associated to these random variables.

Measurements of harmonic voltages and currents were considered already existing at both sides of the transformer.

4.3. Results

Different tests have been performed on the network defined in the previous subsections, in order to both verify the behavior of the optimization procedure and analyze the influence of some factors on the optimal placement of the measurement devices. In particular, the impact of the accuracy of the measurement instruments has been studied.

As for the acceptance criterion that stops the optimization procedure, only the amplitude of the current has been considered and the maximum deviation accepted for each estimated harmonic component of voltage and current was ± 15 %.

In a first series of tests, it has been assumed $U_{meas,a}$% = 1 % and $U_{meas,\varphi}$ = 0.5 crad. The optimal placement shows that 13 devices should be added to the existing 6 to assure the required accuracy to the harmonic components of all the 53 variables in all the reference situations. It should be emphasized that this solution has been found by exploring about 23000 combinations against about $2 \cdot 10^{11}$ that would be necessary with complete enumeration techniques.

In a second test, the use of less accurate instruments has been assumed ($U_{meas,a}$% = 3 % and $U_{meas,\varphi}$ = 1 crad). The optimal placement implies the addition of 15 devices to guarantee the required accuracy to all harmonic components. In this case about 26000 combinations were needed against about 10^{12} required by complete enumeration.

Table 1. Harmonic Currents injected in node 4 and 13.

Harmonic order	Amplitude [A]	Phase [°]
5	23.46	100
7	16.88	-140
11	10.75	-40
13	9.10	-80

5. CONCLUSIONS

The practical implementation of any monitoring strategy aimed at analyzing the harmonic status of an electric power network requires the use of distributed measurement systems and must take into account both economical and metrological aspects.

In this paper an optimization algorithm has been presented to choose the optimal number and position of the measurement devices needed to perform Harmonic State Estimation techniques.

Besides the usual considerations on the observability of the state variables, here the accuracy of the estimated quantities has been introduced as a further constraint. Owing to the flexibility of the numerical procedures employed to evaluate the uncertainty that affects the results, this constraint can be applied to the accuracy of whatever harmonic quantity one can calculate, including harmonic powers and power quality indexes.

One of the main challenges for the development of this work is studying different algorithms to perform Harmonic State Estimation in distribution systems, so that the peculiarities of these systems are exploited in order to achieve meaningful results with a reduced number of measuring instruments. On the other hand, as far as the optimization algorithm is concerned, suitable changes will be required to take into account the reduced cost of installing multiple instruments in a single site, because the predominant cost is in the base unit, while the incremental cost for additional channels is relatively small.

REFERENCES

1. Rens A.P.J., Swart P.H.: *On techniques for the localization of multiple distortion sources in three-phase networks: time-domain verification.* ETEP, Vol. 11, No. 5, 2001, pp. 317–322.
2. Muscas C.: *Assessment of electric power quality: indices for identifying disturbing loads*. ETEP European Transactions on Electrical Power, vol. 8, n.4, 1998, pp. 287–292.
3. Davis E.J., Emanuel A.E., Pileggi D.J.: *Harmonic pollution metering: theoretical considerations.* IEEE Transactions on Power Delivery, vol. 15, n. 1, 2000, pp. 19–23.
4. Castaldo D., Testa A., Ferrero A., Salicone S.: *An Index for Assessing the Responsibility for Injecting Periodic Disturbances.* L'Energia Elettrica, Volume 81, Supplement to N. 5-6 September/December 2004, pp. 134–143.
5. Locci N., Muscas C., Sulis S.: *Multi-point measurement techniques for harmonic pollution monitoring: a comparative analysis.* L'Energia Elettrica, Volume 81, Supplement to N. 5-6 September/December 2004, pp. 129–133.
6. Locci N., Muscas C., Sulis S.: *Investigation on the accuracy of harmonic pollution metering techniques.* IEEE Transactions on Instrumentation and Measurement, Vol. 53, No. 4, August 2004, pp. 1140–1145.
7. Meliopoulos A.P.S., Fan Zhang, Zelingher S.: *Power system harmonic state estimation.* IEEE Transactions on Power Delivery, Vol. 9, N. 3, July 1994, pp. 1701–1709.
8. Watson N.R., Arrillaga J., Du Z.P.: *Modified symbolic observability for harmonic state estimation.* IEE Proceedings on Generation, Transmission and Distribution, Vol. 147, N. 2, March 2000, pp. 105–111.
9. Matair S.S., Watson N.R., Wong K.P., Pham V.L., Arrillaga J.: *Harmonic state estimation: a method for remote harmonic assessment in a deregulated utility network.* DRPT 2000 - International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 4–7 April 2000, pp. 41–46.
10. Yu K.K.C., Watson N.R.: *Three-phase harmonic state estimation using SVD for partially observable systems.* PowerCon 2004 - International Conference on Power System Technology, 21–24 November 2004, Vol. 1, pp. 29–34.
11. Madtharad C., Premrudeepreechacharn S., Watson N.R., Ratchai Saeng-Udom: *An optimal measurement placement method for power system harmonic state estimation.* IEEE Transactions on Power Delivery, Vol. 20, N. 2, Part 2, April 2005, pp. 1514–1521.
12. Larson R.E., Costi J.L.: *Principles of Dynamic Programming.* M. Decker, New York, 1978–1982.
13. Guide to the expression of uncertainty in measurement, ISO, 1995.
14. ISO *Guide to the expression of uncertainty in measurement - Supplement 1 – Numerical methods for the propagation of distributions.* Draft document, 2004.
15. Ghiani E., Locci N., Muscas C.: *Evaluation of uncertainty in measurements based on digitized data.* Measurement, Volume 32, N. 4, December 2002, pp. 265–272.
16. Sasdelli R., Muscas C., Peretto L., Tinarelli R.: *On the characterization of voltage and current transducers in steady-state distorted conditions.* ETEP European Transactions on Electrical Power, vol. 11, n. 6, November/December 2001.
17. Ghiani E., Locci N., Muscas C., Sulis S.: *Uncertainty estimation for DSP-based power quality measurements.* COMPEL (The International Journal for Computation and Mathematics in Electrical and Electronic Engineering), Vol. 23 No. 1, 2004, pp. 92–103.
18. Muscas C., Pilo F., Pisano G., Sulis S.: *Optimal Placement of Measurement Devices in Electric Distribution Systems.* IEEE IMTC/2006, Sorrento (Italy), 24–27 Aprile 2006, pp. 1873-1878.
19. Grady W.M., Samotyj M.J., Noyola A.H.: *Minimizing network harmonic voltage distortion with an active power line conditioner.* IEEE Transactions on Power Delivery, Vol. 6, N. 4, October 1991, pp. 1690–1697.
20. Carpinelli G., Russo A., Russo M., Verde P.: *Inherent structure theory of networks and power system harmonics.* IEE Proceedings on Generation, Transmission and Distribution, Vol. 145, N 2, March 1998, pp. 123–132.
21. Celli G., Pilo F., Pisano G.: *Meshed Distribution Networks to increase the maximum allowable Distributed Generation capacity.* In Proc. of Symposium CIGRE on "Power Systems with Dispersed Generation", Athens (Greece), 13–16 April, 2005.

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