HEURISTIC GRASP FOR PLANNING METERING SYSTEMS FOR ELECTRICAL POWER NETWORK MONITORING

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Abstract: This work presents an heuristic in GRASP for solving the problem of planning metering system for power system state estimation. The meter placement is considered a NP-hard problem. The GRASP is employed to achieve a trade-off between investment cost and reliability of the state estimation process. Tests with the IEEE-14 and IEEE-118 bus were carried out to validate the proposed algorithm.

Keywords: GRASP, State Estimation, Electrical Power Networks Monitoring.

1 Introduction

State Estimation (SE) deals with applications responsible for the construction of a complete and reliable database to be used by advanced functions in an Energy Management System, Monticelli (1999). Data redundancy is determinant for the success of SE. With an adequate level of redundancy, an SE can deal with the problem of detection, identification and elimination of gross errors, temporary loss of measurements, so that the quality/reliability of the estimation will not be affected. The redundancy is evaluated by considering the number, type and topological distribution of the measure points in an electrical power network, Souza (2005)

Highly redundant Metering Systems are always desirable. However it is seldom achieved, as this implies in the investment on metering, data acquisition and communication systems. Additionally, during power system operation, topology changes or temporary malfunction of the data acquisition system may also reduce the redundancy level for SE. Even critical levels may be reached, describing situations of imminent loss of observability and inadequate performance of gross errors detection and identification through bad data processing routines.

This work proposes an algorithm based in a metaheuristic GRASP in order to solve the problem of Planning of Metering Systems for SE. In order to evaluate the proposed algorithm, tests were executed with IEEE 14 and IEEE 118 bus systems, well known in the technical literature. The obtained results are compared with the results obtained with a Genetic Algorithm (GA).

2 Metering System Planning

The redundancy of data is important for an adequate SE process. The "redundancy" term refers to an excess of measures taken from the system with respect to a necessary minimal number of them to estimate all the state variables.

When the redundancy is higher and more qualified, there are better chances that the SE process is successful. However, the investment in measuring increases, and therefore, a close relation between redundancy and associated costs must be found.

The meter placement in transmission networks can be modeled as an optimization problem. The goal is to achieve a solution that minimizes costs of investment in Remote Terminal Units (RTUs) and meters, in order to assure a desirable performance for the SE function.

The metering system planning can be represented as an optimization problem described as:

$$\begin{aligned} &\text{Min } (C_{met}+C_{RTU}) \\ &\text{s.t. observability} \\ &\quad \text{absence of critical measurements} \\ &\quad \text{absence of critical sets measurements} \end{aligned} \tag{1}$$

where C_{met} represents the cost of meters and C_{RTU} is the cost of RTUs to be installed.

In the proposed methodology, it is possible to solve the problem (1), so that the fulfillment of the requirements can be made partially. The flexibility of the fulfillment of the requirements enables a better exploration of the relationship between the investment costs and the quality of the measure system (from the point of view of the networking supervision).

In the formulation proposed in this work, the performance requirements to be considered are: observability, absence of critical measurements and absence of critical sets measurements. The fulfillment of those requirements assures the absence of critical levels of redundancy, which may affect the performance of SE function and consequently the quality of the network supervision.

The determination of the critical redundancy levels can be obtained from the linear state estimation model of Coutto (2001).

A. Linear State Estimation

For a specific network configuration, the operating state and measurements tol be processed are related according to:

$$z = Hx + \varepsilon \tag{2}$$

where x and z are the (n x 1) state and (m x 1) measurement vectors; H is the (m x n) Jacobian matrix obtained from the linearization of the load-flow equations for the current network configuration; ε is the vector of error associated to z.

The objective function, usually solved by a Weighted Least Squares (WLS) method, is defined as follows:

$$J(x) = [z - Hx]^T R^{-1} [z - Hx] \tag{3}$$

B. Observability Analysis

The fulfillment evaluation of the observability requirement is executed through the verification of the non-singularity of the gain matrix G of SE.

$$G = (H^T R^{-1} H) \tag{4}$$

The verification of measurements deficiency for network observability is performed also considering the decoupled between the sets of P – θ (active power–angle) and Q – V (reactive power – tension magnitudes), Clements (1983). Considering measures taken in pairs (active and reactive), an analysis can be done only for the P-θ set.

C. Filtering

The state estimation $\hat{x}$ which minimizes J(x) can be obtained from:

$$\left.\frac{\partial J(x)}{\partial x}\right|_{x=\hat{x}} = H^T R^{-1}\left[z - H(\hat{x})\right] \quad (5)$$

$$\hat{x} = G^{-1} H^T R^{-1} z \quad (6)$$

where $G = (H^T R^{-1} H)$ is the gain matrix.

D. Residual Analysis

When the filtering process is ended, the incoming measurements are compared with their corresponding estimated values and the check for the presence of gross errors is carried out through the normalized residual analysis. The vector of the residual results of the SE, r, is defined by the differences between the measured values and the corresponding estimated values, computed as a function of the estimated state $\hat{x}$:

$$r = z - \hat{z} \quad (7)$$

$$r = z - h(\hat{x}) \quad (8)$$

The vector of the residual results can be interpreted as a random variable with a Normal Distribution, expected zero mean value and covariance matrix E is obtained from:

$$E = R - H\,(H^T R^{-1} H)^{-1} H^T \quad (9)$$

The vector of the residual analysis r is normalized and submitted to the following validation test:

$$r_N(i) = \frac{|r(i)|}{\sigma_E(i)} \leq \gamma \quad (10)$$

$$\sigma_E(i) = \sqrt{E(i,i)} \quad (11)$$

where $\sigma_E(i)$ is the standard deviation of the i*th* component of the residual vector, and γ is the detection limit. Normalized residuals that violated the established limit confirm the presence of GEs

In the presence of one gross error (GE), the erroneous measurement is the one that has the higher normalized residual, Handschin (1975). This justifies the use of the normalized residual test as a GE detection and identification method.

Even though, there are additional tests for the evaluation of the filtering process results, e.g.: the Jacobian test and the weighted residuals**,** Handschin (1975). In this work, the test of the normalized residuals is used.

E. Identification of Critical Measurements and Critical Sets

A measurement turns into a critical one, if its absence from the data set causes a loss of observability in the supervised network. A critical set is defined as a group of measurements that in case of being removed turn the remaining measurements into critical measures.

For the identification of critical measurements and critical sets of measurements, it is considered the methodology of Coutto (2001).

3 GRASP

GRASP (Greedy Randomized Adaptive Search Procedure), proposed by Feo and Resende (1995), is currently one of the most efficient metaheuristic for the solution of different combinatorial optimization problems.

This is an iterative method that has two phases: one for the construction and the other for local search. In the construction phase, a list of candidates is generated, ordered according to their contribution within the objective function. Therefore, one solution is constructed element by element. This construction is probabilistic, because the selection of a new element, that must be part of the solution, is performed randomly from a list called restricted candidate list (RCL), which contains the best elements of the candidate list. This heuristic is also adaptive, because the cost of each iteration of the construction phase (value used by the ordering function) is updated, in order to reflect the changes caused by the selection of the element in a previous iteration.

Considering that the construction phase is probabilistic, the solutions obtained in this phase are probably not the local optimal results. That is the reason why the second GRASP phase is important, as it tries to improve the solution constructed in the previous phase, by working in the neighborhood.

The pseudo-code of a GRASP procedure can be observed in the algorithm of Figure 1. This procedure receives as parameters the maximum number of iterations that will be executed (Max Iterations) and a seed for the random factor (Seed). In steps 3, 4 and 5, there is an execution of the construction phase, local search and the procedure that save the best solution found in the corresponding iteration. As a return, the best solution is obtained at the end of the last iteration.

```
Procedure GRASP (Max Iterations, Seed)
1  Read Input();
2  for m = 1; . . . . ; Max Iterations do
3        Solution Construction (Seed);
4        Solution Local Search (Solution);
5        Update (Solution, Best Solution);
6  end;
7  return Best Solution
End GRASP.
```

Figure 1: Pseudo code of a metaheuristic GRASP

4 Description of the Proposed Heuristic

This work proposes new heuristic, inspired in the metaheuristic GRASP, for the solution of the problem of planning metering system for SE. Modifications in the GRASP algorithm were performed to make it more suitable for the solution of the problem.

As any heuristic, this algorithm does not necessarily obtain a result that is globally optimal. In such cases, a high quality local optimal solution may be found. The final solution is obtained in a polynomial time.

A. Problem Codification

In the proposed model, the evaluation vector represents a metering system plan, that is to say, a set of meters proposed as a solution for a problem, where each location is associated to a measurement type and its corresponding location in the electrical network. The dimension of the evaluation vector corresponds to the maximum number of meters that can be installed in the electrical network.

The evaluation vector elements assume binary values. The value is “1” when the corresponding meter is present in the proposed metering system plan and “0” in the contrary. This is illustrated in Figure 2. The cost associated with each metering plan is obtained by the sum of the individual costs of meters and the costs of the RTUs required for the installation of such meters.

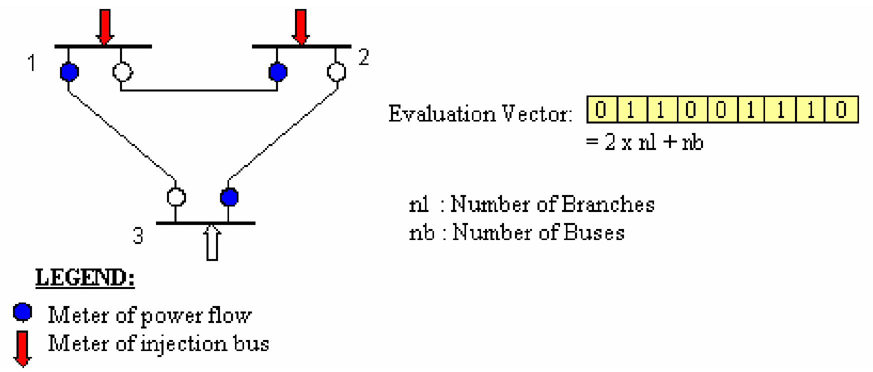

Figure 2: Codification of the Problem

B. Randomized Constructive Algorithm

In the constructive phase of GRASP, a solution is randomly obtained from a list of the best candidates generated by a greedy strategy, described in the algorithm of Figure 3.

```
Procedure Randomized Constructive (C.Vect, Seed)
1  Read Input();
2  Candidate = Sort (List bus, Seed)
3  if(Candidate not observable by List Bus)
4       for m = 1; . . . . ; Number of flows do
5            Install UTR and meters;
6       end;
7  end if;
8  return Constructive Vector
End.
```

Figure 3: Constructive Algorithm

This phase was implemented with a random selection of a bus in a power network, which is shown in the line 2 of the constructive algorithm. This bus is always selected among 20% (twenty percent) of the buses that have the larger number of transmission branches connected to them. This strategy is based on the fact that the allocation of a RTU, with the corresponding measurements, in a bus with many branches connected to it, allows the observability of a larger area in the power network. This can be depicted in two situations shown in Figure 4.

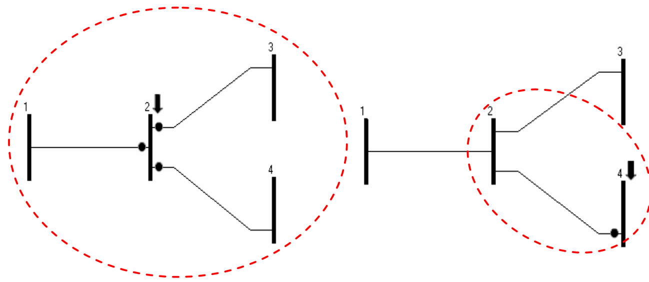

Figure 4: Observable areas

Within the constructive phase, other buses are selected in decreasing order of the number of branches associated to them.

After each bus is selected, it is verified if it is not observed by meters that may have been placed in adjacent buses (previously selected by the constructive algorithm). If the selected bus is still not observed, a RTU and its associated meters are placed. This is represented in the step 5 of the algorithm of Figure 3. This strategy tries to avoid unnecessary meter allocations in the network. The obtained result may be affected by the order in which the buses are selected to be evaluated during the constructive algorithm.

C. Algorithm for local search

After the local search phase, based on the solution created in the constructive algorithm, the solution refinement phase is executed. Three types of local search were defined and executed sequentially: Addition of measurements, Removal of measurements and Changes of bits (where one existing measure is removed and another inexistent measure is inserted). These algorithms are represented in Figure 5

For the requirement of observability analysis and absence of critical measurements, only the option of measurement removal was considered. For the requirement of absence of critical sets of measurement, the options of addition, removal and swap of bits were considered.

```
Procedure Local Search (C. Vect)
for m = 1; . . . . ; Dimension Vector do
    Add_search(C. Vect[ ])
    if (result < best) Then
        best = result
        best_vect [ ]= C. Vect [ ]
    end if
end;
for m = 1; . . . . ; Dimension Vector do
    Remove_search(C. Vect[ ])
    if (result < best) Then
        best = result
        best_vect [ ]= C. Vect [ ]
    end if
end;
for m = 1; . . . . ; Dimension Vector do
    Swap_search(C. Vect[ ])
    if (result < best) Then
        best = result
        best_vect [ ]= C. Vect [ ]
    end if
end;
```

Figure 5: Algorithm for local search

5 Results

In order to evaluate the performance of the GRASP based heuristic proposal, tests were executed with the IEEE14 (14 buses and 20 branches), IEEE 118 (118 buses and 179 branches) and a part of a Brazilian system (61 buses and 74 branches). The requirements of Observability, Absence of Critical Measurements and Absence of Critical Sets were considered for all systems.

The results with the IEEE14 bus system are represented in Table 1 and described in Figures 6 to 9. Table 1, for comparative purposes, also describes the results obtained with a genetic algorithm, Souza (2005) and Villavicencio (2006).

Table 1. Results for the metering system for IEEE 14

System IEEE 14 bus		**Obs.**	**Crit. Meas.**	**Crit. Sets**
GRASP	Cost	458.5	476.5	885.5
	Time	1 sec.	1 sec.	2 sec.
GA	Cost	458.5	563.0	972.0
	Time	4 sec.	13 sec.	13 sec.

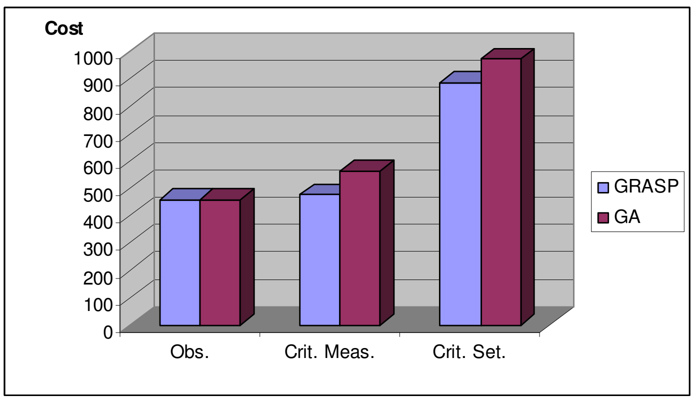

Figure 6: Cost of the metering system plan for IEEE 14: GRASP vs. GA.

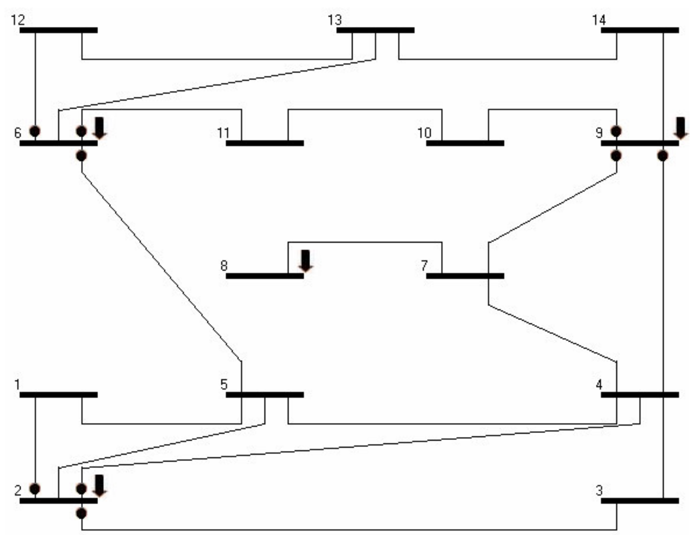

Figure 7: Observability Analysis, IEEE 14 system, using GRASP

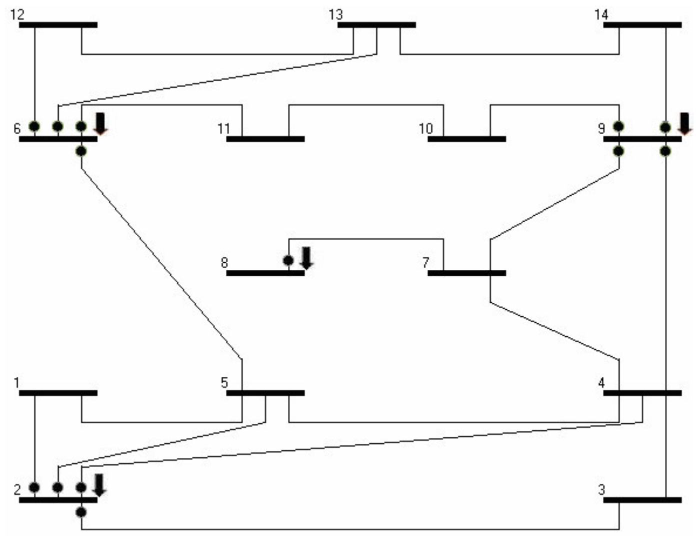

Figure 8: Absence of Critical Measurements, IEEE 14 system, using GRASP.

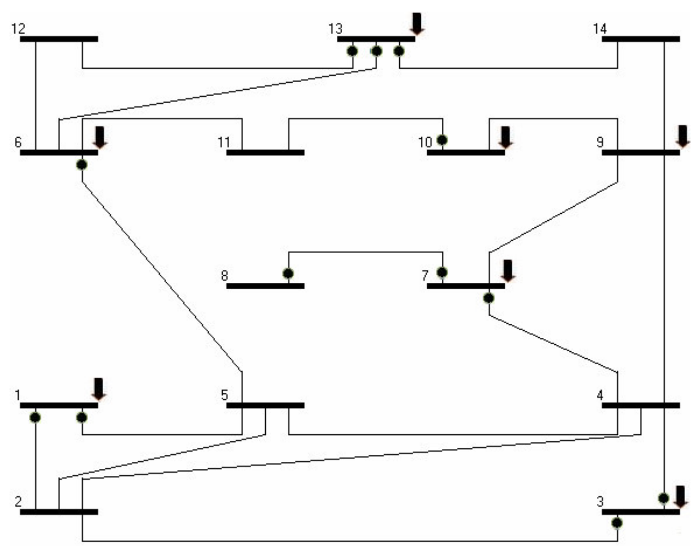

Figure 9: Absence of Critical Sets Measurements, IEEE 14 system, using GRASP.

For the IEEE 118 system, the results are presented in Table 2 and Figure 10.

Table 2. Results for the IEEE 118 System

System IEEE 118 bus		**Obs.**	**Crit. Meas.**	**Crit. Sets**
GRASP	Cost	4758.0	4848.0	7119.0
	Time	61 min	94 min	380 min
GA	Cost	7720.0	8477.5	10753.0
	Time	92 min	183 min	1174 min

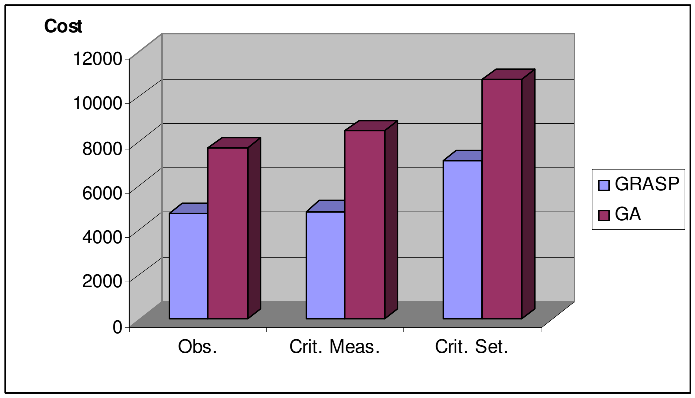

Figure 10: Cost of the metering system plan for IEEE 118 system: GRASP vs. GA.

For a part of the Brazilian system illustrate in Figure 11, the results are presented in Table 3 and Figure 12.

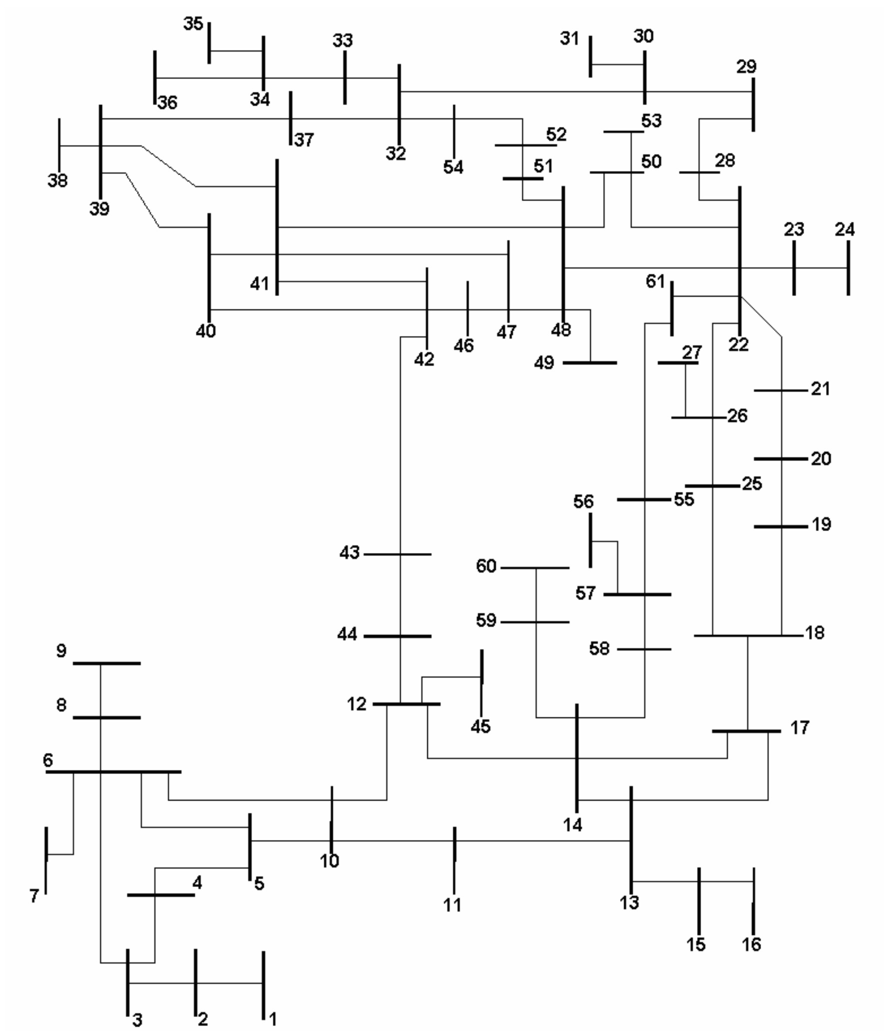

Figure 11: Part of a Brazilian system (61 buses and 74 branches).

Table 3. Results for the metering system for a part of a Brazilian system

Part of Brazilian System 61 bus		Obs.	Crit. Meas.	Crit. Sets
GRASP	Cost	2770.0	2837.5	4674.5
	Time	2.45 min.	6.80 min.	24 min.
GA	Cost	3306.0	3878.0	5381.5
	Time	53 min.	95 min.	609 min.

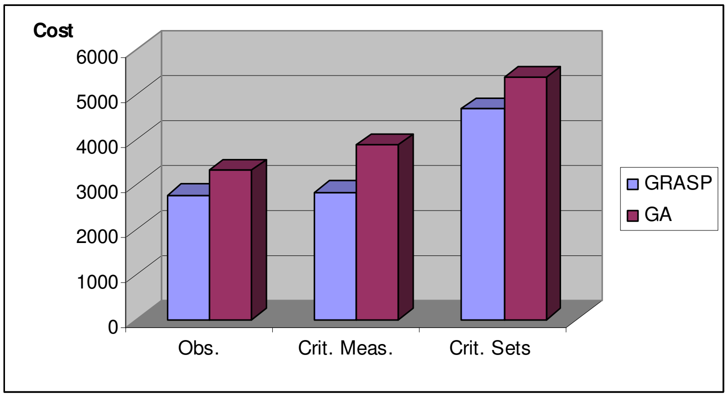

Figure 12: Cost of the metering system plan for a part of a Brazilian system: GRASP vs. GA.

The results obtained with the IEEE 14, IEEE 118 and a part of a Brazilian system show that the proposed algorithm is able to find solutions with low cost and that guarantee the desired performance of the SE function. Comparative results showed that the proposed algorithm is able to find solutions with lower costs and reduced computing times with respect to those obtained with a GA approach.

It is possible to observe in Tables 1, 2 and 3, that when there are more constraints, the costs associated to the obtained solution are higher. This is because the imposed constraints are satisfied in a cumulative way. In other words, the absence of critical measurements requirement is supposed to fulfill the observability requirement. In the same way, the absence of critical sets requirement is supposed to fulfill the previous two requirements.

It can be observed that the total cost increase when considering more constraints can be considered low in view of the benefits obtained with a high quality supervision of the electrical network. Besides, in case of limited financial resources, a planner can decide to take an economical solution that does not consider the fulfillment of all requirements.

In all simulations the relative cost was considered 100.0 for a RTU and 4.5 for a meter. It is important to mention that the allocation of one RTU (and consequently addition of its cost) in a certain bus of the network is necessary, only if the installation of one or more meters (injection of power in the bus or power flow in the terminals of the branches connected to it) is proposed.

6 Conclusions

This work presented a GRASP based heuristic to solve the problem of planning metering systems for Power Systems State Estimation. The knowledge extracted from the experience taken from the technical literature, regarding the problem of planning metering systems, was used for the construction of heuristic procedures that compose the construction and local search phases of the proposed algorithm.

The comparatives results showed that the proposed algorithm is more competitive than the genetic algorithm. This is revealed by the lower metering system costs obtained, as well as by the reduced computational times associated with the proposed approach.

As a future work, new implementation procedures can be created so that they might execute local search phase of heuristic in a even more efficient way.

In addition, it is recommended to consider parallelism of the algorithm that may decrease even more the time execution of the algorithm.

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