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METHODS

Priority-Based Method for Allocation of PMUs in Sub-Transmission and Distribution Networks

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ABSTRACT The increasing uncertainty in power systems, driven by demand variability and renewable production, has increased operational complexity and brought systems closer to their stability limits. Phasor Measurement Units (PMUs) play a vital role in addressing these challenges. Transmission System Operators (TSOs) rely on PMUs during planning stages to validate models for critical decisions, such as setting power exchange limits. However, discrepancies between PMU data and simulations have been observed, and the insufficient integration of PMUs in sub-transmission and distribution networks further complicates the identification of their root causes. This limited integration hinders data accessibility for TSOs, resulting in significant information gaps, especially in systems with Distributed Energy Resources (DERs). Within this context, the main contribution of this paper is the development of an approach based on power flow data to rank the priority of buses outside the main grid for PMU allocation, with the goal of enhancing load models and increasing the TSO's monitoring coverage. For each operating point, buses are ranked by measurement allocation indices, considering load, DERs, and the electrical influence of predefined disturbances. These rankings, combined with a diversified allocation strategy, suggest candidate buses for meter installation. A proof of concept explains the method, followed by its application to the Southeastern subsystem of the Brazilian Interconnected Power System (BIPS). Results show that regionalizing the ranking is essential for identifying prioritized points in all areas and voltage levels. Similarly, a geographic diversity in the distribution of meters is observed in the results, promoting a more representative allocation to capture particular features of each region of the BIPS.

INDEX TERMS Distribution, load modeling, meter allocation, distributed energy resources, phasor measurement unit, sub-transmission.

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I. INTRODUCTION

As power systems grow in complexity, stability analyses require more detailed and accurate models. Dynamic simulations of power systems depend on models of various system components, and one of the key challenges for Transmission System Operators (TSOs) is obtaining reliable models that accurately represent the load and generation connected to distribution systems [1]. This difficulty arises not only from the inherent complexity of capturing diverse end-user load profiles but also from the growing proliferation of Distributed Energy Resources (DERs) connected to medium- and low-voltage networks.

Transmission system disturbances can trigger the protective mechanisms of DERs, causing their disconnection. For this reason, suitable modeling of these devices is essential, as their disconnection can adversely affect the power system's dynamic response [1]. Studies and events in which DER disconnections have impacted power system dynamics have been reported in the literatures [2], [3], and [4]. As an example of the need to minimize this impact, a scheme for setting anti-islanding protection of DERs coordinated with under frequency load shedding procedures was proposed in [5]. These studies highlight the need for accurate dynamic models of DERs in assessing system stability. Recognizing this, the North American Electric Reliability Corporation (NERC) recommends the use of the composite load model, for which the current version incorporates an aggregate DER model, and has been widely adopted worldwide.

Strategic deployment of Phasor Measurement Units (PMUs) is a key action for improving load models used in transmission-level dynamic simulations [6], [7], [8], [9]. Measurements from these units can be leveraged during the planning stage to identify discrepancies between simulation results and real-world system responses [10]. This process exposes shortcomings in existing models, enabling their verification and refinement.

To effectively support load model calibration, PMUs should be installed at frontier buses between transmission and distribution systems, or even within the distribution system. In large power systems, the number of such buses is typically high, which would require extensive PMU deployment to achieve full observability of all distribution systems, even though not all of them have a significant impact on transmission-level dynamic response. Thus, in a context of limited number of PMUs to allocate for this purpose, it is important to select the load buses most sensitive to systemic dynamics.

Recent literature has focused on developing approaches for the independent allocation of meters in transmission, sub-transmission, and distribution networks [8], [9]. In distribution systems, PMU allocation methods are applied to state estimation, islanding detection, fault location, and harmonic estimation [7]. Some approaches, such as [11], [12], use PMU data to identify composite load parameters; however, they do not address PMU allocation for this purpose and instead assume that the measurements are already available at the load buses.

In transmission systems, available PMU allocation methods often have the objective of minimizing the number of placed meters and/or their aggregate cost, or even aim at ensuring full network observability [13], [14], [15], [16], [17]. However, these methods are not suitable for identifying measurement points for load monitoring. Even in systems that have PMU structures installed at distribution systems, the data from these PMUs are typically acquired independently by a limited number of units under the responsibility of Distribution System Operators (DSOs), with the collected data aggregated in standalone concentrators, and TSOs often lack access to this crucial information [1]. Furthermore, the PMU structure that results from the allocation proposed in this paper belongs to the TSO, and only buses that the TSO have access are eligible to PMU allocation.

Within the context established in the previous paragraphs, this paper proposes a methodology to identify the most suitable buses outside the main grid for PMU allocation, aiming to provide measurements for monitoring distribution system behavior during disturbances and for subsequent load model validation. The main assumption of the method is that only a limited number of PMUs is available for this purpose. Therefore, the allocation is not based on achieving full observability of all buses connecting loads to the transmission system, but rather on ranking the buses whose loads have a greater impact on bulk power system dynamics.

In this framework, the primary contribution of this paper is to enhance operational planning information and improve the load models in the TSO database through measurements at strategic points of the low and medium voltage networks. This contribution is novel in terms of PMU allocation and addresses the a current challenge, faced by TSOs, of continuously updating load models, including the dynamic response of DERs. The proposed method tackles the practical issue of allocating a limited number of PMUs with low computational burden and minimal demand on human resources, which represent important features for its application to very large systems.

Additionally, the proposed methodology was designed for initial application in the Brazilian Interconnected Power System (BIPS), through a project conducted in collaboration with the Brazilian National System Operator (ONS). Thus, the project features were defined to enable its application across all geo-electrical regions of the BIPS, which covers a continental area and exhibits a wide variety of load densities and profiles, posing significant challenges for the PMU allocation process. Consequently, this paper also contributes to improving load model validation under such diverse conditions in a large power system.

To address these challenges, the priority allocation method employs an index that incorporates both the electrical influence of major disturbances and the load and DER levels at the candidate bus to receive a PMU. The index computation is based on static analysis, which results in a low computational burden for large power systems. To test and validate the proposed technique, the methodology was initially applied to a reduced system as a proof of concept.

After satisfactory validation, it was implemented on BIPS model (excluding the main grid).

The remainder of the paper is structured as follows: Section II outlines the procedure for establishing the measurement prioritization rankings. Section III examines the applicability of the proposed methodology to a specific operating point in the Brazilian 107-Bus AC-DC Reduced System. Section IV elaborates on the application of this methodology to the BIPS, presenting a diversified meter allocation strategy while accounting for various operating points. Finally, Section V concludes the paper by summarizing its key findings.

II. METHODOLOGY FOR CONSTRUCTING MEASUREMENT PRIORITIZATION RANKINGS

In this work, for each system operating point, lists of the buses of interest are elaborated and ranked in descending order according to the Measurement Allocation Indices (MAIs). By definition, these indices are calculated based on the consideration of two characteristics of each bus: (i) the electrical influence of a predefined set of disturbances on the buses of interest, and (ii) the amount of load and DERs connected to each bus of interest.

Thus, the MAI of the i-th bus in the op-th ranking, related to the op-th operating point, is given by

$$R_i^{op} = \alpha_1 \cdot I_i^{op} + \alpha_2 \cdot M_i^{op}, \tag{1}$$

where

- α_1 is the weight in the MAI related to electrical influence,
- I_i^{op} is the electrical influence of a pre-determined set of disturbances on the i-th bus related to the op-th operating point,
- α_2 is the weight in the MAI related to the amount of load and DERs,
- M_i^{op} is amount of load and DERs at the i-th bus related to the op-th operating point.

It is worth noting that (1) is not applicable to buses that lack load and/or DERs. Hence, for each operating point, a ranking of the buses of the system can be constructed and arranged in descending order according to the MAIs, as presented in the flowchart in Figure 1. This ordered ranking enables the recommendation of meter allocation to priority buses.

For subsequent developments, in order to simplify (1), the superscript op will be omitted.

A. CALCULATION OF ELECTRICAL INFLUENCE ACCOUNTING FOR A SET OF DISTURBANCES

In this paper, the electrical influence is defined as the ability of a specific set of disturbances to affect the electrical quantities of the buses belonging to the system. From the viewpoint of static analysis, calculating this influence based on steady-state voltage variations is intuitive. In this context, it is assumed that short-term dynamics do not drive the system into an unstable condition.

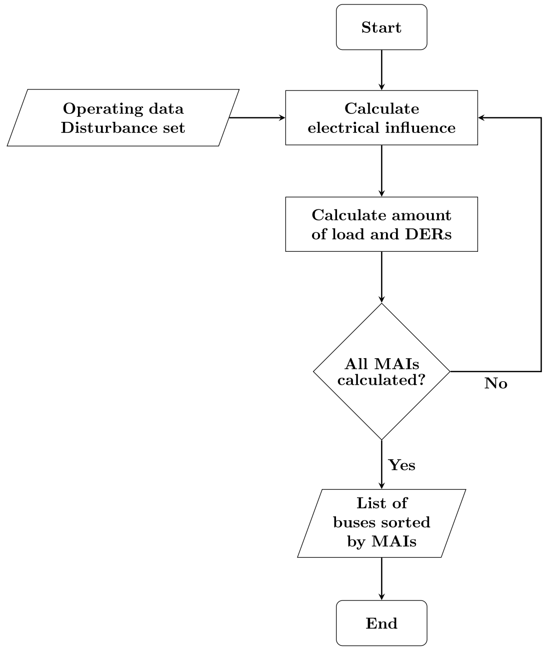

FIGURE 1. Flowchart of the methodology for constructing measurement prioritization rankings.

Thus, given an operating point and a specific disturbance j, the difference between pre-disturbance and post-disturbance voltages for the i-th bus is calculated by

$$\Delta V_i^j = V_i^0 - V_i^j, \tag{2}$$

where V_i^0 represents the pre-disturbance voltage of the i-th bus (base case) and V_i^j represents the post-disturbance voltage of the i-th bus (given the j-th disturbance). Therefore, the electrical influence on the i-th bus, considering a set of disturbances, is calculated by

$$I_i = \frac{\sum_j |V_i^j|}{\max_i \left(\sum_j |V_i^j|\right)}. \tag{3}$$

Equation (3) is applied exclusively to disturbances where the post-disturbance power flow converges. Therefore, disturbances that result in divergence or non-convergence are excluded from (3).

Normalization by the maximum was applied in order to have the electrical influences of each bus in the system always greater than zero and smaller than or equal to one ($0 < I_i \leq 1$), thus facilitating the choice of weights.

B. CALCULATION OF LOAD AND AMOUNT OF DISTRIBUTED ENERGY RESOURCES

In practice, buses with high demand of power and/or high power generated by the DERs should be prioritized in the meter allocation process. For this reason, the representation by net load amount (demanded power minus generated power) is not adequate, as the aforementioned buses could present very small net loads.

Hence, for the i-th bus, the load and DERs amount is calculated by

$$M_i = \frac{P_{di} + P_{gi}}{\max\limits_i \left(P_{di} + P_{gi}\right)}, \tag{4}$$

where P_{di} represents the power demanded by the load at the i-th bus and P_{di} represents the power generated by the DERs at the same bus.

Once again, normalization by the maximum was applied to ensure that $0 < M_i \leq 1$ in order to facilitate the choice of weights.

C. PROPOSED WEIGHT SELECTION

From (3) and (4), the choice of α_1 and α_2 in (1) such that $\alpha_1 + \alpha_2 = 1$ makes the MAI also restricted in a similar manner ($0 < R_i \leq 1$). For load buses, i.e., PQ buses, equal weights were chosen for the electrical influence and the load amount

$$R_i = \frac{1}{2}\left(I_i + M_i\right); \quad \alpha_1 = \alpha_2 = \frac{1}{2}. \tag{5}$$

This means that both indices equally impact the allocation index. For generation buses, i.e., PV buses, the voltages do not change when contingencies are considered. Consequently, the respective calculations of electrical influence do not add any information ($I_i = 0$).

Thus, to avoid penalizing these PV buses, the respective MAIs were computed only by the amount of load and DERs

$$R_i = M_i; \quad \alpha_1 = 0,\ \alpha_2 = 1. \tag{6}$$

III. PROOF-OF-CONCEPT: BRAZILIAN 107-BUS AC-DC REDUCED SYSTEM

To demonstrate the applicability of the proposed method to create rankings for meter allocation, the Brazilian 107-bus AC-DC reduced system was used [18]. This system is composed of three areas named South, Southeast, and Mato Grosso, with a total generation capacity of 22080 MW and a total load of 12679 MW. Additionally, the 107-bus AC-DC system features a bidirectional DC link based on the Furnas/Itaipu model, with a nominal power and voltage of 1566 MW and 600 kV, respectively, connecting the Salto Santiago substation to the Itumbiara substation, as shown in Figure 2.

It is important to emphasize that this system was chosen only as a proof-of-concept, since the target application is sub-transmission and distribution networks in the BIPS, as will be described in Section IV.

In the chosen pre-disturbance operating point, the DC link presents an exchange of 1500 MW transferred from the South area to the Southeast area. The dispatches were modified respecting the maximum and minimum generation limits of the plants, in accordance with the most recent operating points of the BIPS made available by the ONS. For initial validation of the developed prioritization methodology, three distinct disturbances were chosen to be applied to the proof-of-concept system: (i) loss of the Marimbondo hydroelectric plant, (ii) single loss of the 230 kV Itumbiara – Rio Verde transmission line, and (iii) loss of the HVDC link. These disturbances are referenced in the single line diagram in Figure 3 by the colors red, yellow, and blue, respectively.

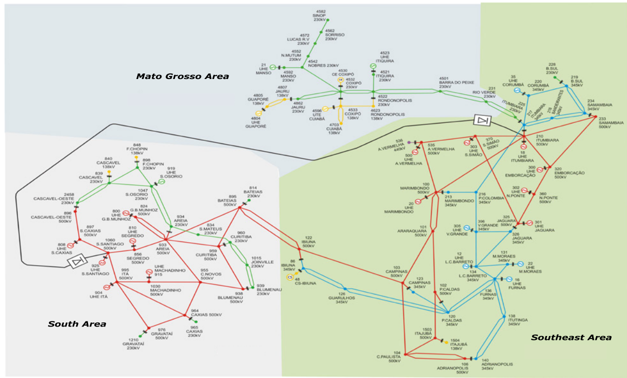

FIGURE 2. Brazilian 107-Bus AC-DC reduced system [18].

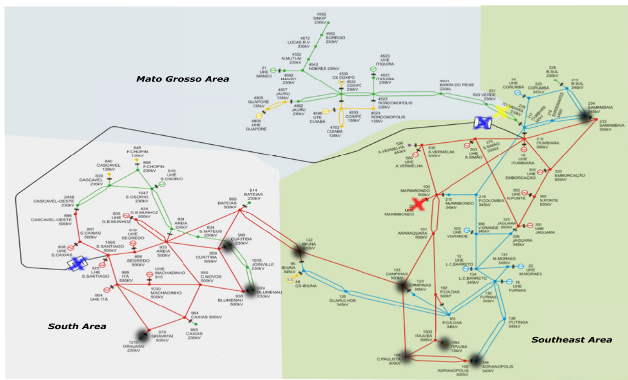

FIGURE 3. Identification of disturbances in the Proof-of-Concept system.

The simulations were performed using ANAREDE® software, developed by CEPEL [19], which is the most widely used power system analysis tool in the Brazilian electric sector. This system does not present DERs and, therefore, only the power demanded by the loads was considered in the load and DERs amount. Additionally, no PV bus showed any demanded power different from zero. Thus, the ranking of prioritized buses was calculated for a set of 39 PQ buses, which can be seen in Table 1. Finally, Figure 4 shows how the calculated MAIs are distributed between each of the three areas of the system. Therefore, it is evident that the selected set of disturbances significantly influenced the Southeast area, which is the region with the highest load concentration.

It is interesting to note that the GRAVATAI-230 bus, which has the largest amount of load (and, thus, was used for normalization of M_i), only ranks 4^{th} in the list, since its respective I_i is quite small. Furthermore, the ITAJUBA-138 bus, which has the largest R_i, only ranks 3^{rd}. This shows

TABLE 1. Measurement ranking for the Proof-of-Concept system.

Position	Bus	R_i	Name	I_i	M_i
1	104	0.7984	C.PAULIS-500	0.8558	0.7410
2	140	0.6765	ADRIANO–345	0.7830	0.5700
3	1504	0.5590	ITAJUBA–138	1.0000	0.1181
4	1210	0.5000	GRAVATAI-230	0.0000	1.0000
5	122	0.4792	IBIUNA—500	0.7956	0.1629
6	939	0.4678	BLUMENAU-230	0.0000	0.9357
7	234	0.4665	SAMAMBAI-345	0.1186	0.8143
8	123	0.4484	CAMPINAS-345	0.5304	0.3664
9	960	0.3439	CURITIBA-230	0.0000	0.6879
10	965	0.3438	CAXIAS—230	0.0723	0.6153
11	231	0.3258	R.VERDE-230	0.5786	0.0730
12	536	0.3212	AVERMELH-440	0.0723	0.5700
13	218	0.3152	BANDEIRA-345	0.1418	0.4886
14	120	0.3021	P.CALDAS-345	0.4576	0.1466
15	814	0.2994	BATEIAS–230	0.0000	0.5989
16	213	0.2787	MARIMBON-345	0.4817	0.0757
17	4501	0.2746	B.PEIXE–230	0.5236	0.0256
18	138	0.2704	ITUTINGA-345	0.4822	0.0586
19	136	0.2329	FURNAS—345	0.4219	0.0440
20	126	0.2085	GUARULHOS345	0.1808	0.2362
21	326	0.1959	JAGUARA-345	0.1688	0.2231
22	86	0.1896	IBIUNA—345	0.3255	0.0537
23	217	0.1887	ITUMBIARA345	0.0810	0.2964
24	4623	0.1795	RONDONOP-138	0.2546	0.1044
25	2458	0.1641	CASCAVEL-230	0.0000	0.3282
26	934	0.1327	AREIA—-230	0.0723	0.1930
27	4703	0.1089	CUIABA—138	0.0694	0.1483
28	834	0.0959	S.MATEUS-230	0.1808	0.0109
29	4807	0.0814	JAURU—-138	0.0579	0.1050
30	4582	0.0775	SINOP—-230	0.1041	0.0508
31	216	0.0696	PCOLOMBIA345	0.0959	0.0432
32	840	0.0647	CASCAVEL-138	0.0000	0.1295
33	4562	0.0618	SORRISO–230	0.1041	0.0194
34	4533	0.0596	COXIPO—138	0.0579	0.0614
35	4572	0.0536	LUCAS-RV-230	0.0926	0.0147
36	228	0.0524	B.SUL—-230	0.0347	0.0700
37	4552	0.0456	N.MUTUM–230	0.0810	0.0103
38	848	0.0443	FCHOPIM–138	0.0121	0.0765
39	1015	0.0285	JOINVILLE230	0.0000	0.0570

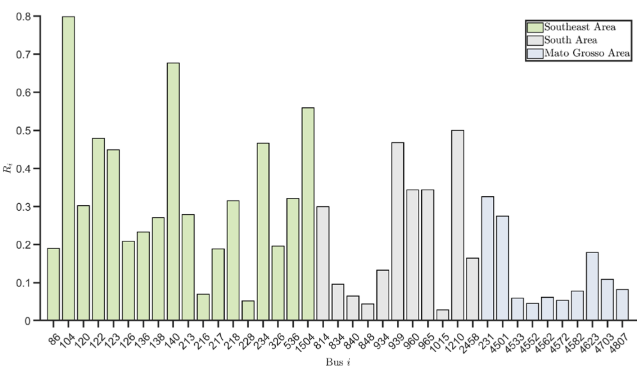

FIGURE 4. Measurement allocation indices for the Proof-of-Concept system.

that the proposed method is able to find an adequate balance between the two features that must be captured to prioritize buses for measurement allocation.

With the prioritization results presented above, the next step is to propose an appropriate set of meters to be installed in this system. Assuming that nine meters should be allocated (three times the number of areas in the system), the chosen buses will be the first nine ranked in Table 1. The geoelectric location of the meters is shown in the diagram of Figure 3.

Analyzing Figure 3, it is evident that no bus from the Mato Grosso region was selected during this process. To ensure diversified measurement points across all areas of the system, regionalized rankings were developed, as depicted in Tables 2, 3, and 4. Consequently, the top three buses from each region can be selected, enabling the redistribution of meters, as depicted in Figure 5.

TABLE 2. Measurement ranking in the Proof-of-Concept system (Southeast).

Position	Bus	R_i	Name	I_i	M_i
1	104	0.8545	C.PAULIS-500	0.7990	0.9100
2	140	0.7487	ADRIANO–345	0.7974	0.7000
3	234	0.6881	SAMAMBAI-345	0.3762	1.0000
4	1504	0.5725	ITAJUBA–138	1.0000	0.1450
5	218	0.5653	BANDEIRA-345	0.5305	0.6000
6	123	0.4726	CAMPINAS-345	0.4952	0.4500
7	122	0.4714	IBIUNA—500	0.7428	0.2000
8	217	0.4521	ITUMBIARA345	0.5402	0.3640
9	536	0.3838	AVERMELH-440	0.0675	0.7000
10	120	0.3368	P.CALDAS-345	0.4936	0.1800
11	213	0.3045	MARIMBON-345	0.5161	0.0930
12	138	0.2611	ITUTINGA-345	0.4502	0.0720
13	126	0.2294	GUARULHOS345	0.1688	0.2900
14	136	0.2239	FURNAS—345	0.3939	0.0540
15	326	0.2158	JAGUARA-345	0.1576	0.2740
16	86	0.1849	IBIUNA—345	0.3039	0.0660
17	228	0.1588	B.SUL—-230	0.2315	0.0860
18	216	0.1045	PCOLOMBIA345	0.1559	0.0530

TABLE 3. Measurement ranking in the Proof-of-Concept system (South).

Position	Bus	R_i	Name	I_i	M_i
1	965	0.8077	CAXIAS—230	1.0000	0.6153
2	934	0.5965	AREIA—-230	1.0000	0.1930
3	834	0.5055	S.MATEUS-230	1.0000	0.0109
4	1210	0.5000	GRAVATAI-230	0.0000	1.0000
5	939	0.4678	BLUMENAU-230	0.0000	0.9357
6	960	0.3439	CURITIBA-230	0.0000	0.6879
7	814	0.2994	BATEIAS–230	0.0000	0.5989
8	2458	0.1641	CASCAVEL-230	0.0000	0.3282
9	848	0.0716	FCHOPIM–138	0.0667	0.0765
10	840	0.0647	CASCAVEL-138	0.0000	0.1295
11	1015	0.0285	JOINVILLE230	0.0000	0.0570

TABLE 4. Measurement ranking in the Proof-of-Concept system (Mato Grosso).

Position	Bus	R_i	Name	I_i	M_i
1	4501	0.5862	B.PEIXE–230	1.0000	0.1724
2	4703	0.5337	CUIABA—138	0.0674	1.0000
3	231	0.5272	R.VERDE-230	0.5618	0.4926
4	4623	0.4756	RONDONOP-138	0.2472	0.7040
5	4807	0.3820	JAURU—-138	0.0562	0.7079
6	4533	0.2351	COXIPO—138	0.0562	0.4141
7	4582	0.2219	SINOP—-230	0.1011	0.3427
8	4562	0.1159	SORRISO–230	0.1011	0.1307
9	4572	0.0944	LUCAS-RV-230	0.0899	0.0988
10	4552	0.0739	N.MUTUM–230	0.0787	0.0692

As demonstrated by the presented simulations, the necessity of constructing regionalized rankings is evident,

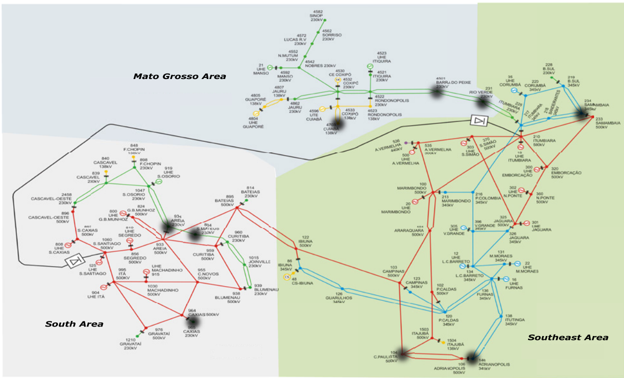

FIGURE 5. Geographical location of meters allocated by area in the Proof-of-Concept system.

as different electrical areas exhibit varying levels of influence, voltage, and load. Furthermore, the results showed meters allocated at electrically close buses. In this context, the presence of redundant measurements constitutes a potential challenge for the application of the proposed method to large-scale systems (such as the BIPS).

IV. APPLICATION OF THE PROPOSED METHODOLOGY TO THE BRAZILIAN INTERCONNECTED POWER SYSTEM

A. DEFINITION OF ELECTRICAL AREAS AND TARGET NUMBER OF METERS

As a starting point, the ONS provided recommendations on the definition of areas for regionalized rankings and suggested an appropriate number of meters per area. On this last point, three distinct measurement scenarios were defined based on a percentage of the total substations in an electrical area. In the pessimistic scenario, only 1% of the total buses in an electrical area have allocated meters, In the intermediate scenario this number rises to 3% and, on the optimistic one, to 5%. The methodology was applied to the regions of São Paulo (SP), Rio de Janeiro and EspÍrito Santo (RJ/ES), and Minas Gerais (MG), which have the largest load centers and the highest penetration of DERs in the BIPS.

The total number of substations in sub-transmission and distribution networks, categorized by electrical areas and voltage levels, for each measurement scenario, is presented in Tables 5, 6, and 7. Although the values of electrical influence and the amounts of load and DERs are normalized, the respective power demand can be quite different depending of the respective voltage level. Hence, this categorization according to voltage level is essential for effective analysis and decision-making in large-scale systems.

B. OPERATION POINTS AND CRITICAL CONTINGENCIES FOR THE BIPS OPERATION

In addition to defining the electrical areas and the target number of meters, the ONS supplied 11 base cases (pre-disturbance operating points) and a list of 61 critical contingencies for the BIPS operation. These 11 base cases

TABLE 5. Available Data (SP Area).

Substation		Meters		
Total Number	Voltage (kV)	1%	3%	5%
6	230	1	1	1
490	138	5	15	25
59	88	1	2	4*
61	66/69	1	2	4*

*Values arbitrarily adjusted (proposed number is insufficient).

TABLE 6. Available Data (RJ/ES Area).

Substation		Meters		
Total Number	Voltage (kV)	1%	3%	5%
257	138	3	8	13
35	69	1*	2*	3*

*Values arbitrarily adjusted (proposed number is insufficient).

TABLE 7. Available Data (MG Area).

Substation		Meters		
Total Number	Voltage (kV)	1%	3%	5%
2	345	1	1	1
7	230	1	1*	1*
326	138	4	10	17
20	69	1	2*	3*

*Values arbitrarily adjusted (proposed number insufficient).

serve as the reference for the Electrical Operation Guidelines studies for the second quarter of 2024 [20]. They incorporate updated assumptions regarding load and distributed generation, ensuring improved adaptation to the evolving operational conditions of the BIPS, as illustrated in Table 8.

C. INITIAL RESULTS: OPERATION POINT OF CASE 6

The methodology developed in Section II was applied to the operation point of case 6. This case presents the network configuration in August 2024, with the assumptions of non-coincident global daytime maximum load per agent on a business day and high DER penetration.

In this context, the most intuitive initial approach involved constructing rankings for each electrical region. Subsequently, the meters would be allocated to the highest-ranked buses (prioritized buses) until all meters were distributed. For simplicity, given the number of monitored buses, the results in this section will be presented only for the SP 138kV region, as it is the largest load center in Brazil. The selected measurement scenario corresponds to the optimistic case (5%), and the results are presented in Table 9.

From the analysis of the BIPS single-line diagram, it is possible to observe that this initial strategy does not take into account the electrical proximity between buses, i.e., meters would be allocated to electrically close buses. In this case, nearby buses (such as BOTUC1-SP138 and EMBOTU-SP138) would receive meters, as shown in Figure 6.

From the perspective of the BIPS, it is essential to ensure adequate geographical diversity of the meters. The question to be answered, therefore, is: *given a meter installed at a specific*

TABLE 8. Reference cases for the quarterly horizon [20].

Case	Network Configuration	Load Premise	DERs Premise
1	First month of the quarter	Maximum non-coincident global daytime load per agent on a business day	High
2	First month of the quarter	Maximum non-coincident global daytime load per agent on a business day	Maximum
3	First month of the quarter	Maximum non-coincident global nighttime load per agent on a business day	Null*
4	First month of the quarter	Minimum non-coincident net global daytime load of DERs per agent on Sundays and holidays	Intermediate**
5	First month of the quarter	Minimum non-coincident global nighttime load per agent on any day	Null*
6	Last month of the quarter	Maximum non-coincident global daytime load per agent on a business day	Maximum
7	Last month of the quarter	Maximum non-coincident global nighttime load per agent on a business day	Null*
8	Last month of the quarter	Maximum non-coincident global nighttime load per agent on a business day	Null*
9	Last month of the quarter	Minimum non-coincident net global daytime load of DERs per agent on Sundays and holidays	Intermediate**
10	Last month of the quarter	Minimum non-coincident global nighttime load per agent on any day	Null*
11	Last month of the quarter	Arbitrary intermediate load, coincident for interconnection study	Maximum

*Residual DERs may occur due to agents' schedules and other generation types.
**Premise for selecting DERs to obtain the lowest net load seen by the main grid.

TABLE 9. List of selected meters, SP 138kV (Initial Results).

Position	Bus	R_i	Name	I_i	M_i
1	2312	0.6059	CONGON-SP138	1.0000	0.2119
2	2311	0.5533	GUARNI-SP138	0.9094	0.1972
3	2208	0.5121	IPE—-SP138	0.8698	0.1545
4	681	0.5120	BRAGAC-SP138	0.0240	1.0000
5	2150	0.4101	BOTUC1-SP138	0.6739	0.1463
6	2173	0.4056	CPICBR-SP138	0.7680	0.0432
7	3128	0.3839	ITAPE4-SP138	0.6082	0.1596
8	2161	0.3825	LENCOI-SP138	0.6670	0.0981
9	2285	0.3611	PRADOP-SP138	0.6842	0.0381
10	3051	0.3555	BIRITI-SP138	0.6449	0.0661
11	7744	0.3511	P.PR02-SP138	0.6520	0.0503
12	4260	0.3491	AUSTA–SP138	0.4096	0.2886
13	4277	0.3472	ITAPE9-SP138	0.6349	0.0595
14	2257	0.3421	BATATA-SP138	0.5222	0.1621
15	2160	0.3409	ITAMBE-SP138	0.4780	0.2038
16	2223	0.3258	PA+YPK-SP138	0.4733	0.1784
17	638	0.3133	CATAN2-SP138	0.2771	0.3496
18	3813	0.3120	LIMEI4-SP138	0.4070	0.2170
19	3176	0.3107	PVENCE-SP138	0.0904	0.5310
20	46222	0.3105	EMBOTU-SP138	0.5961	0.0249
21	4255	0.3097	IBA+BT-SP138	0.4415	0.1778
22	3981	0.3068	SGERT–SP138	0.5648	0.0488
23	4261	0.3055	YL+DUR-SP138	0.4336	0.1773
24	2188	0.3047	CAMPI–SP138	0.2198	0.3897
25	3178	0.3021	PRUDE5-SP138	0.1225	0.4817

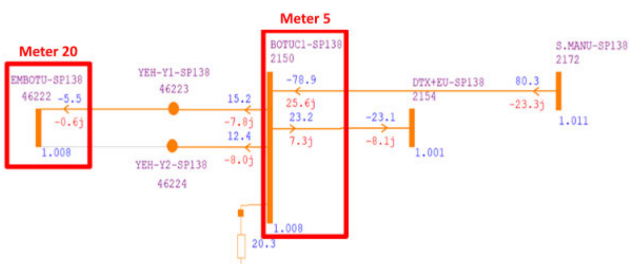

FIGURE 6. Allocation of meters at electrically close buses.

bus and considering its respective measurements, for which set of buses one can infer a similar behavior?

D. DIVERSIFIED METER ALLOCATION STRATEGY

The above question can be answered through the calculation of sensitivities. Ideally, it would be necessary to construct the Jacobian matrices of the converged post-disturbance flows for all operating points. However, given that the list of contingencies consists only of disturbances in elements of the main network, it is assumed that the sensitivities of the buses outside the main network are not significantly different from those related to the converged pre-disturbance power flows.

Thus, for each operation point, it is possible to linearize the power flow equations around the converged pre-disturbance values, as shown in the equation below [21].

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{M} \\ \boldsymbol{N} & \boldsymbol{L} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta \boldsymbol{V} \end{bmatrix} = \boldsymbol{J} \begin{bmatrix} \Delta \theta \\ \Delta \boldsymbol{V} \end{bmatrix}, \tag{7}$$

where

- $\Delta \boldsymbol{P}$ is a vector composed by active power variations at the buses,
- $\Delta \boldsymbol{Q}$ is a vector composed by reactive power variations at the buses,
- $\boldsymbol{J}$ is the Jacobian matrix of the system,
- $\Delta \theta$ is a vector composed by voltage angle variations at the buses, and
- $\Delta \boldsymbol{V}$ is a vector composed by voltage magnitude variations at the buses.

Assuming $\Delta \boldsymbol{Q} = \boldsymbol{0}$, the voltage variation vector can be written as a function of the power variation vector

$$\Delta \boldsymbol{V} = \left[\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{P}} \right] \Delta \boldsymbol{P} = \left[\boldsymbol{M} - \boldsymbol{H} \boldsymbol{N}^{-1} \boldsymbol{L} \right] \Delta \boldsymbol{P} = \boldsymbol{S}\, \Delta \boldsymbol{P}. \tag{8}$$

Matrix $\boldsymbol{S}$ is defined as the sensitivity matrix, representing the sensitivity of $\boldsymbol{V}$ with respect to $\boldsymbol{P}$. Assuming a small variation of active power at the i-th bus of the system, the voltages at buses k and i change as follows.

$$\begin{cases} \Delta V_k = S_{ki}\, \Delta P_i \\ \Delta V_i = S_{ii}\, \Delta P_i \end{cases} \tag{9}$$

Thus, the ratio between the sensitivities of buses k and i to a small active power variation at bus i can be calculated by the ratio of the equations shown in (9).

$$\frac{S_{ki}}{S_{ii}} = \left(\frac{\partial V_k}{\partial P_i} \right) \left(\frac{\partial V_i}{\partial P_i} \right)^{-1} = \frac{\Delta V_k}{\Delta V_i} \tag{10}$$

Although this approach seems promising, its applicability to the system is not efficient. This happens because the matrix $\boldsymbol{N}$ needs to be square, and its inversion has a high computational burden. Therefore, an alternative approach was proposed, in which (7) is solved as a sparse linear system of the form $\boldsymbol{Ax} = \boldsymbol{b}$, considering $\Delta\boldsymbol{Q} = 0$ and a small perturbation in ΔP_i (for instance, 0.1 p.u.).

$$\boldsymbol{J}\begin{bmatrix}\Delta\theta \\ \Delta\boldsymbol{V}\end{bmatrix} = \begin{bmatrix}\Delta\boldsymbol{P} \\ \boldsymbol{0}\end{bmatrix}, \quad \Delta\boldsymbol{P} = \begin{bmatrix}0 \\ \vdots \\ \Delta P_i \\ \vdots \\ 0\end{bmatrix} \tag{11}$$

As a consequence, the ratio between the sensitivities of buses k and i can be indirectly calculated by the ratio of the respective voltage magnitude variations obtained.

$$\beta_{ki} = \frac{\Delta V_k}{\Delta V_i} \tag{12}$$

In case $|\beta_{ki}| > \delta$ (where δ is a sensitivity threshold), it is considered that the voltage at bus k is sensitive to the voltage at bus i. This condition was considered as evidence that it would be possible to infer the behavior of the voltage magnitude at bus k from measurements taken at bus i. Based on this assumption, the following steps can be followed to ensure the geographical diversity of the allocated meters.

First, the measurement rankings for all electrical regions of the system must be calculated. For each ranking built, in the first iteration, a meter is assigned to the highest-ranked bus (the first in the ranking), defined as the i-th bus in the system. Next, the magnitude of the sensitivity ratio, $|\beta_{ki}|$, is calculated for all other buses relative to the previously specified i-th bus. If $|\beta_{ki}|$ is greater than δ, it is considered that the voltage at bus k is sensitive to the voltage at bus i. Thus, bus k can be removed from the ranking since the behavior of the k-th bus can be inferred from the measurement at bus i. In the second iteration, a meter is allocated to the second highest-ranked bus of the ranking resulting from the first iteration, and the remaining steps are repeated. The method is completed when all meters are allocated.

The step-by-step description of the proposed strategy is detailed below.

1) **Input data**: a list with the measurement ranking, the number of meters per electrical region, and the data from the power flow Jacobian matrices before perturbation;
2) **Indicating the first meter in the list**: in this step, the first meter is assigned to the highest-ranked bus in the list, i.e., the first bus ($n = 1$). This bus is then defined as the i-th bus in the system;
3) **Calculating the sensitivity ratio**: the sensitivity ratio of all other candidate buses k, with $k \neq i$, relative to the previously defined i-th bus is calculated. If $|\beta_{ki}| > \delta$, the voltage at bus k is sensitive to the voltage at bus i, and bus k is removed from the ranking;
4) **Indicating the remaining meters in the list**: first, the value of n is incremented by one. Then, the n-th meter is assigned to the n-th bus in the reformulated ranking. This bus is then defined as the i-th bus in the system, and Step 3 is repeated. This process is repeated until all meters in all electrical regions are allocated;
5) **Listing the selected buses for meter allocation**: as a result, a list of buses selected for meter allocation is provided, which will later be unified for the different operating points of the system.

To illustrate this strategy, consider the same operating point and the same electrical region analyzed previously. The corresponding measurement ranking for the first 50 buses is presented in Table 10.

TABLE 10. Measurement ranking, SP 138kV (Case 6).

Position	Bus	R_i	Name	I_i	M_i
1	2312	0.6059	CONGON-SP138	1.0000	0.2119
2	2311	0.5533	GUARNI-SP138	0.9094	0.1972
3	2208	0.5121	IPE—-SP138	0.8698	0.1545
4	681	0.5120	BRAGAC-SP138	0.0240	1.0000
5	2150	0.4101	BOTUC1-SP138	0.6739	0.1463
6	2173	0.4056	CPICBR-SP138	0.7680	0.0432
7	3128	0.3839	ITAPE4-SP138	0.6082	0.1596
8	2161	0.3825	LENCOI-SP138	0.6670	0.0981
9	2285	0.3611	PRADOP-SP138	0.6842	0.0381
10	3051	0.3555	BIRITI-SP138	0.6449	0.0661
11	7744	0.3511	P.PR02-SP138	0.6520	0.0503
12	4260	0.3491	AUSTA–SP138	0.4096	0.2886
13	4277	0.3472	ITAPE9-SP138	0.6349	0.0595
14	2257	0.3421	BATATA-SP138	0.5222	0.1621
15	2160	0.3409	ITAMBE-SP138	0.4780	0.2038
16	2223	0.3258	PA+YPK-SP138	0.4733	0.1784
17	638	0.3133	CATAN2-SP138	0.2771	0.3496
18	3813	0.3120	LIMEI4-SP138	0.4070	0.2170
19	3176	0.3107	PVENCE-SP138	0.0904	0.5310
20	46222	0.3105	EMBOTU-SP138	0.5961	0.0249
21	4255	0.3097	IBA+BT-SP138	0.4415	0.1778
22	3981	0.3068	SGERT–SP138	0.5648	0.0488
23	4261	0.3055	YL+DUR-SP138	0.4336	0.1773
24	2188	0.3047	CAMPI–SP138	0.2198	0.3897
25	3178	0.3021	PRUDE5-SP138	0.1225	0.4817
26	2270	0.2889	IPIRAN-SP138	0.3990	0.1789
27	6604	0.2869	C.GRAN-SP138	0.5346	0.0391
28	4160	0.2866	NESTLE-SP138	0.5101	0.0630
29	2212	0.2846	JARDIM-SP138	0.4031	0.1662
30	2201	0.2776	AMIT-P-SP138	0.1107	0.4446
31	4254	0.2773	LE+DED-SP138	0.5068	0.0478
32	3940	0.2764	PARIQU-SP138	0.5295	0.0234
33	2287	0.2694	R.PRET-SP138	0.4407	0.0981
34	2166	0.2686	MA+P+Y-SP138	0.2090	0.3283
35	2286	0.2595	RE+GUA-SP138	0.0835	0.4355
36	7610	0.2570	GUARJ4-SP138	0.4631	0.0508
37	46236	0.2561	IBM—-SP138	0.4828	0.0295
38	2128	0.2554	LA+ESP-SP138	0.4228	0.0879
39	2159	0.2551	HIPODR-SP138	0.2053	0.3049
40	6585	0.2522	SJRNOR-SP138	0.2692	0.2353
41	2246	0.2520	3PONTA-SP138	0.4522	0.0518
42	2330	0.2499	PRIMAV-SP138	0.2137	0.2861
43	2236	0.2496	PAT+ME-SP138	0.1374	0.3618
44	46212	0.2484	GUARIB-SP138	0.4429	0.0539
45	7620	0.2450	VOTUP3-SP138	0.4111	0.0788
46	2100	0.2446	BVIST–SP138	0.3119	0.1773
47	4269	0.2418	FZGRAN-SP138	0.1959	0.2876
48	2181	0.2409	FAZVEL-SP138	0.3772	0.1047
49	2172	0.2377	S.MANU-SP138	0.4007	0.0747
50	2231	0.2365	RHODIA-SP138	0.3307	0.1423

Contrary to the initial approach, which suggested the allocation of 25 meters to the first 25 buses of the ranking, the iterative approach presented above was applied. In this example, the sensitivity threshold value considered was 0.5 ($\delta = 0.5$). The choice of this value was based on simulations and the analysis of the electrical connection of BIPS buses through its corresponding single-line diagram.

In the first iteration, a meter was allocated to the first bus, which is identified as CONGON-SP138. This bus was then placed in the first position of Table 10. Then, the sensitivity modules were calculated for all the other buses in relation to this first one. In this case, the measurement in CONGON-SP138 did not enable inferences about the behavior of any other bus in the system.

From the second to the fourth iteration, meters were allocated to the buses GUARNI-SP138, IPE—-SP138, and BRAGAC-SP138, respectively. These measurements also did not enable inferences about the behavior of any other bus in the system. In the fifth iteration, a meter was allocated at the bus BOTUC1-SP138, which allowed inference about the behaviour of the voltage magnitude at the bus EMBOTU-SP138. Therefore, bus EMBOTU-SP138 was eliminated from the ranking since it presented $|\beta_{20,5}| = 0.83 > 0.5$, as shown in Figure 7.

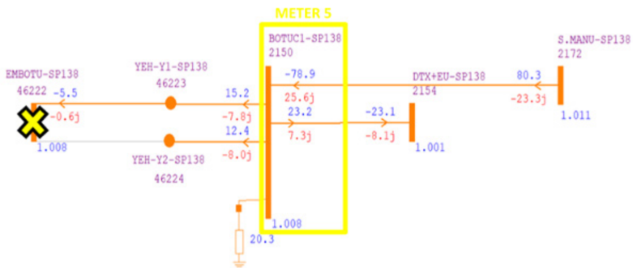

FIGURE 7. Elimination of the EMBOTU-SP138 bus from the ranking, SP 138kV (case 6).

The process continued until all meters were allocated, as illustrated in the list of selected meters in Table 11. Additionally, the color scheme used for shading in Table 10 indicates the selected buses (black font) and the buses discarded by the sensitivity analysis (red font). Buses 30 to 50 also appear in red text because they were not selected by the method due to the limitation in the predefined number of meters for allocation.

The development presented up to this point considered only the operation point of case 6, which belongs to the set of 11 operation points provided by ONS. The next section presents the methodology adopted for unifying the rankings obtained for various operation points of the BIPS.

E. CONSIDERATION OF DIFFERENT OPERATION POINTS

As previously mentioned, the allocation of meters needs to take into account multiple operating conditions, since the rankings vary with respect to the operating point. To do so, the list of meters selected in each operating point for each of the electrical regions served as the bases for assigning a score to each bus in the inverse order of its position in the respective

TABLE 11. List of selected meters, SP 138kV (Case 6).

Position	Bus	R_i	Name
1	2312	0.6059	CONGON-SP138
2	2311	0.5533	GUARNI-SP138
3	2208	0.5121	IPE—-SP138
4	681	0.5120	BRAGAC-SP138
5	2150	0.4101	BOTUC1-SP138
6	2173	0.4056	CPICBR-SP138
7	3128	0.3839	ITAPE4-SP138
8	2161	0.3825	LENCOI-SP138
9	2285	0.3611	PRADOP-SP138
10	3051	0.3555	BIRITI-SP138
11	7744	0.3511	P.PR02-SP138
12	4260	0.3491	AUSTA–SP138
13	2257	0.3421	BATATA-SP138
14	2160	0.3409	ITAMBE-SP138
15	2223	0.3258	PA+YPK-SP138
16	638	0.3133	CATAN2-SP138
17	3813	0.3120	LIMEI4-SP138
18	4255	0.3097	PVENCE-SP138
19	3176	0.3107	IBA+BT-SP138
20	2188	0.3047	CAMPI–SP138
21	2270	0.2889	IPIRAN-SP138
22	6604	0.2869	C.GRAN-SP138
23	4160	0.2866	NESTLE-SP138
24	2212	0.2846	JARDIM-SP138
25	2201	0.2776	AMIT-P-SP138

ranking. The objective of this procedure in to produce a single and unified final list, in which the highest-ranked buses for each case receive the highest score.

For instance, suppose that the diversified meter allocation strategy has been applied to the SP 138kV region in the optimistic measurement scenario (25 meters) for all 11 available operating points. In this case, for each of the operating condition, the bus in the 1st position of the selected meters list will receive 25 points, since 25 meters should be allocated. Subsequently, the bus in the 2nd position will receive 24 points, and so on, until the bus in the 25th position receives only 1 point.

Next, the points obtained by each of the buses in each of the operating conditions are summed, resulting in the final list of allocated meters with the 25 highest-scoring buses. Figure 8 summarizes this process of considering different operating points for the proposed example. Finally, Table 12 shows the final list of meters to be allocated for this region.

In cases of the same score, that is, when two different buses have the same sum of points, the chosen tie-breaking criterion was the sum of MAIs for each of the operating points. For example, a tie can be observed in column 3 of Table 12 between buses 9 and 10, which was ordered by the value presented for the respective buses in column 4.

F. PROPOSED PROCEDURE

The steps developed throughout the previous sections are consolidated in the following. Taking the diversified meter allocation strategy and the consideration of different operating conditions into account, the complete procedure proposed in this paper for prioritizing measurement points outside the main network can now be fully described.

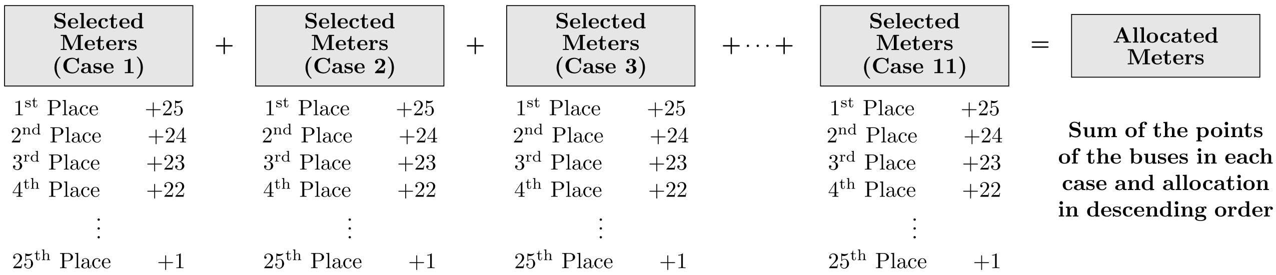

FIGURE 8. Consideration of different operation conditions.

TABLE 12. List of meters to be allocated, SP 138kV.

Meter	Bus	SumPos	SumFac
1	BRAGAC-SP138	265	6.5105
2	PVENCE-SP138	107	3.2200
3	BOTUC1-SP138	92	2.2762
4	LIMEI3-SP138	70	1.6822
5	TROPIC-SP138	65	1.5230
6	AUSTA–SP138	64	1.5609
7	RE+GUA-SP138	63	2.2857
8	CONGON-SP138	53	1.4497
9	GUARNI-SP138	49	1.2692
10	SABESP-SP138	49	1.2362
11	LENCOI-SP138	48	1.2792
12	CAPIV-BIO138	47	1.3554
13	PRUDE5-SP138	45	1.6826
14	MARAMB-SP138	45	1.0880
15	CPICBR-SP138	42	0.8989
16	YARA03-SP138	39	0.9421
17	CEDASA-SP138	39	0.8701
18	UIRAPU-SP138	38	1.2166
19	ITAPE4-SP138	38	0.8338
20	VIRACO-SP138	34	0.8481
21	JAU—-SP138	34	0.8229
22	PPAULI-SP138	33	0.8731
23	SCARL–SP138	32	0.9058
24	PIRAS1-SP138	32	0.7606
25	RCLAR2-SP138	31	1.3828

This proposed procedure, depicted in the flowchart shown in Figure 9, consists in the following steps.

DESCRIPTION OF THE PROPOSED PROCEDURE

1) **Input data:** pre-disturbance operation data, the list of disturbances, the number of meters per electrical region, and the data of the Jacobian matrices of pre-disturbance power flows;
2) **Calculation of the ranking for each region:** the ranking calculation is performed for each combination of electrical region and operating point, based on the construction of the allocation indices;
3) **Diversified meter allocation strategy:** based on the calculated ranking, the iterative, sensitivity-based strategy is applied. Therefore, buses for which the behavior can be infered by a certain measurement are excluded from the ranking;
4) **All rankings calculated?:** this step checks if the rankings have been calculated for all combinations of operating point, electrical area, and voltage level. If there are still combinations for which the ranking has not been calculated, the algorithm goes back to Step 2. Otherwise, the algorithm moves to the next step;
5) **Consideration of different operating points:** points are assigned to the highest-ranked buses in each of the selected meter lists, in the inverse order of the number of meters, as shown in Figure 8;
6) **Output data:** as outputs, the lists of prioritized buses for meter allocation are provided.

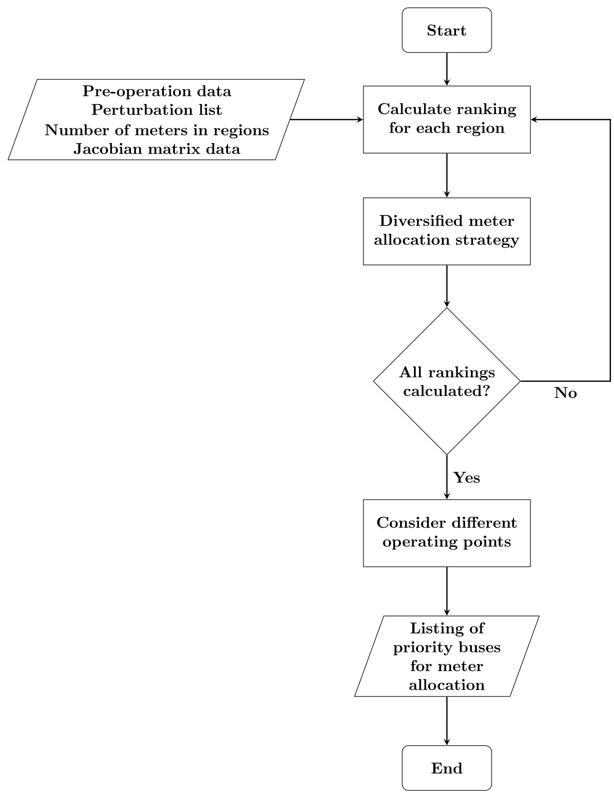

FIGURE 9. Flowchart of proposed procedure.

G. INDICATION OF PRIORITIZED MEASUREMENT POINTS IN SUB-TRANSMISSION AND DISTRIBUTION NETWORKS

Based on the systematization of the proposed procedure for prioritizing measurement points, which is summarized in the flowchart in Figure 9, results were obtained and categorized by electrical area and voltage level for all 11 analyzed operating points. It is important to highlight that the focus was given to the Southeast region of Brazil, and that this definition was made in conjunction with and based on the data provided by the ONS.

The result of the prioritization of measurement points is presented below for the SP, RJ/ES, and MG areas, respectively. Tables 13 to 16 present the results of the prioritization in the São Paulo area for the voltage levels of 230kV, 138kV, 88kV, and 69/66kV, respectively. In 13, only one substation is identified at the 230kV voltage level, located in the city of Aluminio. This substation is associated with the aluminum plant located in the city. According to Table 14, a total of 25 meters are highlighted, covering a diverse range of cities. The same analysis can be made from 15 and 16 for the voltage levels of 88kV and 69/66kV. It is possible to observe, by Figure 10, the quantity and diversity of meters among the cities in the state of São Paulo. It is important to highlight the cities of São Paulo and São José do Rio Preto. According to the proposed procedure, 3 meters were indicated in these cities. Additionally, for the city of Capivari, 2 meters were indicated.

TABLE 13. List of meters to be allocated, SP 230kV.

Meter	Bus	SumPos	SumFac	City
1	CBA—-SP230	11	9.5832	ALUMINIO - SP

TABLE 14. List of meters to be allocated, SP 138kV.

Meter	Bus	SumPos	SumFac	City
1	BRAGAC-SP138	265	6.5105	BRAG. PAULISTA - SP
2	PVENCE-SP138	107	3.2200	PRES. VENCESLAU - SP
3	BOTUC1-SP138	92	2.2762	BOTUCATU – SP
4	LIMEI3-SP138	70	1.6822	LIMEIRA – SP
5	TROPIC-SP138	65	1.5230	LINS – SP
6	AUSTA–SP138	64	1.5609	S. J. DO RIO PRETO – SP
7	RE+GUA-SP138	63	2.2857	FRANCA – SP
8	CONGON-SP138	53	1.4497	S. J. DO RIO PRETO – SP
9	GUARNI-SP138	49	1.2692	BIRIGUI – SP
10	SABESP-SP138	49	1.2362	SÃO PAULO – SP
11	LENCOI-SP138	48	1.2792	LENÇÓIS PAULISTA - SP
12	CAPIV-BIO138	47	1.3554	CAPIVARI – SP
13	PRUDE5-SP138	45	1.6826	PRES. PRUDENTE – SP
14	MARAMB-SP138	45	1.0880	VINHEDO – SP
15	CPICBR-SP138	42	0.8989	CAPIVARI – SP
16	YARA03-SP138	39	0.9421	CUBATÃO – SP
17	CEDASA-SP138	39	0.8701	SANTA GERTRUDES – SP
18	UIRAPU-SP138	38	1.2166	ARARAQUARA – SP
19	ITAPE4-SP138	38	0.8338	ITAPETININGA – SP
20	VIRACO-SP138	34	0.8481	CAMPINAS – SP
21	JAU—-SP138	34	0.8229	JAÚ – SP
22	PPAULI-SP138	33	0.8731	PATR. PAULISTA – SP
23	SCARL–SP138	32	0.9058	SÃO CARLOS – SP
24	PIRAS1-SP138	32	0.7606	PIRASSUNUNGA - SP
25	RCLAR2-SP138	31	1.3828	RIO CLARO – SP

TABLE 15. List of meters to be allocated, SP 88kV.

Meter	Bus	SumPos	SumFac	City
1	BJARD–SP088	39	6.4377	JUNDIAÍ – SP
2	JABAQU-SP088	15	3.6346	SÃO PAULO – SP
3	SAB-IG-SP088	7	1.3132	SÃO PAULO – SP
4	IMERYS-SP088	5	1.4493	SALTO - SP

TABLE 16. List of meters to be allocated, SP 69/66kV region.

Meter	Bus	SumPos	SumFac	City
1	ITARAR-SP069	32	6.5214	ITARARÉ – SP
2	N.ITA–SP069	6	1.3161	NOVA ITAPIREMA – SP
3	BESPER-SP069	6	1.2156	BOA ESP. DO SUL – SP
4	PIRAJ–SP066	6	1.1303	PIRAJU - SP

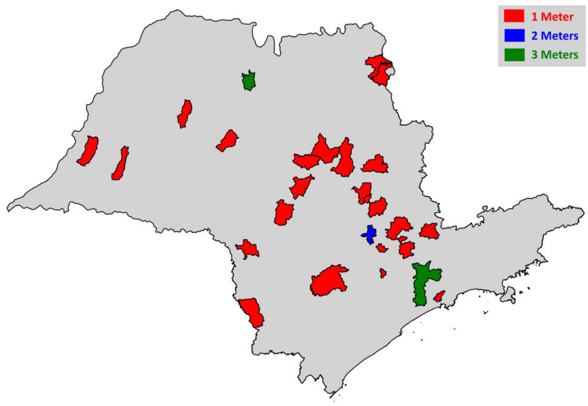

FIGURE 10. Geographic distribution of meters in the SP Area (Area: 248,219.48 km^2; Population: 44,420,459).

Subsequently, the same analysis was performed for the area related to the states of Rio de Janeiro and Espirito Santo. Tables 17 and 18 present the result of the prioritization of measurement points for the voltage levels of 138kV and 69kV. Among the highlighted cities in the prioritization, the city of Rio de Janeiro was indicated to receive 4 meters. In the state of EspÍrito Santo, the city of Serra was indicated for the installation of 3 meters. The quantity and diversity of meters among the cities in the RJ/ES area can be observed in Figure 11.

TABLE 17. List of meters to be allocated, RJ/ES 138kV.

Meter	Bus	SumPos	SumFac	City
1	CSN—UTE002	139	11.0000	VOLTA REDONDA – RJ
2	CST3-4UTE002	69	4.5164	SERRA – ES
3	CST1-2UTE002	58	4.5164	SERRA – ES
4	CAMOR–RJ138	33	1.5619	RIO DE JANEIRO – RJ
5	TAQUAR-RJ138	25	1.5938	RIO DE JANEIRO – RJ
6	F.CANE-RJ138	24	1.3219	RIO DE JANEIRO – RJ
7	V.RED–RJ138	22	1.2438	VOLTA REDONDA – RJ
8	SMARIA-ES138	19	0.9860	STA MARIA DE JETIBÁ – ES
9	MSCON2-RJ138	17	0.9018	RIO DE JANEIRO – RJ
10	C.DIST-RJ138	16	0.8942	C. DOS GOYTACAZES – RJ
11	IBES—ES138	15	1.1324	VILA VELHA – ES
12	ELDORA-RJ138	15	0.9051	DUQUE DE CAIXIAS – RJ
13	NIGTN–RJ138	15	0.8881	NOVA IGUAÇU – RJ

TABLE 18. List of meters to be allocated, RJ/ES 69kV.

Meter	Bus	SumPos	SumFac	City
1	S.LOUR-RJ069	20	5.0436	NITERÓI – RJ
2	JAP—-RJ069	11	3.6201	NOVA FRIBURGO – RJ
3	RBONIT-RJ069	5	1.2474	RIO BONITO – RJ

Finally, the result of the prioritization of measurement points for the electrical area referring to the state of Minas Gerais is highlighted in Tables 19 to 22, for the voltage

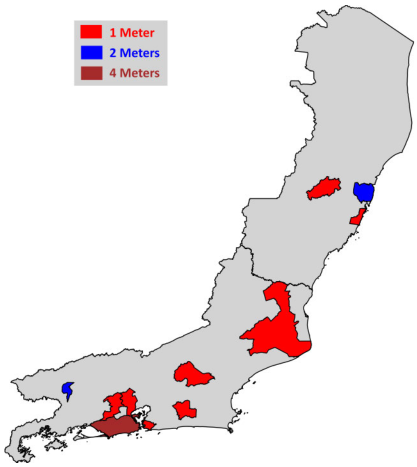

FIGURE 11. Geographic distribution of meters in the RJ/ES Area (Area: 89,824.44 km^2; Population: 16,054,524).

levels of 345kV, 230kV, 138kV, and 69kV, respectively. In this electrical area, the cities of Belo Horizonte, Juiz de Fora, and Uberlândia were indicated for the installation of 2 meters each. Figure 12 illustrates the geographic location of the meters in the cities of the Minas Gerais area.

Notably, the city of Catalão, situated in the state of Goiás, is listed as part of the Minas Gerais region. This classification arises from the direct connection between the Catalão bus and the Emborcação bus in Minas Gerais, designating it as a boundary bus between the two regions.

TABLE 19. List of meters to be allocated, MG 345kV.

Meter	Bus	SumPos	SumFac	City
1	NLIMA6-MG000	10	9.5682	NOVA LIMA - MG

TABLE 20. List of meters to be allocated, MG 230kV.

Meter	Bus	SumPos	SumFac	City
1	WMIPT1-MG230	9	7.9265	IPATINGA - MG

TABLE 21. List of meters to be allocated, MG 138kV.

Meter	Bus	SumPos	SumFac	City
1	GEROUR-MG138	160	6.1997	CONS. LAFAIETE – MG
2	PIRAC1TAP138	151	5.8332	PIRAPORA – MG
3	PIRAC2TAP138	116	4.8395	PIRAPORA – MG
4	GOBAIN-MG138	79	3.4419	BARBACENA – MG
5	DOWCOR-MG138	61	2.5255	SANTOS DUMONT – MG
6	ARCEJF-MG138	53	3.4994	JUIZ DE FORA – MG
7	VOTTMA-MG138	39	1.7569	TRÊS MARIAS – MG
8	BDESP2-MG138	28	1.8699	BOM DESPACHO – MG
9	CENTRO-MG138	27	1.5861	BELO HORIZONTE – MG
10	JFOR4–MG138	27	1.4227	JUIZ DE FORA – MG
11	CATALA-GO138	26	1.1442	CATALÃO – GO
12	ARAGUA-MG138	26	0.9559	ARAGUARI – MG
13	UBERL6-MG138	25	0.9814	UBERLÂNDIA – MG
14	UBERL7-MG138	23	0.9321	UBERLÂNDIA – MG
15	NEVES3-MG138	22	0.9029	RIB. DAS NEVES – MG
16	SION—MG138	20	0.8070	BELO HORIZONTE – MG
17	BETIM4-MG138	19	0.8903	BETIM - MG

Using the proposed procedure, the meters are evenly distributed in the cities corresponding to the main load centers

TABLE 22. List of meters to be allocated, MG 69kV.

Meter	Bus	SumPos	SumFac	City
1	JMONL3-MG069	25	7.3989	J. MONLEVADE – MG
2	MURIA1-MG069	16	6.3001	MURIAÉ – MG
3	RODEIR-MG069	8	2.2498	RODEIRO - MG

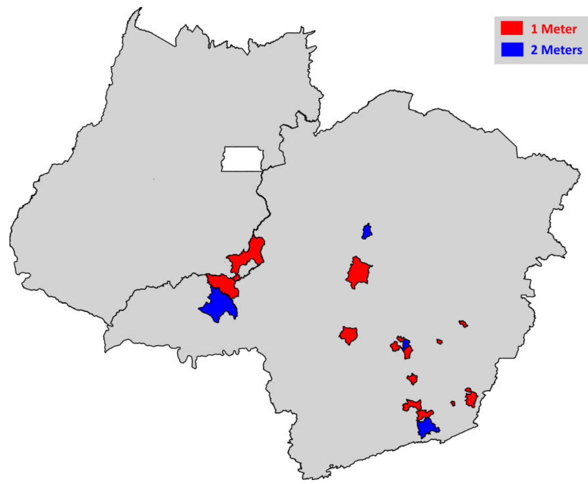

FIGURE 12. Geographic distribution of meters in the RJ/ES Area (Area: 586,513.983 km^2; Population: 20,539,989).

of the states of São Paulo, Rio de Janeiro, EspÍrito Santo, and Minas Gerais. On the other hand, it was expected that metropolitan areas of the respective capitals would present a larger number of indicated meters, as these represent the larges consumption centers. This expectation is confirmed in the results obtained.

V. CONCLUSION

This study proposes a method for prioritizing buses indicated for the placement of PMU meters outside of the main network, aiming to improve load modeling and to enhance the monitoring coverage of the TSO. The prioritization strategy took into account the amount of load, DERs, and the electrical impact of probable system disturbances. Initially, the procedure was tested on the 107-bus AC-DC equivalent system as a proof of concept. Based on this investigation, it was determined that regionalizing the ranking is critical for identifying the priority of locations across all areas and voltage levels. Additionally, an approach to ensure geographical diversity in meter deployment was developed.

To apply the approach to the BIPS, the ONS provided operational and contingency data, as well as information on electrical areas, target meter numbers, and pre-disturbance operating point Jacobian matrices. A diversified meter allocation strategy based on sensitivity was then created and used in the procedure. This technique efficiently avoided unnecessary meter placements by identifying buses whose behavior could be inferred from measurements at locations with higher priority. The methodology was designed with two key objectives: to ensure adequate coverage of each area by prioritizing significant load centers and to maintain the geographical diversity necessary for robust load model validation. This approach goes beyond simple heuristics based solely on load density, ensuring more strategic coverage for robust model validation. For this purpose, the methodology proved effective, allocating a greater number of meters to the metropolitan regions of São Paulo and Rio de Janeiro, for example, with the remaining meters distributed across the whole geoelectrical area under consideration.

The method relies only on static analysis data, so the computational burden becomes feasible for a large-sized system such as the BIPS. The simulation network of the BIPS comprises over 12,000 buses, more than 170,000 km of high-voltage transmission lines ($\geq$230 kV), and a load range varying between 50 and 105 GW.[1] This approach was applied to all geoelectrical zones of the country without requiring excessive demands on human resources or computation time. However, validation using dynamic RMS simulations for severe disturbances is recommended to ensure that the post-disturbance operating condition contains a stable equilibrium point for the system.

It is important to remark that the ranking method described in this paper can be easily adapted for applications to other countries with similar problems of load modeling and an institutional arrangement that permits the sharing of data between TSOs and DSOs. The key degrees of freedom in the methodology – including the weighting factors for electrical influence and load amount, and the sensitivity threshold – were designed to address the inherent regional heterogeneity of large-scale systems. These parameters provide the operator with the flexibility to prioritize different system features and to ensure geographical diversity, aligning with the specific objectives of the respective TSO.

Although based exclusively on static analysis results, the present methodology is an important first step in the allocation of PMUs outside the bulk power grid in large-scale systems. A natural development of this research includes the application of dynamic analyses, where data from these initial PMU installations will be used to better define load dynamic behavior and guide the placement of additional meters for load model validation. The application of post-contingency data will also be explored to improve method accuracy, along with the development of computational strategies to reduce the computational burden, ensuring the method remains feasible for practical applications to large systems.

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