DER AND LOAD ALLOCATION FOR AN UNBALANCED DISTRIBUTION NETWORKS STATE ESTIMATOR

Gil SAMPAIO
INESC TEC – Portugal
gss@inesctec.pt

Carolina JANEIRO
INESC TEC – Portugal
ana.c.janeiro@inesctec.pt

Jorge PEREIRA
INESC TEC – Portugal
jpereira@inesctec.pt

Luís SECA
INESC TEC – Portugal
luis.seca@inesctec.pt

Paulo VIEGAS
EFACEC – Portugal
paulo.seixas.viegas@efacec.pt

Nuno SILVA
EFACEC – Portugal
nuno.silva@efacec.pt

Alberto RODRIGUES
EFACEC – Portugal
arodrigues @efacec.pt

ABSTRACT

This paper describes the work done in the 3PHASE project, regarding the development of a state estimator for distribution networks handling substantial integration of DER (Distributed Energy Resources), AMI (Advanced Metering Infrastructure) data and unbalanced and asymmetrical configurations. The load and DER power allocation presented here, as part of a DMS system, constitutes a first estimation of the network, assuming an extreme importance for other studies as it helps solve the lack of measurements problem.

INTRODUCTION

The objective of the 3PHASE project is to provide new approaches and developments for the above problem statement and it is an initiative promoted by EFACEC (automation and smart grid solutions supplier) in partnership with INESC TEC (scientific partner).
Considering the worldwide trend of investing in new solutions able to manage distribution networks, these systems must be flexible and increase the efficiency of the network management while maximizing the integration of distributed energy resources. New methodologies must address present and future realities, beyond the state of the art, such as:

- Information from smart metering systems, able to increase the awareness of consumption and of distributed generation in some points of the network, in order to potentiate power applications;
- Renewable distributed production assets, not dispatchable with highly unpredictable behaviour;
- Renewable distributed production assets supplemented by local energy storage systems, making them controllable and with more predictable behaviour, but with a dynamic behaviour working as a generator or as a load;
- Distributed energy storage assets.

Operation strategy for distribution networks has been changing for modern systems and two major challenges exist: a deregulated business environment and an increase of energy production from renewable resources. This requires monitoring and control of network by means of a modern DMS (Distribution Management System) [1].
The real-time measurements in distribution networks are usually limited to source substation, head of feeders, larger renewable resources and larger consumers. This does not enable a WLS-based state estimator since it requires redundancy. The introduction of pseudo measurements for the loads and the DERs without associated measure devices, and of virtual measurements for the zero node injection nodes, can improve that condition. One must therefore rely on other type of data, recorded in commercial files, to try to infer the values of loads [2].
A reliable estimation of the load consumption and the DER contribution may be important, even essential, to run some of the power system applications. Besides, it can play an important role in short and long-term planning purposes such as, system capacity and service reliability studies.

UNBALANCED DISTRIBUTION NETWORKS STATE ESTIMATOR

State estimation is one important tool of the DMS. Nevertheless, a large part of the distribution network continues with a very limited observability.
Figure 1 presents the procedure sequence included in the state estimator tool developed within the 3PHASE project. This paper is focused on describing processes based on particular and practical functioning characteristics of loads and DERs allocation to improve the system observability.

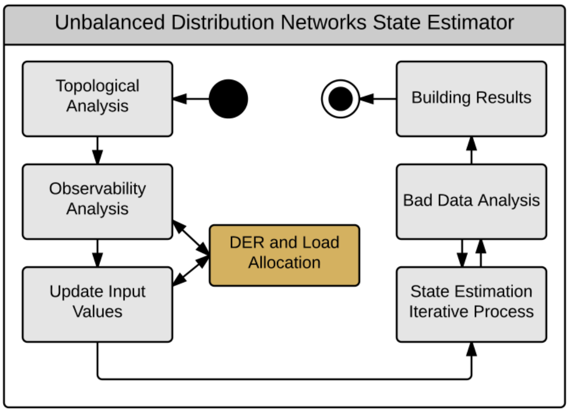

Figure 1 - Process diagram of the Unbalanced Distribution Networks State Estimator

These processes were designed to deal with unbalanced distribution systems allowing studies that consider effects of non-transposed lines on radial or meshed networks, including three-phase, two-phase or single-phase hybrid systems, and equipment that can be either connected to all phases or not. The line modelling can be accomplished by resorting to the Carson's equations, allowing the determination of the self and mutual impedances of overhead lines and underground cables with great accuracy [3]. Analysis of the network elements modelling, resembling the special characteristics of distribution systems, are found in [4]-[7]. A general representation of a distribution system with N conductors can be formulated into a $N \times N$ primitive impedance matrix. Then, using the Kron's reduction technique, a convenient reduction can be applied into a 3×3 matrix in the phase frame, consisting of the self and mutual equivalent impedances for the three phases.

DER AND LOAD ALLOCATION

DER allocation and load allocation are essential functions for the estimation of load power at several MV/LV secondary substations and at different points of the network, as well as for the estimation of the generation/consumption from DERs. The location and availability of measurements impacts the system observability, in particular, missing measurements regarding DERs and loads contributes negatively to it.

It is worth noting that we are not concerned about how the data is obtained or how the consumer typical curves are designed. Our aim is to obtain, from a minimum amount of information, a solution capable of performing a load and DER allocation as starting point to other modules, specifically for this project, the state estimator module. Nevertheless, the type of data will have a direct impact in the results to be used in subsequent modules. For instance, the WLS method, commonly used in the state estimation, can easily accommodate different levels of confidence to the input data.

There are few studies in the literature regarding specific load or DER modelling techniques for distribution networks allocation analyses. Typically, demand curves are used, which are compiled with data from meters spread over the network [5], [8], [9]. In [10], a real-time load modelling technique is presented which incorporates the use of customer class curves and provides a measure of uncertainty in the estimates. To express unknown or uncertain measurement values, the authors of [2] use fuzzy set techniques. In [6], it is presented a process which iterates between the load flow computation and the WLS estimation achieving, simultaneously, load allocation, by finding load scaling factors, and state estimation, by using pseudo and real-time measurements with the power flow equations as constraints. These load scaling factors are applied over forecasted load values. Also [1] follows an iterative procedure for the state estimation with a step dedicated to the load allocation. Initially forecasts for the loads and distributed generators are made from normalized daily consumption and generation curves, respectively. Then, during the WLS-based state estimation, those pseudo measurements are readjusted to fit the real-time measurements.

In this work we present a method for the load and DER allocation that is constituted by some techniques and rules to cover a wider group of possibilities regarding the type of information available. Not focusing in any particular technique, it follows a priority sequence of techniques to turn the system under analysis observable. In this sense, the method tries to provide the most efficient and reliable estimation of the load given the data to start with.

Load Classes

Typically, the loads in a MV network will be MV/LV substations, either public or private. Based on the approach used in [2], we have classified them in four general types, namely:

- Type POWER – Substations for which one only knows transformer installed capacity and/or peak load; capacitors are treated as loads by being transformed into reactive power values under nominal voltage;
- Type ENERGY – Substations for which there is also knowledge about their load composition in terms of three classes of consumers (domestic, industrial and commercial) and their energy consumption, including at peak, normal and light hours for some of them;
- Type CURVE – Substations for which there is also a model that allows a forecast of the load at a given hour;
- Type MEASURED – Substations where there are real-time power consumption measurements.

ALLOCATION ALGORITHM

The DER and load allocation algorithm is prepared to work on radial parts and on weakly meshed parts of the selected network area, if there are valid measurements at the root. The user will be able to specify, via an external parameter ($\lambda \in [0, 1]$) the amount of relative weight to affect each of two criteria – power and energy consumption – in the estimation of the load value. This is a tuning process to be done taking into account system history and operator experience. Also, for the power criterion another external parameter ($m \in [0, 1]$) will be used to balance between peak power and installed power.

The algorithm is divided into a few steps and includes an iterative stage, as described in Figure 2. That is, a primary DER and load allocation is performed, however, the results will not be coherent with the Kirchhoff's laws for power flows once the losses in the circuits have not been considered. Therefore, after the first load assignment, a corrective iterative procedure will be applied to finally define a set of loads coherent with the power flow equations. This iterative process is derived from other forward/backward sweep methods for power flow, such as [11][1].

In order to maintain a straightforward approach, the problem can be decoupled in a phase frame if the mutual impedance effects are neglected. In fact, as this module represents a first estimation of the network, preceding the state estimation one, the small impact of those effects is an avoidable burden.

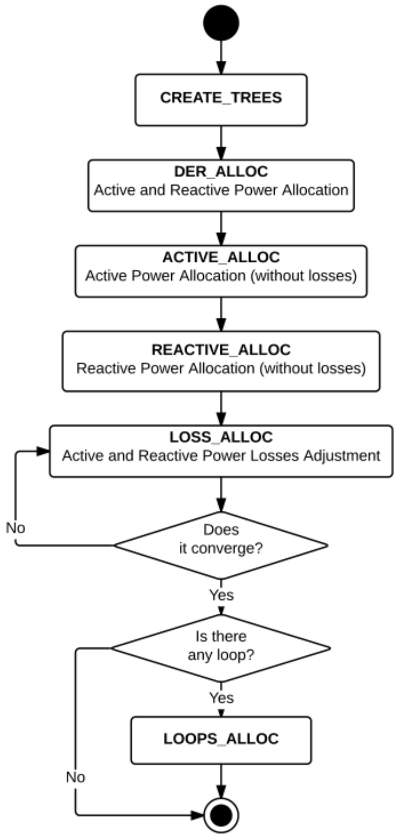

Figure 2 - Algorithm for the active and reactive power allocation

The general logic of the allocation for each phase at time t is the following:

CREATE_TREES

For each line and transformer winding
  If there is a valid measurement and there are no injection points without measurement or loops in the candidate subtree
    Save the node as root and form a subtree
    Sum the power of type MEASURED loads and DERs with measurements
    Subtract from the corresponding root the latter sum
For each root
  Subtract to the predecessors roots (from the leafs to the root of the main tree) its measurement values

DER_ALLOC

For each DER without measurement
  If the tree where it belongs has no loads
    The active and reactive power equals the root
  Else if a forecasted diagram, scheduling information or automatic control model is available
    Determine the active power
    If the mean power factor or a default value is available determine the reactive power
  Else
    Set its production to nominal values

ACTIVE_ALLOC

For each subtree
  For the set of loads type CURVE
    Based on the hour, estimate from the typical substation load curves the value of the load
    Sum the contribution of these loads and subtract them to the root
    If the result of the subtraction is negative
      The procedure is restarted treating loads type CURVE as type ENERGY
  For the set of loads type CURVE, ENERGY and POWER
    Calculate the intermediate power criterion using the balancing parameter m with the peak power and the installed power
  For the set of loads type ENERGY and CURVE determine the intermediate energy criterion with the average power consumption for the period. The ratio between the intermediate energy and the intermediate power criteria of these types is used to determine the intermediate energy criterion of type POWER loads
  For the set of loads type ENERGY and POWER two allocations are made fitting now to the root
    The intermediate power criterion
    The intermediate energy criterion
For each load of type ENERGY and POWER, a primary load allocation is obtained by weighing with λ the power allocated with the power and the energy criteria

REACTIVE_ALLOC

For each load
  Determine a intermediate reactive power using a measured, estimated or default power factor with the active power allocated previously
For each load
  Allocate fitting the power to the root measurement

LOSS_ALLOC

Until a convergence criterion is satisfied
  (Backward phase) For each subtree
    For each node following the direction from the leafs to the root
      Calculate the charging admittance of the node
  (Forward phase) For each subtree
    For each node following the direction from the root to the leafs
      Calculate the voltage of the node
      Calculate the losses of the branch
      Add, in proportion, the losses to the loads of the subtree

LOOPS_ALLOC

For each meshed area with measurements in the boundary
  Call the ACTIVE_ALLOC

Call the REACTIVE_ALLOC

ILLUSTRATIVE EXAMPLE

A simple example will be used to better explain the algorithm developed. For that, the electrical distribution network from Figure 3 was considered.

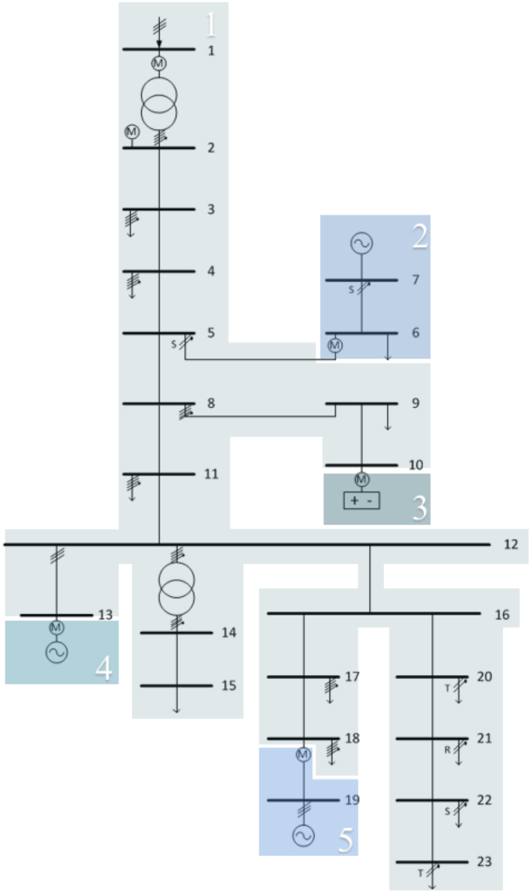

Figure 3 – Unbalanced distribution network under consideration

The algorithm is applied for each phase of the system. As shown in Figure 3, phase S is the one which is present in all network. Due to this reason and for simplification purposes, the algorithm will be explained only for phase S.

Elements from the network will be referred to by their name and corresponding nodes. As an example, the line that connects nodes 22 and 23, will be line 22-23. Elements represented by the letter M in Figure 3 correspond to measure devices.

The algorithm starts by determining the roots that will be used to create subtrees. The roots are related to nodes with measurements that satisfy the conditions previously explained. For this example, the roots will be located at nodes 1, 6, 10, 13 and 19. These roots originate the subtrees represented in Figure 3, by highlighted areas numbered from 1 to 5.

The next step consists of allocating the generation / consumption of the DERs.

For the subtrees created from nodes 10 and 13, since the DER is connected directly to the measure device and there are no loads, the power allocated to DER 10 and DER 13 will be the same as the root.

The subtree originated from node 19 differs from the previous in the fact that the DER is connected to the line 18-19 and not directly to the measure device. In these circumstances, the line impedance is neglected and the power will also be the same as the measurement at the root.

Finally, the subtree created from node 6 constitutes a more difficult case, as both the load and the DER power are unknown. Due to this reason, the DER power value will be fixed on its nominal value and the value for the load will be then calculated based on the subtree balance, as long as the load limits allow it (the excess would have to be discounted to the DER to guarantee that balance).

The other steps of the algorithm are followed afterwards as previously described, in order to complete the load allocation. Calculations vary according to the load type:

- Type CURVE: power values are directly obtained from a forecast model (e.g. load 3);
- Type POWER and type ENERGY: active power values are allocated based on the formula:

$$P_{allocated} = (1-\lambda)P_E + \lambda P_P \qquad (1)$$

Where P_E and P_P correspond to the power allocated with the energy criterion and the power criterion, respectively, and λ is a parameter that defines the weight of each criterion. The intermediate energy criterion of each type POWER load was determined with the ratio between the two intermediate criteria for type ENERGY and CURVE loads.

So, for load 9, for example, the intermediate power criterion (P'_P) is calculated considering $P_{peak} = 1.6$ *p.u.*, $P_{installed} = 1.9$ *p.u.* and $m=0.5$.

$$P'_P = (1-0.5)\times 1.6 + 0.5 \times 1.9 = 1.75 \text{ p.u.}$$

$$P_P = P'_P \times \frac{P_{root}}{\sum P'_P} = 1.75 \times \frac{5.8}{10.85} = 0.935 \text{ p.u.}$$

The energy criterion, considering $P_{average} = 1.2$ *p.u.* ($P'_E = P_{average}$) is:

$$P_E = P'_E \times \frac{P_{root}}{\sum P'_E} = 1.2 \times \frac{5.8}{7.51} = 0.927 \text{ p.u.}$$

Considering $\lambda=0.5$, the allocated power for phase S will be:

$$P_{allocated} = (1-0.5)\times 0.927 + 0.5 \times 0.935 = 0.93 \text{ p.u.}$$

Furthermore, the intermediate reactive power (Q') is calculated based on the formula:

$$Q' = P_{allocated} \times \tan(\cos^{-1}\phi) \qquad (2)$$

Being $\cos\varphi$ the power factor.

Afterwards the value of $Q_{allocated}$ is calculated by proportionally distributing the root measurement value for each load. Considering $\cos\varphi = 0.8$, the value of $Q_{allocated}$ will be:

$$Q' = 0.93 \times 0.75 = 1.46 \text{ p.u.}$$

$$Q_{allocated} = Q' \times \frac{Q_{root}}{\sum Q'} = 0.56\ p.u.$$

Finally, the power losses in the branches are iteratively determined with the backward/forward sweep method.

In this example the allocation for meshed parts of the network was not performed. Nonetheless, as described above, if there was any loop, it would follow a similar treatment as a radial part with the exception that the losses would not be determined.

Results obtained for the three phases of the system are presented in Tables 1-3. Since the losses are very small, the number of significant figures used is not enough to represent them.

Table 1 – Values of active (P) and reactive (Q) power for each phase (R, S, T) of the measure device

Phase	**R**		**S**		**T**	
Power	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)
M1	8.2	6.8	6.4	7	9	5.6
M6	-	-	2	0.2	-	-
M10	-1.5	0	-1.5	0	-1.5	0
M13	2.3	0	2.3	0	2.3	0
M19	-4.2	0	-4.2	0	-4.2	0

Table 2 - Values of active (P) and reactive (Q) power for each phase (R, S, T) of the DER

Phase	**R**		**S**		**T**	
Power	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)
DER 7	-	-	2.5	0	-	-
DER 10	-1.5	0	-1.5	0	-1.5	0
DER 13	2.3	0	2.3	0	2.3	0
DER 19	4.2	0	4.2	0	4.2	0

Table 3 - Values of active (P) and reactive (Q) power for each phase (R, S, T) of the Load

Phase	**R**		**S**		**T**		**Type**
Power	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	
Load 3	1.10	0.50	1.30	0.90	0.90	0.20	CURVE
Load 4	1.67	0.74	1.31	0.79	1.94	0.88	POWER
Load 6	-	-	0.50	0.20	-	-	POWER
Load 9	1.24	0.55	0.93	0.56	1.38	0.63	ENERGY
Load 11	3.80	2.60	3.90	1.50	2.50	0.60	CURVE
Load 15	1.54	0.69	1.15	0.70	1.71	0.78	ENERGY
Load 17	1.67	0.74	1.31	0.79	1.94	0.88	POWER
Load 18	1.39	0.62	1.10	0.66	1.36	0.62	POWER
Load 20	-	-	-	-	1.03	0.47	ENERGY
Load 21	0.78	0.35	-	-	-	-	ENERGY
Load 22	-	-	1.90	1.10	-	-	CURVE
Load 23	-	-	-	-	1.23	0.56	POWER

CONCLUSIONS

This paper presents a method for the load allocation of distribution networks with considerable penetration of distributed energy resources lacking in measurements. The procedure is suitable to be applied to unbalanced and asymmetrical distribution networks with radial or meshed configurations. A simple example is used to show how general and straightforward its application can be. The results obtained are compatible with practical constraints of network distribution equipment.

The basis to develop this new allocator are derived from a DMS package for balanced three-phase networks currently available in the market. The experience and sensitivity acquired over the years improving this software together with the new challenges found, and others envisioned, to manage distribution systems justify this new approach.

Despite the use of this new module as resource of a state estimator software, and since the problem of observability can affect others, we expect it to be applied to more modules of a power system library, such as the power flow.

REFERENCES

[1] A. T. Sarić, A. Ranković, 2012, "Load reallocation based algorithm for state estimation in distribution networks with distributed generators", *Electric Power Systems Research*, vol. 84, no. 1, pp. 72-82.

[2] V. Miranda, J. Pereira, J.T. Saraiva, 2000, "Load allocation in DMS with a fuzzy state estimator", *Power Systems, IEEE Transactions on*, vol.15, no.2, pp.529-534.

[3] W. H. Kersting, 2007, *Distribution System Modeling and Analysis*, CRC Press, Boca Raton, FL.

[4] J. B. V. Subrahmanyam, 2000, "Load flow solution of unbalanced radial distribution systems", Journal of Theoretical and Applied Information Technology, vol. 6, no. 1, pp. 40-51.

[5] C.N. Lu, J.H. Teng, W.H.E. Liu, 1995, "Distribution system state estimation", *Power Systems, IEEE Transactions on*, vol.10, no.1, pp.229-240.

[6] I. Dzafic, M. Gilles, R.A. Jabr, B.C. Pal, S. Henselmeyer, 2013, "Real Time Estimation of Loads in Radial and Unsymmetrical Three-Phase Distribution Networks", *Power Systems, IEEE Transactions on* , vol.28, no.4, pp.4839-4848.

[7] M.C. de Almeida, E.N. Asada, A.V. Garcia, *2006*, "Effects of load imbalance and system asymmetry on three-phase state estimation", *Power Engineering Society General Meeting, IEEE*, pp.6.

[8] W.H. Kersting, W.H. Phillips, 2008, "Load allocation based upon automatic meter readings", *Transmission and Distribution Conference and Exposition, 2008. T&D. IEEE/PES*, pp.1, 7, 21-24.

[9] Y.C. Lee, M. Etezadi-Amoli, 1993, "An improved modeling technique for distribution feeders with incomplete information", *Power Delivery, IEEE Transactions on*, vol.8, no.4, pp.1966-1972.

[10] A.K. Ghosh, D.L. Lubkeman, R.H. Jones, 1997, "Load modeling for distribution circuit state estimation", *Power Delivery, IEEE Transactions on*, vol.12, no.2, pp.999-1005.

[11] M.A. Matos, 2003, "A new power flow method for radial networks", *Power Tech Conference Proceedings, 2003 IEEE Bologna*, vol.2, no., pp.5.