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# Metering design for power networks using observability indicators

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ABSTRACT

A state estimation process is highly influenced by the level of the measurement redundancies. However, due to financial and operational constraints, redundancy is in practice limited, making the power systems metering design a challenging problem. Therefore, for the first time, a methodology to design a metering system for state estimation in power systems is proposed, in which the metering placement is modeled as a combinatorial constrained optimization problem, where the final goal is to maximize the system redundancy – expressed by observability indicators – subjected to investment constraints. A Genetic Algorithm and a Greedy Randomized Adaptive Search Procedure, combined with a constructive heuristic are investigated for the metering design problem. Tests with IEEE-14, IEEE-30, IEEE-118 bus systems and part of a real Brazilian system are carried out to evaluate the performance of the proposed methodology. The results also show that, for the IEEE-118 bus system, 30% of the total cost of the measurements and RTUs is required to ensure observability, whereas 32% and 60% are necessary to eliminate the network critical measurements and to obtain a system without critical sets, respectively.

## 1. Introduction

The monitoring and control of an electrical system is performed through advanced Energy Management System (EMS) analysis tools based on a reliable database obtained through the processing of real-time measurements by the State estimation (SE) of the power system [1]. The success of the SE process relies on data redundancy, which is highly influenced by the amount, type, quality and location of the measurements installed in the electrical power system. These measurements are, in general, active/reactive power injections and flows, voltage and current magnitudes. The metered quantities are gathered and transmitted to EMS through the Remote Terminal Units (RTUs) [1]. Recently, the synchrophasor technology provided voltage and current angle measurements by Phasor Measurement Units (PMUs). Some works have shown the benefits that the today and future SE's can achieve by incorporating these devices in their monitoring process [2,3].

For monitoring and control, an appropriate level of measurement redundancy allows the SE to effectively process the acquired data, and also to detect and identify possible Bad Data (BD) presented in the database, even though temporary loss of measurements or topology changes occur in the power system [4].

The design of a metering system is a problem that requires dual optimizations such as, minimization of investment costs and maximization of the system redundancies. These two objectives are conflicting because improving one deteriorates the other. Therefore, the challenge of this work is to balance these goals.

Several meter placement methods were described in the literature for electrical power systems. Observability, reliability and robustness are considered in [5,6] without the investment cost minimization integrated in the search optimization presented in [7]. In [8,9] a metering system is designed for a basic electrical power system, which also takes into account the occurrence of network changes or measurement losses. Nevertheless, only the observability requisite is established.

Methods based on intelligent system techniques have also been proposed in order to obtain optimal metering systems [10–12]. Nevertheless, reliability requirement is not explicitly considered, thus, compromising BD suppression capability of the estimation process. In [13], a Genetic Algorithm (GA) is employed to design metering systems without critical measurements, sets and cost minimization. Investment costs are considered in [14] only in a single scenario. In [15,16], a GA is employed to assure SE reliability in different topological scenarios with low cost systems. The steady-state GA presented in [17] and the evolutionary algorithm well described in [18] have been implemented to achieve a metering system with no critical RTU. Pseudo-measurements were processed in [19,20] to restore observability in power systems. The robustness of the presented methods shows that the idea is suitable to be used in practical SE processes. In [21], a hybrid Ant Colony

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Optimization (ACO) uses a probabilistic constructive heuristic to derive robust and reliable metering systems. In [22], the authors proposed an alternative method to design an electrical power metering system based on a tree vertex cover problem, which led to the implementation of a faster algorithm that also reduces the measurement units. A fast and cost-effective algorithm is proposed in [23] to improve computational efficiency of metering design systems in large power systems. A key aspect of the evaluated ACO is to provide better exploration of several trade-offs between cost and reliability to the system planner.

Recently, methods for PMUs placement have also been proposed in [24–26]. It is known that measurements from PMUs provide valuable information for the SE process. However, due to financial constraints, it is consensual that PMUs should be installed to reinforce existing metering plans [27,28]. Therefore, PMU placement has not been considered in the present scope.

A new formulation to design SE metering systems in power networks is proposed in this paper. For the first time, it is proposed to constraint the investment cost, optimizing a metering plan that maximizes the redundancy measurement, translated in a set of observability indicators. Described in [29], these indicators aim to quantize deficient data in global and local levels of the SE. The proposed methodology is an approach that reflects a real business operating. The employment of optimization algorithms like GA and Greedy Randomized Adaptive Search Procedure (GRASP) to solve the proposed metering placement problem is evaluated. Simulation results with the IEEE 14, 30 and 118-bus systems, and part of a real Brazilian system, illustrate the applicability and the relaxation on the investment costs of the proposed method. The results also show that, for the IEEE-118 bus system, 30% of the total cost of the measurements and RTUs is required to ensure observability, whereas 32% and 60% are necessary to eliminate critical measurements from the network and to obtain a system without critical sets, respectively. Similar performance was obtained in the other tested systems.

## 2. Theoretical background of meter placement

A compromise between redundancy and cost must be taken into account to achieve a well-planned metering system. In order to accomplish this, the meter placement problem is customarily modeled as a combinatorial optimization problem, in which the investment cost is minimized, subject to redundancy constraints, here understood as the absence of critical requirements to the state estimation process. This Section presents a theoretical background on data redundancy conditions for SE and formalization of metering design as an optimization problem.

### 2.1. The redundancy requirements

An adequate data redundancy is achieved through a design of a metering that considers the amount, the type and the location of the measurements. A well succeed SE process should meet observability, reliability, robustness and cost requirements [21]. Observability is obtained if the SE process is realized in the entire network, whereas reliability is characterized by identification and suppression of BD measurements. The robustness is assigned if observability and reliability are still met in the networks susceptible to topological changes and/or temporary loss of measurements. The cost requirement is attended when the data acquisition investment cost is minimized.

An active power-angle model $P\theta$ is a linearized and decoupled SE that normally takes into account observability analysis [2]. Let $G$ the gain matrix of the SE process obtained as:

$$G = H^t R^{-1} H \tag{1}$$

where $H$ is the Jacobian matrix derived from the linearization of the load-flow equations and $\boldsymbol{R}$ the diagonal covariance matrix of the measurement noise vector [1].

A system is observable if $G$ is nonsingular, which can be checked during its factorization and reliability is obtained in the residual analysis of the SE [1]. Therefore, residual analysis, critical measurements and critical sets should not be presented in the metering system. The normalized residual vector $\boldsymbol{r}$, calculated as the difference between the measurement vector $z$ and its correspondent filtered $\hat{z}$, is validated as follows:

$$r_N(i) = \frac{|r(i)|}{\sigma_E(i)} \leqslant threshold \tag{2}$$

$$E = R - HG^{-1}H^t \tag{3}$$

where $\sigma_E(i) = \sqrt{E(i,i)}$ is the standard deviation of the *ith* component of the residual vector. The presence of BD is signaled by threshold violations.

Critical measurement ($C_{meas}$) is an unaffected measurement during the filtering process. Thus, a $C_{meas}$ is identified if:

$$r(i) = z(i) - \hat{z}(i) = 0 \tag{4}$$

$$\sigma_E(i) = \sqrt{E(i,i)} = 0. \tag{5}$$

Normalized residuals of measurements belonging to a critical set ($C_{set}$) are equal and their correlation coefficients present maximum values. Suppose that measurements $i$ and $j$ belong to the same $C_{set}$. Then, it follows that:

$$\rho(i,j) = \frac{r_N(i)}{r_N(j)} = 1 \tag{6}$$

$$\gamma(i,j) = \frac{E(i,j)}{\sqrt{E(i,i)}\sqrt{E(j,j)}} = 1. \tag{7}$$

The loss of a $C_{meas}$ leads to unobservability, while the loss of any $C_{set}$ measurement makes $C_{meas}$ the remaining measurements, which means that $C_{meas}$ is not detectable in the SE filtering. It is also shown in Eq. (6) that $C_{set}$ cannot be identified, although the detection of bad measurements. An efficient methodology for detecting/identifying $C_{meas}$ and $C_{set}$ can be found in [30].

As an environment combinatorial problem that depends on the amount, type, quality and location of the measurements, the meter placement for SE is a difficult optimization problem that also needs to establish a compromise between metering plans redundancy and cost.

### 2.2. Observability indicators

The network redundancy is commonly assessed through an observability check and identification of critical measurement and sets. However, instead of a qualitative description of observability, a quantitative one can be performed using observability indicators [29]. This Subsection introduces the basic aspects of the observability indicators.

#### 2.2.1. Imminent loss of observability

The network unobservability become imminent if there are $C_{meas}$ among the measurements, since the loss of any $C_{meas}$ leads to observability loss. Thus, the risk of unobservability is related to the number of $C_{meas}$. Considering that each measurement has equal probability to become unavailable, the following index $\alpha$ reflects the probability of system unobservability in the measurement loss:

$$\alpha = \frac{N_{Cmeas}}{m} \times 100\% \tag{8}$$

where $N_{Cmeas}$ is the number of $C_{meas,}$ $m$ is the total number of measurements. The index $\alpha$ represents the quantification of how far the metering plan is from the "*m-1*" observability condition.

#### 2.2.2. $C_{meas}$ occurrence

When a $C_{set}$ is formed, the probability of occurrence of additional $C_{meas}$ is related to the number of measurements $M_{Csets}$ that belongs to