Impact of the State Estimation in Different Scenarios and Topologies in a Power Distribution System

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***Abstract*—The acquisition of data in the scope of distribution system is extremely important for the operation of the electrical system, due to this be the most complex segment in Brazil and for being study object growing within the evolution directed to smart grids. In this scenario, the importance of obtaining information that directly influence the analysis of real-time monitoring variables is verified. However, the large-scale allocation of meters along the distribution network becomes an impractical practice due to the cost of these equipment. Within this context, the State Estimation (SE) method comes as a great allied, because it employs methods such as power flow to obtain data in places where no meters are available. In addition, their location directly affects the quantity and relevance of the information provided for system observability. Therefore, this article highlights the analysis of a low voltage Power Distribution Systems (PDS) from the SE perspective. In this way, it is tried to change the arrangement of the meters and the quantity of the meters in the network, to apply an Index of Increase in State Estimation Accuracy (IISEA). In summary, the impact of the remote measures in the estimation of states is evaluated, aiming, to obtain conclusions that help in a better view of the general panorama of the network. For this reason, focusing on the analysis of the impact of remote measurements in the estimation of states in PDS, the *DIgSILENT PowerFactory 2017* software is used to obtain the results.**

Keywords*—*DIgSILENT PowerFactory, State Estimation, Power Flow, Remote Measurements, Power Distribution Systems.

I. INTRODUCTION

The Brazilian territory is covered by a large and complex Electric Power System (EPS) that has its bases consolidated in the areas of generation, transmission and distribution of electricity, and are the main structure of service to all sectors of consumption in the country. According to data from the Brazilian Institute of Geography and Statistics, Brazil has a population projection of about 209 million inhabitants [1], and no year 2008, about 95% of the population already had access to electric network, of which 85% are in the residential sector [2].

On an annual basis, power utilities recorded high technical and commercial losses (losses that inevitably appear) and by 2015, Brazil had more than 77 million "Consumer Units" [3]. In this way, it is evident the great importance of research and investments in the distribution segment.

In the context of EPS improvement, in the middle of the 20th century, the concept of smart grids emerged, defined as a futuristic, integrated and innovative upgrade strategy consumer flavor [4]. Within the group of characteristics contained in smart grids are energy storage, real-time monitoring, demand side scheduling, network reconfiguration, Distributed Generation (DG), smart meters, real time consumption, energy efficiency, alternative energy sources and a new technologies and tools allied to the Electric Energy Distribution Systems (EEDS) [5]. One of the concepts that establishes a basis of the smart grids is a more comprehensive monitoring of them in real time. However, the EEDS, especially the Brazilian ones, are very complex for a short and medium term to have total monitoring.

The function of the State Estimator (EE) is to merge remote measurements with other pseudo measures, acquired by historical and topological data and for direct methods such as power flow calculation. In general terms, state estimation comprises real measures with pseudo measures. Therefore, with these two sources of information together, one can determine the current state of the system.

The measures obtained by the method of SE are of paramount importance, since they can effectively describe the situation of certain points of EEDS. The large-scale allocation of meters along the distribution network becomes an unfeasible practice due to the cost of these devices, being that the EE employs methods such as power flow to obtain data in places where no meters are available. In addition, the location of meters directly affects the quantity and relevance of the information provided for system observability. To the detriment of these factors, it is necessary to evaluate the impact of the meters in the estimation of states, because they may contain errors associated with the information provided or if they are poorly allocated in relation to the network configuration.

For this reason, focusing on the analysis of the impact of remote measurements in the estimation of states in SDEE, the DIgSILENT PowerFactory 2017 software is used to obtain the results. This program has as one of its applications, besides generation, transmission, distribution and GD systems, the state estimation method. In this work, therefore, different configurations and arrangements of smart meters will be studied

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along a distribution network, using the state estimation method and an Index of Increase in State Estimation Accuracy (IISEA).

II. State Estimator in Distribution Systems

The classical methods of SE are widely applied in transmission systems. However, it should be noted that when the methods are employed in EEDS (which have a radial structure) convergence problems can occur [4]. Among the characteristics of the distribution network, which give great challenges to the implementation of the presented methods, the following stand out:

- Spacing of the admittance matrix caused by the radial structure of the system.
- Equipment with low impedance (switches and other maneuvering devices).
- Relation between reactance and resistance of conductors.
- Sections with high impedance.

In a general context, even with the presentation of the difficulties encountered to consolidate the SE in the distribution area, state estimation has become not only a challenge to EEDS, but also a great allied to the requirements of operation, observability, maintenance, identification and detection of network problems.

A. Index of Increase in State Estimation Accuracy

Milbradt [5] determined an Index of Increase in State Estimation Accuracy (IISEA), which was based on the average of all the uncertainties of the measures used in the estimation, besides being weighted by their weight. The objective of the development of this index lies in the precise installation of a meter at one point within the network, to obtain remote measurements to improve the solution of the estimator at that point. Therefore, to consolidate the objective in question, the impact of the uncertainty of a measure and other pseudo measures of the system should be positive, concluding that there will be benefits in the installation of a meter at the point under analysis [4]. The IISEA can be obtained, according to (1).

$$\text{IISEA} = \frac{\sum_{i=0}^{n} \delta_i W_i}{\sum_{i=0}^{n} W_i} \quad (1)$$

At where the variables are defined by:
δ_i: Percentage of uncertainty associated to measure i;
W_i: Weight associated with measure i.

It should be noted that there is no mathematical/vector study that proves the (1), however the equation is considered in the same way for units obtained from the meters individually. In addition, the application of the same will be used to obtain possible solutions to improve the state estimator, since the lower the value calculated for the index, the better the state estimation, because the number of errors and uncertainties is smaller. Likewise, the larger the IISEA, the greater the number of uncertainties in the network or measurement errors, opening space for identification of more precise points for allocation and/or insertion of measurement devices.

B. Analysis of meters by the Estimation Method

The DIgSILENT PowerFactory software provides an example of SE in its database based. That example contains three case studies, which are defined by measures without disturbance, measures with disturbances and the case of non-observability of the network. The first case would be, in the real system, a network with error-free measurements at all points of interest. In the second case, current, active and reactive power measurements are obtained, but the values have disturbances and deviations, which interferes with accuracy of the results. In the third case study, there is a network non-observability scenario, since several measurements were taken from the configuration models where convergence is not completed for the measurement points.

It should be noted that the three case studies provided by the software are evaluated within the same simulation scenario defined by a network model representing a small MV and LV distribution system as shown in Fig. 1. The system is supplied by a substation with two transformers in parallel that make the HV/MV connection (one of the transformers is in standby mode). In addition, the EPS of the example is divided into three voltage levels: 115 kV - HV (substation bus - red color), 20 kV - MV (industrial area and sub transmission - green color) and 400 V - LV (other loads - blue color) and operates at 50 Hz.

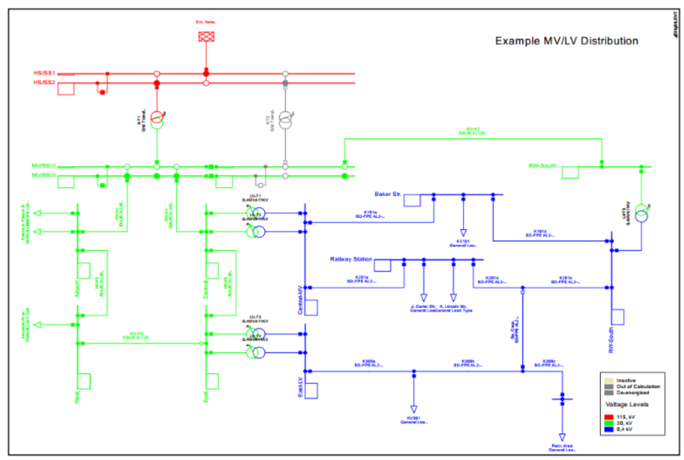

Fig. 1. Base scenario of the MT/LV distribution network.

In this work, the second case study provided by the DIgSILENT PowerFactory 2017 (that is defined by measures with disturbances) will be considered. This case approaches a model closer to the real one because it considers imperfections in the measurements obtained. In this way, it was sought to take as initial information the results obtained for the disturbed measurements environment, where the simulation base scenario is modified (in relation to the original) and presented in Fig. 2.

According to the simulation environment presented in Fig. 2, it should be noted that there were 16 irregular measurements within the 25 smart meters used, being 7 measurements of P, 7 measurements of Q and 2 measurements of I, as shown in Fig. 4. In addition, we can observe all the results, for the network under analysis, in TABLE I. .

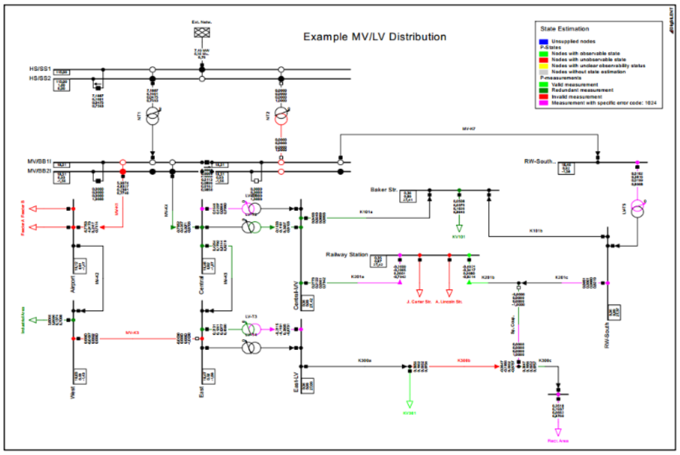

Fig. 2. Modified base scenario for measures with disturbances.

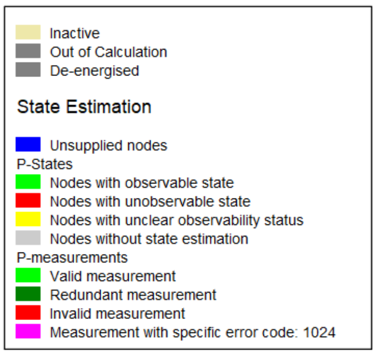

Fig. 3. Legend of State Estimation.

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'Distribution Power System\MV\Cub 1\Cub 1\Qmea  (MV-K1; BB21).StaExtqmea'
'Distribution Power System\K300\Term. Strip 2\Cub 2\Imea  (K300c; Term. Strip 2).StaExtimea'
'Distribution Power System\K300\Term. Strip 2\Cub 3\Pmea  (Sp. Coup.; Term. Strip 2).StaExtpmea'
'Distribution Power System\Central\Cub 6\Pmea  (LV-T1; Central).StaExtpmea'
'Distribution Power System\Central\Cub 6\Qmea  (LV-T1; Central).StaExtqmea'
'Distribution Power System\East\Cub 2\Qmea  (LV-T3; East).StaExtqmea'
'Distribution Power System\East-LV\Cub 1\Pmea  (LV-T3; East-LV).StaExtpmea'
'Distribution Power System\RW-South\Cub 6\Imea  (K201bc; RW-South).StaExtimea'
'Distribution Power System\RW-South\Cub 6\Pmea  (K201bc; RW-South).StaExtpmea'
'Distribution Power System\RW-South\Cub 6\Qmea  (K201bc; RW-South).StaExtqmea'
'Distribution Power System\RW-South MV\Cub 4\Pmea  (LV-T5; RW-South MV).StaExtpmea'
'Distribution Power System\RW-South MV\Cub 4\Qmea  (LV-T5; RW-South MV).StaExtqmea'
'Distribution Power System\Railway Station\Cub 2\Pmea  (K201a; Railway Station).StaExtpmea'
'Distribution Power System\Railway Station\Cub 5\Imea  (K201bc; Railway Station).StaExtimea'
'Distribution Power System\Railway Station\Cub 5\Qmea  (K201bc; Railway Station).StaExtqmea'
'Distribution Power System\Recrat.\Cub 1\Pmea  (Recr. Area; Recrat.).StaExtpmea'
'Distribution Power System\Recrat.\Cub 1\Qmea  (Recr. Area; Recrat.).StaExtqmea'
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Fig. 4. Irregular measures found in the network.

TABLE I. RESULTS FOR THE BASELINE SCENARIO.

Analysis Point	*P* (MW) Measured	*P* (MW) Calculated	Deviation (%)
Industrial Área → West	3,0075	3,0066	0,0290
K101a → Central-MV	0,0822	0,0493	39,9788
K201a → Central-MV	0,3053	0,2773	9,1685
K201a → Railway Station	0,1989	0,2699	35,6883
K201bc → RW-South	0,5973	0,5051	15,4367
K201bc → Railway Station	0,5411	0,4921	9,0549
K300b → Term. Strip 1	0,3237	0,3556	9,8305
K300b → Term. Strip 2	0,4529	0,3547	21,6803
K300c → Term. Strip 2	0,4004	0,3547	11,4102
KV101 → Baker Str.	0,0525	0,0508	3,2355
LV-T1 → Central	0,0909	0,1644	80,8195
LV-T2 → Central-MV	0,1800	0,1633	9,2637
LV-T3 → East	0,2077	0,2131	2,6033
LV-T3 → East-LV	0,2737	0,2115	22,7324
LV-T5 → RW-South MV	0,6057	0,5102	15,7706
MV-K1 → Airport	6,0160	5,7753	4,0004
MV-K1 → BB2l	6,2204	5,9074	5,0323
MV-K3 → East	0,0900	0,0000	100,0000
MV-K3 → West	0,0700	0,0000	99,9984
MV-K4 → Central	0,7424	0,7552	1,7244
MV-K5 → Central	0,4656	0,4264	8,4135
NT2 → BB1r	0,0950	0,0000	100,0000
Recr. Área → Recrat.	0,5050	0,3518	30,3377
Sp. Coup. → Term. Strip 2	0,0500	0,0000	100,0000
Sp. Coup. → Term. Strip 3	0,0200	0,0000	100,0000

III. METHODOLOGY

A. *Determination of measurement weight*

Considering the measures of TABLE I. , it is tried to determine a criterion of weight to be applied to the IISEA. Therefore, two weight criteria are evaluated, in which the IISEA is applied to each of them, to select the most concise to be used later in the network analysis.

1) *Equal weights for measurements*

In this criterion, a weight equal to all the measures found in the network was attributed, that is, defined by a unit equivalent to 1 per unit (*p.u.*). Thus, the IISEA is applied for the measurements obtained in TABLE I. , considering the percentage of uncertainty of each measure.

$$IISEA = 33{,}4484\%$$

2) *Weight defined by power in meters*

In addition to the egalitarian criterion, it was tried to consider the calculation of the IISEA in relation to the active power measured in the network meters. For this, the final weight of the measurement is a linearization *p.u.*, based on the largest absolute value found among the measurements acquired only by the meters. In this way, the values found in TABLE II. can be observed.

$$IISEA = 8{,}2822\%$$

The IISEA is calculated on the standardized remote measures in *p.u.* as a weight criterion. This indicator is more representative, since it considers the proximity to the centers of load.

TABLE II. ANALYSIS OF THE MEASUREMENTS BY THE POWER CRITERION IN THE METERS.

Analysis Point	*P* (MW) Measured	Per Unit (*p.u.*)
Industrial Área → West	3,0075	0,4835
K101a → Central-MV	0,0822	0,0132
K201a → Central-MV	0,3053	0,0491
K201a → Railway Station	0,1989	0,0320
K201bc → RW-South	0,5973	0,0960
K201bc → Railway Station	0,5411	0,0870

Analysis Point	*P* (MW) Measured	Per Unit (*p.u.*)
K300b → Term. Strip 1	0,3237	0,0520
K300b → Term. Strip 2	0,4529	0,0728
K300c → Term. Strip 2	0,4004	0,0644
KV101 → Baker Str.	0,0525	0,0084
LV-T1 → Central	0,0909	0,0146
LV-T2 → Central-MV	0,1800	0,0289
LV-T3 → East	0,2077	0,0334
LV-T3 → East-LV	0,2737	0,0440
LV-T5 → RW-South MV	0,6057	0,0974
MV-K1 → Airport	6,0160	0,9671
MV-K1 → BB2l	6,2204	1,0000
MV-K3 → East	0,0900	0,0145
MV-K3 → West	0,0700	0,0113
MV-K4 → Central	0,7424	0,1193
MV-K5 → Central	0,4656	0,0748
NT2 → BB1r	0,0950	0,0153
Recr. Área → Recrat.	0,5050	0,0812
Sp. Coup. → Term. Strip 2	0,0500	0,0080
Sp. Coup. → Term. Strip 3	0,0200	0,0032

B. Changing meter locations

The location of the 25 meters evaluated in the base scenario was modified, to establish two different provisions for the same scenario, to present the results below. In addition, the disposition of the meters in this study was chosen in a random manner, without any allocation criteria. Below is the configuration of two meters layout models, as highlighted in Fig. 5 and Fig. 6.

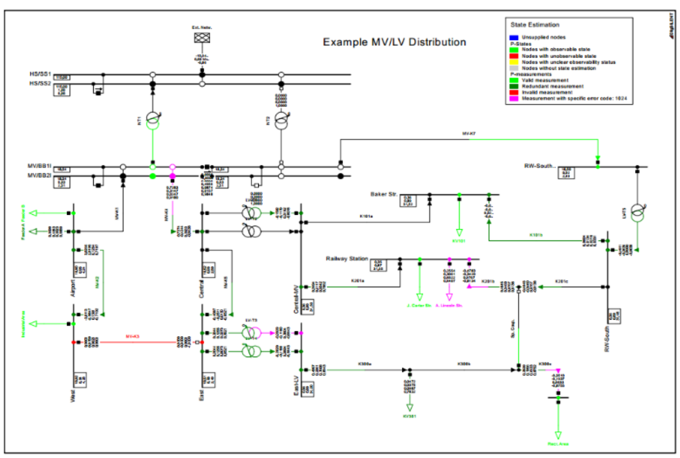

Fig. 5. First arrangement of meters in the network.

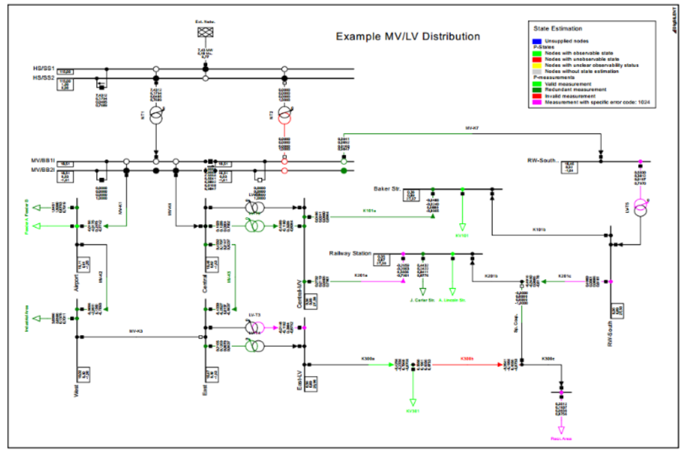

Fig. 6. Second arrangement of meters in the network.

C. Changing the number of remote measurements

To establish a more comprehensive assessment of the impact of the remote measures on the distribution network under analysis, it is sought, in addition to the modification of the location of the meters along the EPS under study, to increase the number of meters in it. Therefore, we try to simulate the scenario for 32, 40 and 50 meters, seeking to apply the IISEA and obtain the results to be presented. Therefore, to observe the evolution of the precision increase indicator, the base scenario with the addition of meters is provided by Fig. 7, Fig. 8 and Fig. 9. It should be noted that the addition of the meters was chosen in a random manner, without any allocation criteria type.

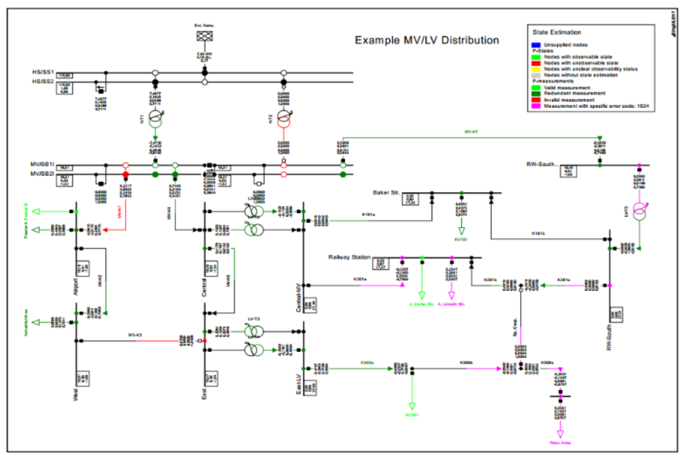

Fig. 7. Distribution network with 32 meters.

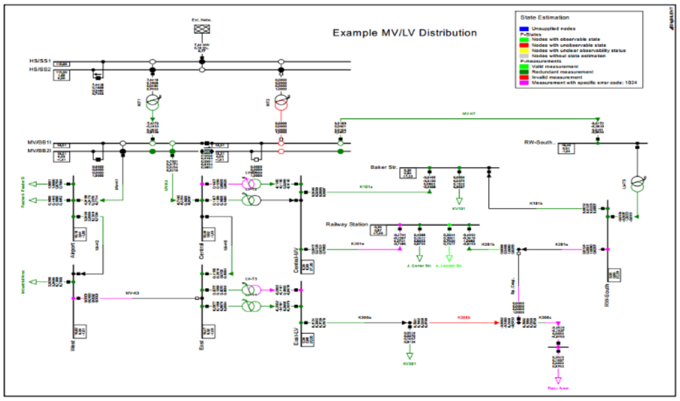

Fig. 8. Distribution network with 40 meters.

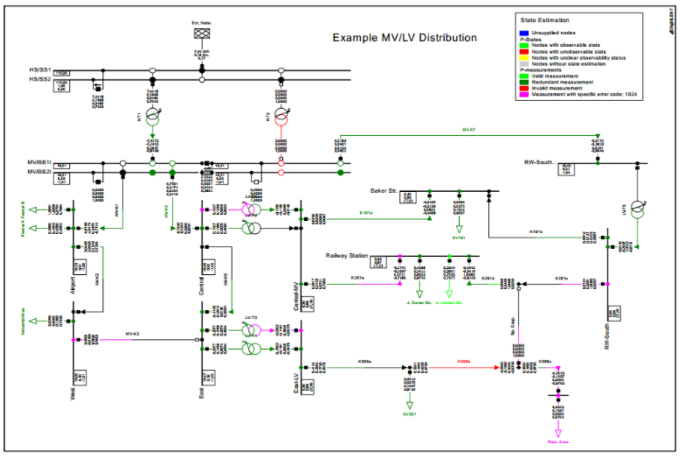

Fig. 9. Distribution network with 50 meters.

IV. Results

A. *Change in the Disposition of Meters in the Network*

For each case study, defined by the array and number of meters in the network, the *PowerFactory* software provides output results for all measures points, including the irregular measurements, as the scenario is defined by measures with disturbances. According to the random location of the 25 meters, indicated by Fig. 5, the first array of meters in the network was established. This structure seeks to provide the results for a different configuration of the basic network. Applying the IISEA (1) in the data obtained by the simulations, it was verified that for this condition, the index has a value of **8.2822%**. Still, of these 25 meters, 12 presented irregularities.

To obtain more information, in comparison to the two previous environments, a second arrangement of meters in the network was sought. The location of the meters along the network can be observed in Fig. 6. In the same way, the IISEA (1) was applied to the data obtained by the simulations and the index is **5.7344%**. For this case, 25 meters showed irregularities as well. Therefore, in relation to the disposal scenarios, the second is the least affected by irregularities, since it presents a smaller IISEA. In addition, we can see the difference of the values in relation to the base scenario, according to TABLE III.
.

TABLE III. Comparison of IISEA for each array of meters in the network

Measurement layout	IISEA (%)
Base Scenario	8,2822
First disposition	5,7344
Second disposition	4,8064

B. *Variation of Meter Amount*

In addition to the change in the arrangement of the meters in the EPS, it was sought to add meters in the network at random. Thus, the environments defined by Fig. 7, Fig. 8 and Fig. 9 for 32, 40 and 50 meters, respectively, were implemented. Therefore, it is possible to determine the results using the software output report and following the methodology of translating these values to *p.u*.

In the case of 32 meters, it was verified that 17 measures became irregular; for the case of 40 meters, 22 measures presented irregularities; and for the case of 50 meters, 26 measurements became irregular, respectively.

Therefore, the IISEA was calculated by considering the number of measurements in each configuration, presenting the results in TABLE IV. . Among the four values calculated for the index (considering the base scenario), the scenario of 32 meters is the least affected by the disturbances.

TABLE IV. Comparison of IISEA for each number of meters in the network

Numbers of meters	IISEA (%)
25 (Base Scenario)	8,2822
32	3,7669
40	4,4845
50	4,2138

V. Discussion

Among the values calculated for the IISEA in TABLE III. and in TABLE IV. , it is observed that the addition of meters resulted in improvements in the observability of the network, since the best index reached for that case (arrangement of 25 meters) was **4.8064%**, while that for all incremental quantities of meters, the calculated values by the index were smaller. In view of this, the increase of remote measures in the EPS under analysis, caused an improvement in the estimation of states.

Besides that, the case of 32 meters in the network was pointed out with smaller deviations and uncertainties. For 32 meters, a total of 17 irregular measurements were determined, for 40 meters there were 22 irregular measurements and for 50 meters, 26 irregularities were obtained. Therefore, it should be noted that even with more meters in the network for cases of 40 and 50 measurement devices, the number of irregularities and deviations observed was higher than the number of 32 meters. In the case of meter arrangement, high deviations lead to greater uncertainties, as well as lower measured power values and proximity to several incorrect measurements, result in a higher IISEA value.

VI. Conclusions

To approach the state estimation method within the energy distribution systems, an analysis of the impact of remote measurements in the estimation of states within a small distribution network provided by *DIgSilent Power Factory 2017* software was elaborated. Within this network, which is an example of the program database, the case study of measures with disturbances was selected, which was modified for the simulations and obtaining the results.

The environment elaborated for the change in the array of meters in the network, presented the second provision as scenario less affected by disturbances. The IISEA calculated varied around **4,8064%**, being observed 12 measures with disturbances in the simulation. In this way, as the number of uncertainties and deviations are lower, besides the power measurements are close to the higher loads, the index is lower, resulting in a more stable operating environment for the measurements obtained at the points where there are meters.

In addition to this, the addition of meters in the network provided a considerable improvement compared to previous scenarios, as well as identifying more precise points of measures, and indicated places where improvements are needed. The lowest IISEA achieved, among all the simulation scenarios, was **3.7669%**, for 32 meters in the network, with 17 irregular measures. Although the environments configured for 40 and 50 meters show more measurements within the same analysis scenario, they have more disturbances and deviations. Therefore, the values of **4.4845%** and **4.2138%** of IISEA, for 40 and 50 meters, respectively, showed possible points for improvement (reallocation of meters) in front of observed deviations.

Therefore, it is concluded that the arrangement and quantity of remote measures along the distribution network directly affects the estimation of states. Considering the IISEA, by the criterion of weight, it is observed that the same gets worse, due to many high deviations in the measurements, distancing of the centers of load or proximity of large loads with incorrect measurements, misallocated meters, low number of information on network and errors from the meters themselves, among other possibilities. On the other hand, the index improves with the decrease in deviation values, with a proximity to large load centers with precise measurements, well-allocated and calibrated meters, instrumentation errors absence, and, course, the increase in the number of remote measurements.

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