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Metering System Planning for State Estimation via Evolutionary Algorithm and H_Δ Matrix

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***Abstract*— This paper proposes a methodology for metering system planning for state estimation purposes. The proposed methodology is based on Evolutionary Algorithms (EAs) and on the analysis of the called H_Δ matrix. By analyzing the structure of this matrix, which is obtained via a triangular factorization of the Jacobian matrix, the proposed methodology can determine reliable metering systems (RMS). In this paper a metering system is considered as reliable if it is observable and has no critical measurements; critical sets neither critical Remote Terminal Units (RTU). An EA is developed to find the best RMS with minimal investment cost. The developed EA uses a fitness function that measures the installation cost of meters and RTUs from a given RMS. One relevant advantage of the proposed methodology is its strategy to obtain RMS. An indirect chromosome encoding representing a preferential order of meters installation combined with properties of the H_Δ matrix guarantees the proposed EA generates only feasible solutions, i.e. RMS. The proposed methodology was tested in the IEEE 6, 14, 30 and 118 bus systems, as well as in a real Brazilian system, providing to be reliable. The results obtained by the proposed methodology were compared with those obtained by other two existing methods for metering system planning.**

***Index Terms*— Power System, State Estimation, Metering System, Evolutionary Algorithm, Indirect Encoding.**

I. Introduction

STATE estimator (SE) is an essential software tool in modern power systems. Its aim is to obtain the best estimate of the current system state by processing a set of real-time redundant measurements, and network parameters stored in a data base. Independently of which SE is used, its performance depends on the available metering system, that is, on the topological distribution of the established meters and Remote Terminal Units (RTUs) on the system.

Metering system for SE should satisfy some basic requirements, as follows [1]-[2]: (i) Observability and reliability requirements: it should ensure the system observability during normal operating conditions, as well as during the loss of 1 or 2 metering points, or even when one RTU fails (during the operation of a power system, communication failures may happen and lead to unavailability of measurements and/or RTU); (ii) Bad data processing requirement: the redundancy level of the available measurements should be high enough to guarantee the absence of both critical measurements (CMs) and critical sets (CSs). This can be stated because it is not possible either to detect the presence of bad data in critical measurements or to identify those data in measurements pertaining to critical sets of measurements.

Several methods have been proposed for metering system planning in electrical power systems [1]-[5].

The method based on the analysis of H_Δ matrix [1] (AHM) determines the locations to install meters and RTUs in a power system. This analysis efficiently returns a reliable metering system (RMS), that is, a metering system that satisfies all the two technical requirements previously mentioned.

Moreover, the method based on the AHM enables the identification of critical RTUs[1] in a simpler and more direct way than other methods for metering system planning [2]-[4]; however, it does not take into account financial issue.

This paper proposes a methodology that enables the obtaining of RMS taking into account the conflicting requirements of investment cost and reliability of metering system. The proposed methodology is based on Evolutionary Algorithms (EAs) and on the method for metering system planning based on the AHM [1].

The proposed EA investigates the search space composed exclusively of RMSs (feasible solutions) in order to find the RMS of minimal investment cost. The feasibility is guaranteed by the AHM. An H_Δ matrix is produced through a triangular factorization of the Jacobian matrix. Different order of the columns of the Jacobian matrix (corresponding to meters) results in distinct H_Δ matrices. The computational representation of each individual (called chromosome) is an array with a preferential order of the columns. A fitness function measures the installation cost of meters and RTUs from a given RMS.

EAs are based on the species evolution theory, which is founded on the biological principles of nature selection and reproduction [6]. In an EA, which imitates natural systems, evolution is based on the survival of the fittest, where the best

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[1] A critical RTU is a unit whose removal from the metering system makes the power system non-observable.

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individuals will in general transfer their genetic material for the individuals of the next generation. This adaptive process has been largely investigated to solve complex optimization problems.

It is important to highlight that methods based on EAs have already been proposed for planning RMSs. In the metering placement method presented in [7], a Genetic Algorithm (GA) is employed to achieve a trade-off between investment cost and the technical requirements of a metering system under many different topology scenarios.

However, this method does not ensure metering system reliability in case of loss of RTUs. The metering placement method proposed in [2] uses a steady-state genetic algorithm for cost optimization subject to guarantee observability and absence of critical measurements, critical sets and critical RTUs.

The first metering placement method based on both EAs and H_Δ matrix is presented in [8]. This method performs the planning of RMSs taking into account investment cost. However, as its search process is not constrained to feasible search space it losses efficiency. The reason for that is the chromosome encoding used in [8] that is the same encoding used in the methods proposed in [2]-[7].

The methodology proposed in this paper uses an indirect chromosome encoding, a preferential order for the installation of meters used for calculation of H_Δ matrices, that constrains the search process to the feasible search space.

As a consequence, the possibility of finding a RMS of minimal investment cost is increased. The developed approach is evaluated for IEEE 6-bus, 14-bus, 30-bus, and 118-bus test systems, as well as with part of a real Brazilian system.

The paper is organized as follows: Section II reviews the theoretical background; Section III presents the proposed methodology; Section IV presents simulations results and a comparison among the results obtained by the proposed methodology and other two existing methods for metering system planning; and Section V shows the conclusions.

II. Theoretical Background

This section presents the method for metering system planning based on the AHM proposed in [1], as well as basic EA concepts relevant to this paper.

Usually, the linearized and decoupled state estimator is adopted to perform observability analysis [1]-[2]-[7]-[9]. Hereafter, for the sake of simplicity, the $P\theta$ model will be used, and the corresponding Jacobian matrix will be called H matrix (this matrix relates active power measurements to voltage phase angles).

A. Method for metering system planning based on the analysis of the H_Δ matrix

Considering the $P\theta$ model, the following theorem can be stated:

Theorem (proved in [10]): Let H be the Jacobian matrix associated with a power system of n buses and m available active power measurements, where $m > (n\text{-}1)$.

If this system is $P\theta$ observable ($rank(H_{P\theta}) = n\text{-}1$), then there exists an interchange of basis C in the state space, where the H_Δ matrix is obtained, that is:

$$H_\Delta = \left[\begin{array}{c|c} I_{(n-1)} & \begin{matrix}0\\ \vdots\end{matrix} \\ \hline R & 0 \end{array}\right] \tag{1}$$

where: I- identity matrix of dimension $(n\text{-}1)x(n\text{-}1)$; R- submatrix of dimension $[m\text{-}(n\text{-}1)]x(n\text{-}1)]$.

Remark 1: The last column of H_Δ is composed only of zeros and corresponds to the bus taken as reference of phase angle.

The measurements corresponding to the rows of submatrix I are called Basic measurements[2], naturally obtained during the factorization process. The measurements corresponding to the rows of submatrix R are called Supplementary measurements. The linear transformation used to obtain the H_Δ matrix is made in the state space. Consequently, the H_Δ matrix is obtained by means of Gauss elimination procedure applied to the rows of H matrix.

Analyzing the H_Δ matrix structure, it is possible to identify the critical p-sets of measurements [10].

<u>Definition 1</u>: A critical p-set of measurements for $p \geq 1$, of an observable power system, is the set of p measurements which, when removed from the measurement set, makes the system unobservable; however, the removal of any set of k measurements of this set, with $k < p$, does not make the system unobservable.

The p measurements corresponding to the p nonzero elements of a column of H_Δ form a critical p-set containing only one Basic measurement. Consequently, through the nonzero elements that appear in the H_Δ matrix, it is possible to identify all the critical p-sets formed only by one Basic measurement. To identify the critical p-sets formed by more than one Basic measurement an iterative process interchanging one non-critical Basic measurement with one redundant Supplementary measurement becomes necessary [10]. It is important to highlight that this process requires only re-factorization in a very sparse matrix.

In a general way one could see a critical p-set as a measurement redundancy level index, i.e., the measurement of a critical 1-set (critical measurement) has a redundancy level equal to zero, the measurements that belong to at least one critical 2-set have redundancy level equal to one, the measurements that belong to at least one critical 3-set have redundancy level equal to two, and so on. In a formal way the redundancy level may be defined as:

<u>Definition 2</u>: The redundancy level of a measurement is equal to the number (p-1) which corresponds to the smallest critical p-set that measurement belongs to.

With respect to the number of meters and RTUs of an already existent metering system, the method proposed in [1] enables enhancing the reliability of a metering system in two

[2] In the sense they are sufficient to assure the system observability.

manners: (i) Through the selection and installation of candidate meters, which consists in the installation of new meters in substations which already have RTUs and some meters; (ii) Through the selection and installation of candidate RTUs, which consists in the installation of meters and RTUs in substations where these equipments do not exist.

In order to obtain RMS the method proposed in [1] comprises three phases. All these phases are based on the analysis of the H_Δ matrix structure, which is obtained via a triangular factorization of the Jacobian matrix (H matrix). The selection of candidate measurements and RTUs is performed through the triangular factors obtained during the factorization of the H matrix, as presented in [1]. As a consequence, the first step of the method is to construct the H matrix. This is performed from a list containing all candidate meters (the *i-th* row of matrix H corresponds to the *i-th* candidate meter in the list). In that list, each candidate meter is related to the corresponding candidate RTU.

The phases of the method presented in [1] are:

Phase 1: Observability analysis and restoration: the first objective of this phase is to verify if the existing metering system is already observable. If not, the method will determine where meters and RTUs must be installed, in order to turn the metering system observable. Observability analysis and restoration is performed via triangular factorization of the H matrix.

Phase 2: Redundancy level analysis and restoration: the objective of this phase is to provide a metering system free of both CMs and CSs. Reference [10] it was demonstrated that a CS of an observable-measurement set is composed of measurements which belong to critical 2-sets of measurements. As a consequence, to obtain a metering system free of CMs and CSs, it is sufficient to guarantee the absence of any critical p-set of measurements with $p \leq 2$. The first analysis to be performed in this phase is to verify if there is any critical p-set, with $p \leq 2$, in the metering system obtained after the execution of phase 1. This is performed through the non-zero elements of the H_Δ matrix, obtained from the H matrix partially factored in phase 1. If there is no critical p-set with $p \leq 2$, this phase is finished. Otherwise, the method will search for candidate measurements and RTU giving information of the equivalent state corresponding to the column associated to that critical p-set.

Phase 3: RTUs criticality analysis and restoration: the first step in this phase is to verify if there is any critical RTU in the metering system obtained after the execution of phases 1 and 2. If there is no critical RTU, this phase is finished. On the other hand, the method will determine where meters and RTUs must be installed to turn redundant those critical RTUs.

B. Evolutionary Algorithms

Although the optimality of the final solutions cannot be guaranteed, EAs have presented relevant results for several optimization problems with non smooth (or even discontinuous) objective functions as well as for combinatorial problems.

In an EA, each proposed solution of a problem is treated as an individual and is computationally represented by a data structure named the *chromosome*. Each element (character) in a chromosome is called a gene.

The success of the optimization process depends on an appropriate design of a *fitness function* for the problem being solved. The fitness values of individuals in a given population are employed to drive the evolution process.

The processing sequence of an EA involves initialization of a population of individuals (a set of solutions is produced), selection of best individuals (based on a given criteria), genetic operators are applied to the best individuals to produce new individuals.

The most widely used strategies for individual selection are the Roulette and Elitism. In the Roulette strategy, individuals with higher fitness values have more probability to be selected. In the Elitism strategy individuals with higher fitness values will be always selected.

The basic genetic operators are crossover and mutation. The crossover operator is responsible for the recombination of genetic materials (strings of character) of two individuals to generate new individuals in the next population. Crossover is performed in two steps: first two individuals (parents) of the new generation are selected; at the second step, strings of characters are swapped to create two new individuals (sons), see Fig. 1.

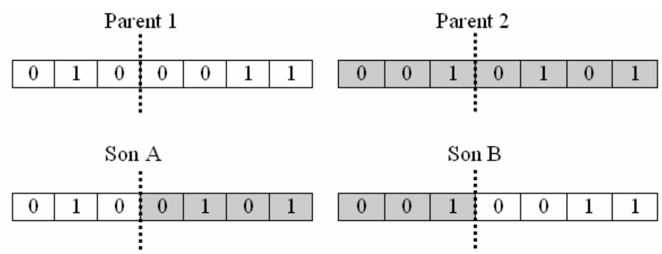

Fig. 1. Crossover example

There are several different ways to generate new individuals from crossover (a crossover of one point, two points, multipoint and uniform).

The mutation operator introduces diversity in the population. It randomly changes one or more genes from a chromosome. That diversity enables a better exploration of the solution space during the search for the global optimum, which is more difficult to obtain using only the crossover operator. Also, it reduces the probability of being stuck in a local optimum. Fig. 2 shows a search process that achieves the global optimum.

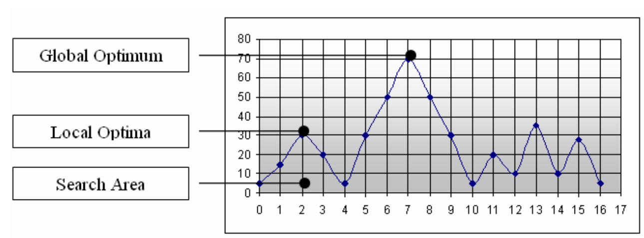

Fig. 2. Local optimum, global optimum and search area

Note that the mutation operator should allow changing between local search spaces.

III. Proposed Methodology

The proposed methodology can be used to plan new RMSs, as well as to evaluate an existing metering system and, if necessary, to indicate where meters and RTUs must be installed in order to obtain a RMS. In this paper the proposed methodology will be used to plan new RMSs.

The proposed methodology is based on EA and on the method for metering system planning based on the AHM proposed in [1]. As shown in the previous section, that method enables determining RMSs from the analysis of a list containing all candidate meters. That list relates each candidate meter to the corresponding candidate RTU and is used to construct the *H* matrix (the *i-th* row of *H* matrix corresponds to the *i-th* candidate meter in the list).

The selection of candidate meters and RTUs to be installed is performed during the triangular factorization of the *H* matrix that is executed in order to obtain the H_Δ matrix. As a consequence, depending on the order that each candidate meter is placed on the list, the method may select different number of meters and RTUs in order to obtain a RMS.

As the cost of a metering system depends on the number of installed meters and RTUs, the proposed methodology uses an EA to found the list with the order that produces the RMS of minimal investment cost.

The proposed methodology comprises two steps:

Step 1: The EA randomly produces several lists (individuals) containing all candidate meters. In each one of these lists, the meters are placed in a different order;

Step 2: The method for metering system planning based on the AHM proposed in [1] is applied to each one of the lists produced in Step 1. As a consequence, a RMS is obtained for each one of those lists. In other words, to each one of those lists, that method selects the candidate meters and RTUs necessary to be installed in order to obtain a RMS. The cost (fitness) of each one of the obtained RMSs is calculated from the number of its selected meters and RTUs. The optimal solution is the RMS of minimal investment cost.

A. Proposed Evolutionary Algorithm

The fundamental aspects of the proposed EA are defined in this section.

- Chromosome: each chromosome (individual) is represented by an array of pairs (c_M,c_U), where c_M is a candidate meter and c_U is the corresponding candidate RTU. The chromosome dimension corresponds to the maximum number of candidate meters (Cm_{total}) that can be installed and depends on the system under consideration. The difference among individuals is the order in which the candidate meters are placed in the array. Fig. 3 shows two examples of the proposed chromosome representation for a radial 3-bus power system.
- Population: the size of the population is fixed and does not change during the processing of the proposed EA;
- Fitness function: the values returned by this function are used to drive the search process of the EA. As a consequence, this function must be adequately formulated to the problem being solved. In this paper, the fitness function is formulated as:

$$\boldsymbol{f = cm * n_{Med} + c_{Rtu} * n_{Rtu}}, \tag{2}$$

where *cm* = cost of meters; n_{Med} = number of selected candidate meters; c_{Rtu} = cost of RTUs; n_{Rtu} = number of selected candidate RTUs.

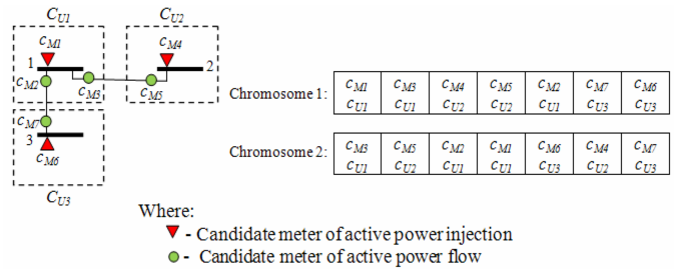

Fig. 3. Chromosome representation for a radial 3-bus power system

The fitness function of the methods for metering systems planning proposed in [2]-[7]-[8] applies penalty factors for the solutions that do not achieve one of the requirements of a RMS. On the other hand, the proposed fitness function does not apply penalty factors, since the proposed methodology only produces individuals that satisfy those requirements, that is, all produced individuals are RMSs.

- Selection strategy: in the proposed EA individuals are selected using Elitism [6]. This ensures that the best fitted individual in a generation will appear in the population of the next generation.

- Reproduction operators: it is used one-point crossover.

The best simulation results were obtained performing crossover between the best individual of the population and all the others.

IV. Simulation Results

In order to validate the proposed methodology, the IEEE 6-bus, 14-bus, 30-bus, and 118-bus system, as well as part of a real Brazilian system, have been employed to carry out simulation studies.

The proposed methodology has been implemented using C++ programming language and the results were obtained using a 2.0 GHz Athlon XP PC with 512 MB of RAM.

In all the simulations it is assumed that RTUs are associated to the buses of the bus-branch model of a given network. Hence, an RTU failure leads to the loss of every measurement connected to the corresponding bus.

As it was done in references [2]-[7]-[8], the relative cost adopted for meters and RTUs were 4.50 and 100.00 monetary units (MU), respectively.

Table I shows the simulation results carried out with the IEEE 6-bus, 14-bus, 30-bus, and 118-bus systems, obtained considering a maximum number of generation equal to 200 with population of 20 individuals.

Via an exhaustive search algorithm, it was demonstrated that the result obtained by the proposed methodology to the IEEE 6-bus system is the global optimum. The proposed methodology obtained this result in the second generation.

TABLE I
SIMULATION RESULTS FOR THE IEEE 6-BUS, 14-BUS, 30-BUS, AND 118-BUS SYSTEMS

Bus	Meters		Time (sec)	RTUs	Cost (MU)
	Flow	Injection			
6	6	5	5	5	549.50
14	14	9	15	9	1003.50
30	33	20	63	21	2338.50
118	159	47	7590	70	7927.00

Fig. 4 shows the result obtained for the IEEE 14-bus system.

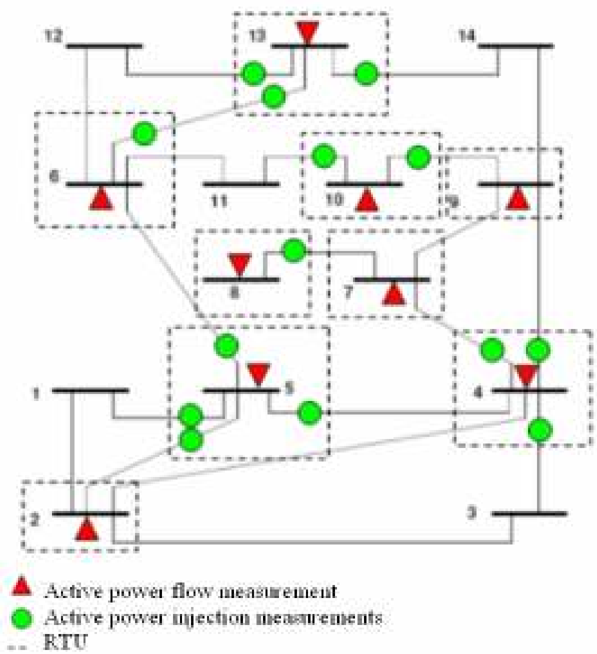

Fig. 4. RMS obtained for the IEEE 14 bus system

Table II presents the simulation results obtained by three different methods for metering system planning applied to the IEEE 14-bus system. Lines (1) and (2) show, respectively, the simulation results of the application of the methods presented in references [2]-[8]. Line 3 shows the simulation results of the application of the proposed methodology.

TABLE II
COMPARISON BETWEEN ARTICLES

	Meters		RTUs	Cost (CM)
	Flow	Injection		
(1)	9	7	10	1072.00
(2)	9	7	11	1172.00
(3)	14	9	9	1003.50

According to Table II, the RMS with minimum cost was obtained by the methodology proposed in this paper. One of the reasons for this result is that the proposed methodology performs metering system reinforcement given priority to selection of candidate meters instead of candidate RTUs. This represents a good difference in terms of RMS cost, because the cost of a RTU is greater than the cost of a meter.

It is important to emphasize that the combination of the new chromosome encoding with the properties of the H_Δ matrix enables to achieve the expected solution with few generations. This because that combination constrained the search process only to feasible regions, that is, each generated individual is a RMS.

Table III shows the number of generations used by the three methodologies considered in Table II, when they were applied to obtain a RMS with a minimum cost for the IEEE 30-bus system. A fair and comprehensive comparison among the proposed methodology and the existing ones, based solely on published results, is virtually impossible, because the reported simulations refer to different scenarios and, what is equally important, vital information on the input data is many times missing.

TABLE III
NUMBERS OF GENERATIONS

	Population	Generations
(1)	150	8.673
(2)	40	300
(3)	40	200

Table IV presents the simulation results obtained by the methodology presented in [7], line (1), and those obtained by the proposed methodology, line (2), applied to the Brazilian system illustrated in Fig. 5. In both simulations it has been assumed that there were no previously installed meters and RTUs. The results obtained by both methodologies consider only one topology scenario. However, the results obtained by the methodology presented in [7] may contain critical RTU, but the result obtained by the proposed methodology does not contain any critical RTU.

TABLE IV
SIMULATION RESULTS FOR PART OF A REAL BRAZILIAN SYSTEM

	Meters		RTUs	Cost (MU)
	Flow	Injection		
(1)	68	39	49	5381.50
(2)	86	29	42	4717.50

According to Table IV, the metering system with minimum cost was obtained by the methodology proposed in this paper.

Fig. 5 illustrates part of a real Brazilian system, responsible for energy supply in São Paulo area, with 61 buses and 74 branches (from ELETROPAULO). This system was used in [7], in order to evaluate the methodology presented there. As mentioned before, the methodology presented in [7] employed a GA to achieve a trade-off between investment cost and the technical requirements of a RMS under many different topology scenarios. However, this methodology does not ensure metering system reliability in case of loss of RTUs.

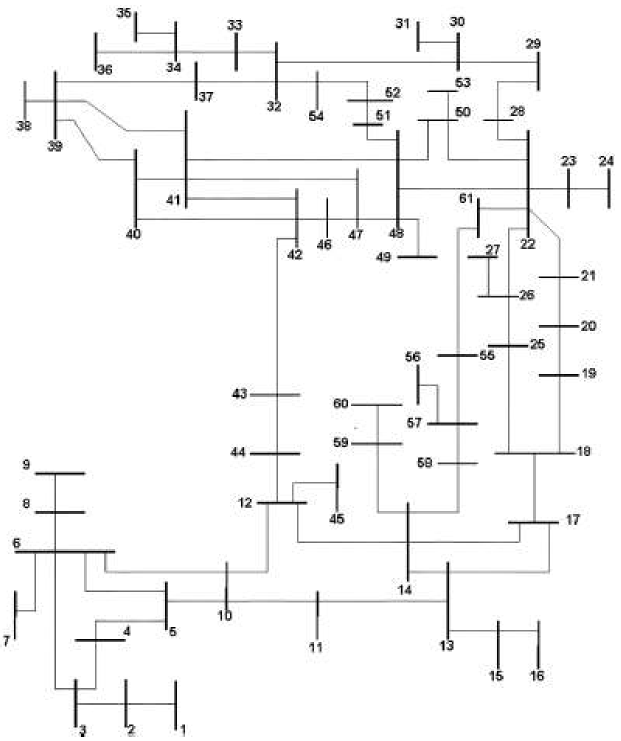

Fig. 5. ELETROPAULO System

V. CONCLUSIONS

This paper proposes a methodology that allows obtaining RMS taking into account the conflicting requirements of investment cost and reliability of metering systems. The proposed methodology is based on Evolutionary Algorithms and on the method for metering system planning based on the AHM proposed in [1].

In order to illustrate the potentiality of the proposed methodology, simulation results of its application to the IEEE 6-bus, 14-bus, 30- bus and 118- bus systems, as well as to part of a real Brazilian System, were presented. These results suggest that the proposed methodology is reliable, computationally efficient, and suitable for application to large-scale power systems.

As the proposed methodology is based on the analysis of linear dependence (or independence) among the system equations (H_Δ matrix rows), so it can be applied to any kind of equations. As a consequence, it can be extended to design RMS composed of conventional measurements (power and voltage magnitude measurements) and synchronized phasor measurements (provided by Phasor Measurement Units [11]).

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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