INTELLIGENT STATE ESTIMATOR SYSTEM FOR DISTRIBUTION SYSTEMS

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ABSTRACT

This paper presents a distribution system state estimation (SE) algorithm for application to radial distribution networks. This method exploits the radial nature of the network and uses forward and backward propagation scheme to estimate the line flows, node voltage and loads at each node, based on the measured quantities.

The SE applied is the Weighted Least Square approach (WLS) and some techniques where applied to allow the SE for distribution systems, such as, the method proposed uses the branch currents as the system state and the introduction of pseudo measurements from historical load data produced based on customer billing data through statistical processes.

INTRODUCTION

Electric utilities require better management and control of the distribution network to evaluate and reduce energy losses, which represents an important challenge for distribution companies in Brazil. It relies on having knowledge of the state of the distribution circuit. For this, many systems have been installed on the distribution systems that can be used for analysis and control. However, economical limitations and measurement problems make it impossible to have a perfect picture of the system. Measurement instruments cannot be installed every place where they are needed and the measured data are subject to error, so the data may be incomplete, inaccurate and unreliable. Therefore, a research and development (R&D) project, in association with AES Sul, a south Brazilian electric utility, which attends more than one million clients, has been executed.

To reduce the concerns previously exposed, the state estimation technique is one effective way and has been applied in transmission systems for a long time. This technique can be described as the process of producing the best possible estimates of the real value of the system states using the system topology and parameters together with the information available. However, distribution differs from transmission systems in some peculiarities, such as radial topology, three-phase unbalanced system, high resistance to reactance ratio and very limited number of measurements. These characteristics make the distribution system SE more challenging, consequently, transmission SE cannot be applied unreservedly.

DEFINING SYSTEM TRAITS

The main technique used is the Weighted Least Square approach (WLS), however, rather than using the node voltages as the system state, the method proposed uses the branch currents for primary voltage level, which decouples the state estimation problem into three sub problems, one for each phase.

The restriction to the limited number of measurements is attenuated by introducing pseudo measurements from the historical load data. The load data is produced based on the customer billing data, collected in measurement campaigns and then converted in class-specific load curves through a statistical process.

A three-phase state estimation is also necessary in order to analyze all phases of a feeder, because lines are usually short and untransposed and loads can be three-phase, two-phase or single-phase.

On the other hand, this method is not adequate for the secondary voltage level, considering that most of it is not a radial topology and has only voltage measurement. To deal with this difference, the traditional WLS approach is applied on the secondary voltage level, using the node voltages as the system state. So, after the state estimation in the primary voltage level is converged, the nodes voltages are used by the secondary voltage level state estimation.

STATE ESTIMATION

The introduction of WLS based state estimation can be found in [1]. In SE, the model used to relate the measurements and the state is:

$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{v} \tag{1}$$

where $\boldsymbol{z}$ denotes the vector containing the measurements, $\boldsymbol{h}(\boldsymbol{x})$ the equations relating the measurements to the state variable vector, $\boldsymbol{x}$, and $\boldsymbol{v}$ is the vectors of measurement errors. WLS state estimation tries to find a system state, by solving the following optimization problem:

$$\begin{aligned} min_x\, J(\boldsymbol{x}) &= \sum_{i=1}^{m} w_i \left(z_i - h_i(\boldsymbol{x})\right)^2 \\ &= [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})]^T \boldsymbol{W} [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] \end{aligned} \tag{2}$$

Where w_i is the weight associated with measurement z_i and the result of $\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})$ is called the residual vector.

This problem is minimized by differentiating it with respect to $\boldsymbol{x}$, and setting the resulting nonlinear equation to zero. Then the nonlinear equation is solved iteratively by Newton's method, computing the correction $\boldsymbol{x}^{k+1} = \boldsymbol{x}^k + \Delta\boldsymbol{x}^k$.

$$[\boldsymbol{G}(\boldsymbol{x}^k)]\Delta\boldsymbol{x}^k = \boldsymbol{H}^T(\boldsymbol{x}^k)\boldsymbol{W}[\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x}^k)] \quad (3)$$

Where $\boldsymbol{G}(\boldsymbol{x})$ is called the gain matrix and is usually chosen as:

$$\boldsymbol{G}(\boldsymbol{x}^k) = \boldsymbol{H}^T(\boldsymbol{x})\boldsymbol{W}\boldsymbol{H}(\boldsymbol{x}) \quad (4)$$

Where $\boldsymbol{W}$ is the covariance of $\boldsymbol{v}$, and then $\boldsymbol{W}_{ii} = \sigma_i^2$ is the variance of i-th measurement, assumed to be a Gaussian distribution with zero mean and $\boldsymbol{H}$ is the Jacobian matrix of $\boldsymbol{h}$.

TECHNICAL APPROACH

The SE solution is found using methods of network flows based on the Forward/Backward Power Flow [3], since each section of a radial distribution feeder is connected radially. The backward step starts at the end nodes and passes backward over each section, calculating the current or power flows of each line. The forward step starts at the source, which may be the substation of the feeder, and proceeds forward over each section, calculating the voltage of each bus, from the known substation voltage. The SE calculation is introduced in the backward step, updating the current of each line. The Fig. 1 shows the detailed algorithm of the approach.

The measurements are obtained from meter equipment installed in the system and calculated from the historical load data, called pseudo measurements.

The pseudo measurements are obtained from load curve measurements, taken from samples representing each type of consumer, stratified by level of consumption or demand, per level of voltage, rendering the typical curves and their market percentage. The process is divided in steps utilizing the techniques of hierarchical classification and cluster analysis, explained below.

The meter equipment has its measurement accuracy, allowing the calculation of the variance related to the measurement and the matrix $\boldsymbol{W}$. In case of pseudo measurement usage, the variance employed is 1, avoiding problems of matrix inversion.

Other forms to reduce the problem of limited number of measurements are introducing zero power injection measurement and reducing the number of buses without measurement (buses without load). This process is called Network Reduction and is applied to avoid bad conditioning of the gain matrix, considering the substantial number of buses without load in a real distribution system.

Load Characterization

This process calculates the standard deviations and mean of each class-specific load curve representing each category. Consequently, representing each category by more than one class-specific load curve reveals the load characteristics differences within a class-specific.

The load characterization is accomplished by using a method known as Dynamic Cloud Method [4], which is constituted of three steps: 1- Cluster analysis (through the k-Means Method); 2- Setting strong profiles and 3- Reduction of strong profiles (using Ward's Method).

After the measurement campaigns, the customer billing data is converted in class-specific load curves through the cluster analysis, using the method of k-Means.

Setting the strong profiles requires checking whether the individuals, who were part of a specific group, are together in all other experiments. However, setting the strong profiles may significantly increase the number of groups, so, once these groups have been determined, the strong profiles need to be reduced to an adequate number. Ward's Method is used for this purpose, as it merges the strong profiles in succession until it reaches a preset figure. In order to select which groups need to be merged, the method calculates all the distances between the nuclei of the strong profiles and merges both profiles whose distance between nuclei is the smallest of all those calculated. At each of the mergers, the variance of each new group that was formed is then calculated, in order to control its homogeneous nature, i.e. the quality of the group. At the end of Ward's Method, the typical load curves are obtained for each type of consumption that has been analyzed.

From the monthly energy consumption of each customer and from the typical load curves of the utility company calculated before, it is possible to obtain a load curve for each customer, multiplying the monthly average demand (monthly energy divided by monthly hours) by its typical load curves.

Branch Current Based SE Method

This approach uses the branch currents as state variable (5), which decouples the state estimation problem into three sub problems, one for each phase [2].

$$x_{l\varphi} = [I_{rl\varphi}, I_{xl\varphi}] \qquad \varphi = 1,2,3 \quad (5)$$

Where I_{rl} is the real part and I_{xl} is the imaginary part of the line current of the l-th line of each phase φ. For notational simplicity, the subscript φ, for phase index, will be suppressed.

Measurement Functions

1) Branch Power Measurements: The branch power measurement of each phase, from bus k to bus m is represented as:

$$\begin{aligned} P_{km} &= V_{r,k}\, I_{r,km} + V_{x,k}\, I_{x,km} \\ Q_{km} &= -V_{r,k}\, I_{x,km} + V_{x,k}\, I_{r,km} \end{aligned} \quad (6)$$

So the corresponding Jacobian matrix entries are:

$$\begin{aligned} \frac{\partial P_{km}}{\partial I_r} &= V_{r,k} \qquad \frac{\partial Q_{km}}{\partial I_r} = V_{x,k} \\ \frac{\partial P_{km}}{\partial I_x} &= V_{x,k} \qquad \frac{\partial P_{km}}{\partial I_x} = -V_{r,k} \end{aligned} \quad (7)$$

If measurement and state variables are in the same branch and phase. Otherwise, all the entries related to the branch power measurement are zero.

2) Power Injection Measurements: The power injection measurement of each phase, at bus k is represented as:

$$P_k = V_{r,k} \sum_{m\Omega k} I_{r,km} + V_{x,k} \sum_{m\Omega k} I_{x,km}$$
$$Q_k = -V_{r,k} \sum_{m\Omega k} I_{x,km} + V_{x,k} \sum_{m\Omega k} I_{r,km} \quad (8)$$

where $m\Omega k$ are the buses connected to bus k.
So the corresponding Jacobian matrix entries are:

$$\frac{\partial P_k}{\partial I_r} = V_{r,k} \quad \frac{\partial Q_k}{\partial I_r} = V_{x,k}$$
$$\frac{\partial P_k}{\partial I_x} = V_{x,k} \quad \frac{\partial P_k}{\partial I_x} = -V_{r,k} \quad (9)$$

If measurement and state variables are in the same branch and phase. Otherwise, all the entries related to the power injection measurement are zero.

3) Current Magnitude Measurements: The branch current magnitude measurement of each phase, from bus k to bus m is represented as:

$$|\dot{I}_{km}| = \sqrt{{I_{r,km}}^2 + {I_{x,km}}^2} \quad (10)$$

So the corresponding Jacobian matrix entries are:

$$\frac{\partial|\dot{I}_{km}|}{\partial I_r} = \cos(\alpha)$$
$$\frac{\partial|\dot{I}_{km}|}{\partial I_x} = \sin(\alpha) \quad (11)$$

where,

$$\alpha = \tan\left(\frac{I_{x,km}}{I_{r,km}}\right) \quad (12)$$

If measurement and state variables are in the same branch and phase. Otherwise, all the entries related to the branch current magnitude measurement are zero.

4) Voltage Magnitude Measurements: The voltage magnitude measurement of each phase, at bus k is represented as:

$$\dot{V}_k = \dot{V}_o - \sum_{l=1}^{n} \dot{\boldsymbol{Z}}_l \dot{\boldsymbol{I}}_l \quad (13)$$

Where $\dot{V}_o$ is the substation voltage vector, $\dot{\boldsymbol{Z}}_l$ is the line impedance matrix of line l, $\dot{\boldsymbol{I}}_l$ is current vector of line l and n is the number of lines connecting the bus k to the substation bus o.
However, the impedance between phases can be ignored, because it is much smaller than that of the same phase, decoupling, then, the phases.
Thus, the relation between the voltage magnitude measurement and the state variable is:

$$|\dot{V}_k| = \sqrt{\Re^2 + \Im^2} \quad (15)$$

Where,

$$\Re = \dot{V}_{r,o} - \sum_{l=1}^{n} \dot{I}_{r,l}\, \dot{\boldsymbol{Z}}_{r,l} - \dot{I}_{x,l} \dot{\boldsymbol{Z}}_{x,l}$$
$$\Im = \dot{V}_{x,o} - \sum_{l=1}^{n} \dot{I}_{r,l}\, \dot{\boldsymbol{Z}}_{x,l} - \dot{I}_{x,l} \dot{\boldsymbol{Z}}_{r,l} \quad (14)$$

So the corresponding Jacobian matrix entries are:

$$\frac{\partial|\dot{V}_k|}{\partial I_r} = -\mathrm{Z_r}\cos(\alpha) - \mathrm{Z_x}\sin(\alpha)$$
$$\frac{\partial|\dot{V}_k|}{\partial I_x} = -\mathrm{Z_x}\cos(\alpha) - \mathrm{Z_r}\sin(\alpha) \quad (16)$$

where,

$$\alpha = \tan^{-1}\left(\frac{\Im}{\Re}\right) \quad (17)$$

If the measurement and state variable are in the same branch and same phase. Otherwise, all the entries related to the voltage magnitude measurement are zero.

Voltage Based SE Method

The original SE method, that uses the bus voltage as state variable, is applied for the secondary voltage level. The complete explanation can be found in [1].

The State Calculation Algorithm Outline

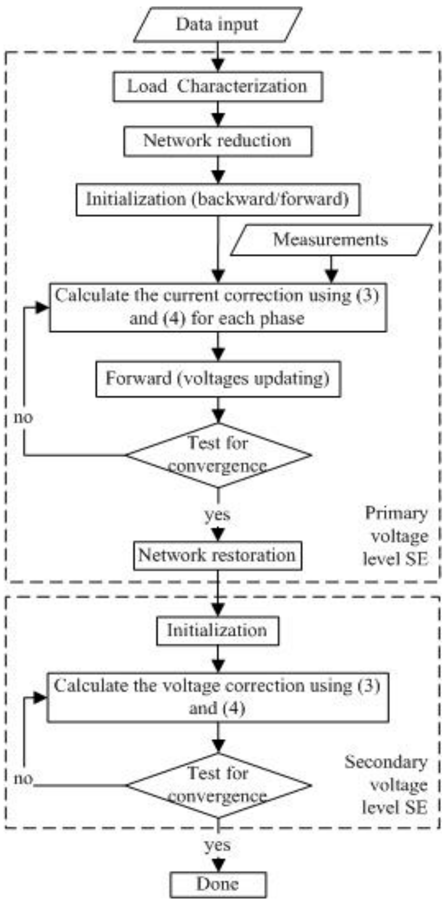

Figure 1: SE algorithm flow chart

SIMULATION RESULTS

In order to evaluate the proposed state estimation method, simulations are carried out on 3 feeders of the substation Venancio Aires 1 from AES Sul.

The calculation was applied for each phase and in four different periods of the day. Each period represents the low, medium, high and peak loads, found in the Tables 1, 2 and 3 indicated by P-1, 2, 3 and 4.

Pseudo measurements were obtained by processing the historical customer load data and assigned to each bus.

The feeder AL009 is unbalanced distribution network, which has 3 current meters and contains:

- 124 lines (76after the network reduction);
- 22 load buses;
- Total load of 0.25MW and 0.11MVar;

Table 1: Comparisons of metered and calculated values of current (A) per phase of feeder AL009

Meter	P	Metered			Calculated		
85		A	B	C	A	B	C
	1	2,00	2,20	1,50	1,92	2,10	1,47
	2	3,70	3,60	3,00	3,26	3,19	2,75
	3	3,70	3,70	2,70	3,26	3,26	2,52
	4	2,90	3,00	2,30	2,68	2,75	2,19
1403		A	B	C	A	B	C
	1	0,60	0,70	0,60	0,60	0,70	0,60
	2	1,50	1,50	1,50	1,47	1,47	1,47
	3	0,70	0,80	0,75	0,70	0,80	0,75
	4	0,60	0,70	0,60	0,60	0,70	0,60
1404		A	B	C	A	B	C
	1	0,20	0,17	0,10	0,20	0,17	0,10
	2	0,20	0,17	0,10	0,20	0,17	0,10
	3	0,50	0,40	0,20	0,50	0,40	0,20
	4	0,40	0,30	0,20	0,40	0,30	0,20

The feeder AL004 is unbalanced distribution network, which has 2 current meters and contains:

- 353 lines (229 after the network reduction);
- 66 load buses;
- Total load of 5,36MW and 2,39MVar;

Table 2: Comparisons of metered and calculated values of current (A) per phase of feeder AL004

Meter	P	Metered			Calculated		
93		A	B	C	A	B	C
	1	3,00	2,50	2,50	2,03	2,09	2,11
	2	3,50	3,50	3,50	3,29	3,38	3,42
	3	4,40	4,70	4,60	4,31	4,52	4,56
	4	3,50	3,70	3,80	3,45	3,63	3,69
1157		A	B	C	A	B	C
	1	13,10	12,50	13,40	13,10	12,52	13,38
	2	25,30	24,00	26,50	25,29	24,09	26,29
	3	31,50	30,00	31,50	31,24	30,10	31,74
	4	25,30	24,50	25,60	25,35	24,42	25,74

The feeder AL005 is unbalanced distribution network, which has 2 current meters and contains:

- 222 lines (128 after the network reduction);
- 40 load buses;
- Total load of 3,55MW and 1,54MVar;

Table 3: Comparisons of metered and calculated values of current (A) per phase of feeder AL005

Meter	P	Metered			Calculated		
606		A	B	C	A	B	C
	1	11,00	12,50	11,30	10,72	12,11	11,16
	2	19,00	21,00	19,00	18,85	21,13	18,57
	3	29,00	32,50	29,00	28,74	32,29	29,15
	4	25,00	26,00	25,00	24,03	26,74	24,36
989		A	B	C	A	B	C
	1	21,00	23,00	21,00	20,60	22,61	20,61
	2	33,00	37,00	33,00	33,02	36,57	32,16
	3	53,50	58,90	52,70	53,50	58,86	52,68
	4	44,70	49,00	43,70	44,56	48,75	43,74

Tables 1, 2 and 3 show satisfactory results of the methodology proposed, but it is still been tested and will be better analyzed with other distribution systems.

CONCLUSIONS

The methodology proposed here was implemented as a computational system developed for AES Sul, a Brazilian energy distribution company that sponsored this research. The benefits of this proposed method are the computational efficiency by using the branch currents as the system state and using the historical load data as measurement, allowing the WLS approach for distribution systems and make it very suitable for practical applications. Using the methodology proposed is possible to evaluate the real technical and non-technical losses, and then, identify the regions with discrepancy, helping on the execution of a fraud combat plan.

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