POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Input Data for a State Estimation Algorithm

LAUREA MAGISTRALE IN ELECTRICAL ENGINEERING - INGEGNERIA ELETTRICA

Author: Valentina I. Garcia Castro

Advisor: Prof. Gabriele D'Antona

Academic year: 2023-2024

---

1. Introduction

Nowadays, the electrical network is not the same as it used to be. Initially, the generation of electrical energy was **centralized**; nevertheless, this panorama has changed over time, and the generation is increasingly becoming **decentralized**. With this being said, is logical to think that the way in which the network has been analyzed and managed has also suffered some alterations; changes that are necessary to keep track of the numerous advances of the network, making it more intelligent every day. One of those changes is, for example, the necessity to make State Estimation analysis (SE) also to the low voltage grid and not only to the transmission network, as it was in the past.

The objective of this project is to to prepare the input data for an algorithm to develop state estimation on a low-voltage distribution network, using the IEEE-906 low-voltage feeder, as it will be shown in the next sections.

2. Literature Review

For the operation of any electrical power system, control and decision-making processes need real-time data; for this matter, a real-time computer with a model of the network (Central Control System) and a data acquisition system (meters) are used [3]. These control systems can be classified into two types:

- Raw System
- Estimation System

Regarding the latter, only the quasi-steady state or static operation of the power system is considered, hence the process is called: Static-State Estimation (SSE).

It should be said that the SSE results as a combination of 2 fields: **electrical network modeling** and **statistical estimation theory**. whose goal is converting the "prior knowledge" x^- and the available measurements z, such that $z(x) \sim p(z|x)$, into "posterior knowledge" x^+, which probability density function can be evaluated at present time. For this purpose, the *"State Estimator"* should be capable of the following processes.[1]

1. Filtering Measurements: A set of rudimentary techniques are carried out to detect and discard measurements that are erroneous or confusing.
2. Modelling the network: Based on the status of the switches and breakers and the physical layout of the substations it is modeled the structure of the electrical network model.
3. Analyze observability: Determine whether the system's state can be obtained using the measurements available.
4. Estimate: Calculates the state that best

adapts the measurements captured remotely.
5. Detect the errors: Based on certain statistical properties of the estimation, this function detects the presence of possible errors in the set of measures. If redundancy is adequate, these measures can be identified and eliminated.

In some cases, such as the case of electrical networks, the complexity of the measurement model makes it very difficult to obtain the PDF, therefore the best way to describe the behavior of the meter is to use the mode, mean, and median of the set of measurements ($\tilde{x}$), these values are also called **estimates** of the measurand x, while the function to convert the data into the estimates is called **statistic**.[2]

3. Study Case

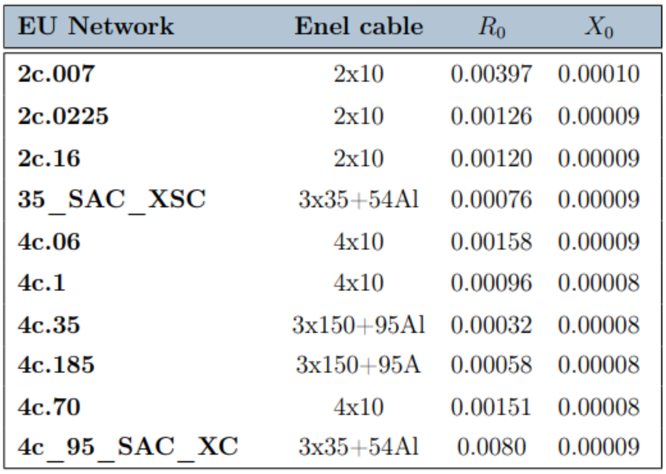
In this project, the goal is to prepare the input data for an algorithm to estimate the state of an LV grid. For that purpose, the IEEE European low voltage test feeder is used. The following sections will give an overall description of the mentioned network and the assumptions that have been taken into account to achieve the main goal.

3.1. IEEE 906 LV Network

The first and only model that is now accessible for research and studies at the distribution level in Europe is the IEEE European LV Test feeder. Since an extensive knowledge of the operational condition of the DN is vital for its management and control, this model is frequently utilized for the study and planning of Low Voltage (LV) distribution networks. The European low-voltage test case was developed to meet the following features:

- Phase to phase voltage of 416 V.
- 24h load profile.
- Time-series simulation results over one day and static power flow calculation results at some key moments are provided.

The model is composed of 906 low voltage nodes, connected to the MV system by a Step-down transformer, radially connected by 905 branches along with 55 load buses, each one provided with the load shapes of 24-hour data with 1-minute time intervals for single phase loads: distributed so: 21 for phase A, 19 for phase B, 15 for the phase C. The distribution lines are defined by codes (See 1, EU Network) and their length, each code specifies the zero-sequence resistance and admittance, nevertheless, there's no available information about the geometry of each conductor, reason why some modifications were carried out to make this network a suitable input for the state estimation algorithm that is going to be used.



EU Network	Enel cable	R_0	X_0
2c.007	2x10	0.00397	0.00010
2c.0225	2x10	0.00126	0.00009
2c.16	2x10	0.00120	0.00009
35_SAC_XSC	3x35+54Al	0.00076	0.00009
4c.06	4x10	0.00158	0.00009
4c.1	4x10	0.00096	0.00008
4c.35	3x150+95Al	0.00032	0.00008
4c.185	3x150+95A	0.00058	0.00008
4c.70	4x10	0.00151	0.00008
4c_95_SAC_XC	3x35+54Al	0.0080	0.00009

Figure 1: Matching Enel and IEEE Codes

To start, given that the geometry of the conductors used to model the IEEE-906 network is not available, and this information is needed to compute the inductance for each branch, necessary to have a better estimation, for this project will be introduced a change of the conductors, using commercial Enel cables, as shown in Table 1. The matching was based on the per-length unit resistance and admittance, and the structure of the cable (number of phases and neutral).

Then, with this modification, we gathered all the required data to compute the needed information, such as:

- Topology of the feeders.
- Branches impedances: resistance and self & mutual inductances. (Next Section)
- Network working conditions.

3.2. Impedance Matrix Computation

The Figure shows all parameters of a three-phase line, as in the network of study.

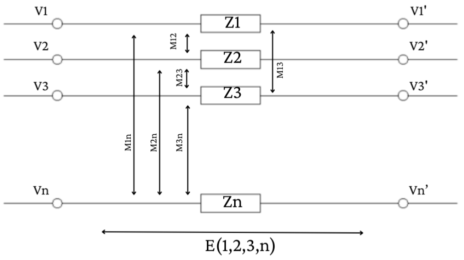


Figure 2: Representation of a three phase feeder

From the above scheme, using Kirchhoff's laws we will have

$$\begin{cases} V_1 - E_1 - V_1^{'} + E_1^{'} = 0 \\ V_2 - E_2 - V_2^{'} + E_2^{'} = 0 \\ V_3 - E_3 - V_3^{'} + E_3^{'} = 0 \end{cases} \tag{1}$$

$$\begin{cases} I_1 + I_2 + I_3 + I_n = 0 \\ I_n = -I_1 - I_2 - I_3 \end{cases}$$

From this we can express:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_n \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \end{bmatrix}}_{C} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

$$I_{4x1} = C_{4x3} * I_{3x1} \tag{2}$$

By the ohm law, we can also say $E = Z * I$, therefore:

$$E_{4x1} = \underbrace{R_{4x4} + jL_{4x4}}_{Z_{4x4}} * I_{4x1} \tag{3}$$

Now, from 1 we can say in general $V' = V - (E - E^{'})$, so in this way:

$$V_{3x1}^{'} = V_{3x1} C_{3x4}^{T} * E_{4x1} \tag{4}$$

Replacing 3 into 4, we will have

$$V_{3x1}^{'} = V_{3x1} - C_{3x4}^{T} [Z_{4x4} * I_{4x1}] \tag{5}$$

And replacing 2 into 5, it becomes:

$$V_{3x1}^{'} = V_{3x1} - \underbrace{C_{3x4}^{T} * Z_{4x4} * C_{4x3}}_{Z_{3x3}} * I_{3x3} \tag{6}$$

Now let's work on the portion of 6 that we called Z_{3x3}, since $Z_{4x4} = R_{4x4} + jL_{4x4}$ we will have:

$$Z_{3x3} = C_{3x4}^{T} * [R_{4x4} + jL_{4x4}] * C_{4x3}$$

Where

$$R_{3x3} = C_{3x4}^{T} * R_{4x4} * C_{4x3}$$

and

$$L_{3x3} = C_{3x4}^{T} * L_{4x4} * C_{4x3}$$

The impedance matrix of each line of the system will be computed following the above steps and having into account the commercial enel conductor parameters.

4. Simulations and results

The computed data serves to build the impedance matrix for each feeder of the network, information that is useful for the computation and estimation of the state of the system. In this section, the steps to prepare the input data for a state estimator will be described.

The estimation process starts by filtering the measurements, for that purpose, a dataset of measurements should be available. In the current study case, we are supposing that the power of the loads is known due to the "smart meters" installed in the points of consumption. Another available data is the voltage value in the slack bus, understanding the slack bus, as the secondary substation, where the LV network starts, usually provided of voltmeters.

On the other hand, the accuracy of the estimation depends on the measurements that are gathered. These measurements are affected by errors from different sources, and unless these erroneous data are identified, the estimated state can be deficient. Therefore, some preliminary steps should be run before executing the estimation.

State estimators should have filters to find obvious inconsistencies in the set of measurements and correct them or delete the data. This step was also performed by the algorithm under study. With the filtering, errors in measurements are evaluated before the estimation process, being identified directly from the measurement value.

Another important step was checking the observability. As mentioned before, observability consists on clearly defining the different zones of a system, analyzing the available data. In this case, since the available measurements that were linearly independent were less than the state variables; after analyzing the observable zones of the system, some virtual measurements were defined. The virtual measurements were the voltages, it means it was assumed that in every node there was a voltmeter, letting us know that the voltage of the bus was, initially the same as in the slack bus.

Now, let's see how to deal with errors during the estimation process. It is common, to make the following assumptions on the statistical properties of measurement errors:

- Errors follow a normal distribution-.
- The expectation of the error is zero, it means $E(e_{1,2,\ldots,m}) = 0$, where m is the number of measurements, in this case, the powers at the load and the voltage at the slack bus, as shown before.
- errors are independent.

For this case, since no physical meter was installed, and therefore the accuracy can not be determined, it was assumed an accuracy equal to the analog meters, that can vary from 1% to 5%. This accuracy represents the standard deviation of the error σ_e and therefore is possible to compute with this value the covariance matrix.

After using the data computed, and the available data for the 906-Network, the following results were obtained, regarding the voltages (See Figure 5) and the currents flowing through the branches(See Figure 3). As expected, branches currents are decreasing downward the source bus, and for each phase, on the ramifications, the currents on the branches are zero, if the load is not connected to that phase. In this sense for example, in Figure 4, it is shown a comparison plotting of the branches currents, for the three phases, and it is indicate the value of the corrent on branch 33, branch that is connected to the Load1 in phase A, therefore, for phases B and C the current flowing is, as expected 0.

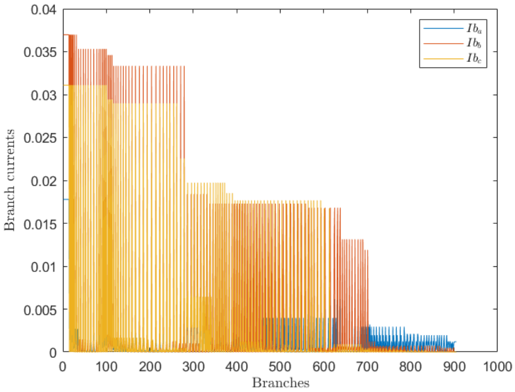


Figure 3: Branch currents on the three phases - comparison

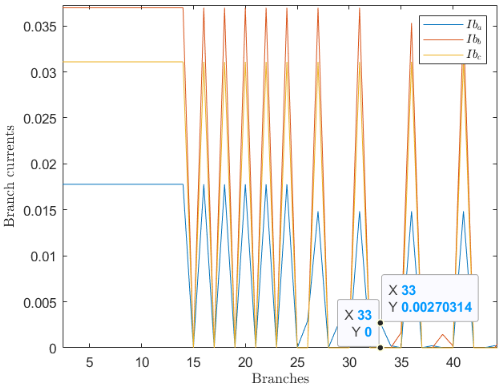


Figure 4: Branch currents on branch 33 - comparison

The same thing happens with the voltages on every node. For each phase, it is shown a different voltage level, this, because the voltage drop on each branch is proportional to the current flowing in the same. However, this aspect, evidences an imbalance of the system, which can cause damages on the different equipment.

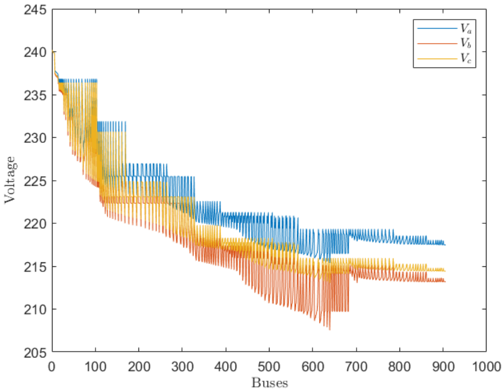


Figure 5: Voltages on the three phases-comparison

5. Conclusions

Ever since the State Estimation idea was first developed in the 1970s, it has been an essential component of electrical system management and operation worldwide. As it was mentioned before on this document, the subject of state estimation in distribution networks was a completely forgotten topic, but recently since there was insufficient funding, it has been gaining more interest. Furthermore, it should be mentioned that traditional distribution networks were passive systems with unidirectional and predictable energy flows, nonetheless, the integration of distributed energy resources is growing at an increasing rate, drawing the interest of multiple academics to this issue.

The objective of this document, in addition to summarizing the evolution of this problem since its interest arose until now, was to prepare a low-voltage network, that was initially developed to be used for a different purpose, but that given its structure, was also usefull to be used as input for an estimation algorithm.

The coherence of the system, to be used for this purpose, was proved by running the estimation, and obtaining expected results. In this sense, it was observed that voltages and currents respect all the electrical laws. For example, the relation between current and voltage, was always respected; moreover it was always evident that since the network was passive, and not distributed generation was present, there were not risings on voltages, and instead the voltages decrease always in the direction of the load, while, voltages increases in the direction of the source.

the results obtained after running 5 iterations presented a minimum error (less that 1%), compared with the results obtained after mathematical computations; and this is explained by the precision of the methods that were used: Matlab and a cientific calculator. Therefore the results were very acceptable

Moreover, the project's outcomes have created opportunities for further research, since the obtained system is a complete input and this is the very first step to test different methods for estimation. Besides, the proposed algorithm can be also used to obtain a variety of parameters of the network, for example it can be thought to realize further development on the algorithm to obtain the thermal state, given the electrical state. It can also be used to propose a different solution according to the developments in algorithms that provide advances and open future lines of research.

References

[1] Milan Prodanovic Barry Hayes. State estimation techniques for electric power distribution systems. *8th European Modelling Symposium*, 2014.

[2] Gqabriele D'Antona. Class notes - estimation, 2021-2022.

[3] John Peschon Robert E Larson, William F. Tinney. *State Estimation in Power Systems.* IEEE Transactions on Power Apparatus and Systems, 1970.