METHODOLOGY AND RESULTS OF A FIELD EXPERIMENT OF DISTRIBUTION STATE ESTIMATION IN THE FRENCH NETWORK

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ABSTRACT

New centralized advanced automation functions that underlie the Smart Grid need a real-time view of the MV network operating point. To do so, a distribution state estimation function can be included in existing Distribution Management Systems. This concept is widely used in Transmission Networks, but only at a research phase in distribution networks. This article describes the results of a first field experiment of such function in ERDF's MV network. The main purpose of this experiment is to confirm previous results obtained through simulations on the impact of sensors' type and placement on the performances of the algorithm [1].

INTRODUCTION

Distribution State Estimation (DSE) is at the heart of future Distribution Management Systems (DMS) and a necessary step towards the Smart Grid. The algorithm of distribution state estimation is a non linear optimization that uses a limited number of measurements (which may be of different types: voltages, currents, active/reactive power …) acquired by a SCADA, combined with the network model in order to estimate the electrical state of the network in real time (in the range of 1 to 3 minutes). Such information becomes essential for Distribution Network Operators (DNOs) in order for example to detect and deal with voltage constraints arising due to the connection of Distributed Generation in the MV and LV networks.

A DSE algorithm has been developed by EDF R&D and its performances were first tested using a network simulator [1]. ERDF (French DNO) having recently decided to experiment a centralized Voltage Control function, the validation of the DSE algorithm on real field data became part of the project critical path [2]. Therefore, this paper presents new results and the performances of this algorithm with on field retrieved data.

First the DSE algorithm tested and the experiment conditions are described. Then the methodology used for assessing the performances of the algorithm is explained. In the last part of this paper, the results are depicted as well as the perspectives foreseen after this first experiment.

DESCRIPTION OF THE DSE ALGORITHM

The objective of DSE is to determine the most likely state of the distribution system based on quantities that are measured. In EDF R&D's algorithm, voltage amplitude and phase angle (slack bus taken as reference of phase) at each node have been chosen as the primary state variables to be estimated, while other values such as branch currents, power flows and MV/LV substations' active and reactive power are considered as the secondary state variables. The latter are deduced from both the network model and the primary state variables derived by the DSE.
Measurements used by the DSE are classified according to three families:

- real measurements,
- pseudo-measurements,
- virtual measurements.

Real measurements are metered on the system; pseudo-measurements are load models; virtual measurements are additional values used when the value is clearly identified (for instance, zero load injections at nodes with no load connected).

In order to provide the expected estimation, DSE needs a dynamic database which provides in real time : the topology and electrical parameters of the distribution network, the configurations of the metering system such as the sensors' types, characteristics and placement in the network.

The DSE formulation is defined by an objective function subject to the measurements model and a constraint equation linking virtual measurements to the state variables. Therefore, the goal of DSE is to determine an estimate of these state variables that minimizes the objective function. The latter is expressed as the function of the measurement residuals $\rho(r_i)$ subject to constraints given by the measurement equations.

$$\hat{x} = \arg\min J(x) = \sum_{i=1}^{m} \rho(r_i) \qquad \text{objective function}$$

subject to :

$\boldsymbol{z_i} = \boldsymbol{h_i}(\boldsymbol{x}) + \boldsymbol{r_i}$ equation considering the ith real or pseudo-measurement equation

$\boldsymbol{c}(\boldsymbol{x}) = \boldsymbol{0}$ equality constraints equation corresponding to virtual measurements

The state estimator algorithm involves the iterative solution of equations depending on the formulation chosen. An initial value has to be set for the state vector X_{init}. Similarly to the resolution of a power flow, the X_{init} value typically corresponds to the flat voltage profile. Therefore, all bus voltages are assumed to be at the same value and in phase with each other.

The algorithm tested with field measurements is based on a weighted least-square constrained approach which has been developed with Matlab.

PRESENTATION OF THE EXPERIMENT CONDITIONS

For the purpose of another project carried out by ERDF, sensors have been installed in several MV/LV substations of two MV feeders connected the same HV/MV substation. Moreover, active power and reactive power transits measurements are available at the HV/MV substation for both MV feeders.

Figure 1 illustrates the position of the sensors along both instrumented MV feeders. These sensors monitor Low Voltage RMS voltages on a 10 minutes basis and Low Voltage active and reactive power on a 10 minutes basis. Voltage sensors have an accuracy of about 1 to 1.5%.

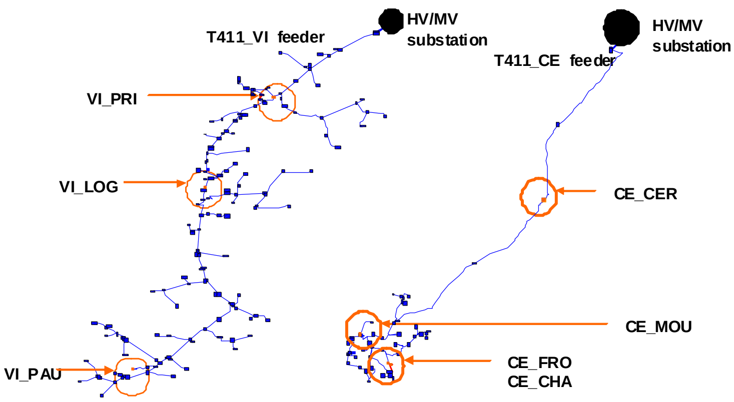

Figure 1: Sensors position in the MV network

As the network was not instrumented for the sole purpose of testing the DSE algorithm, sensors' positions in the network are not optimal for the DSE experiment. Moreover, the measurements are made on the LV side of the transformer which is not suitable for an MV distribution state estimation. However, these sensors data can be used to verify the different properties obtained through simulations in [1].

Sensors have a GSM connection with a central server based in EDF R&D's site. The daily load curves based on 10 minutes average measurements are retrieved every week. These data have then to be manually treated in order to calculate the MV voltage from the LV measured voltage and the MV/LV transformer characteristics (transformer impedance, and off-load tap changer position). Similarly, the active power and reactive power on the MV side of the transformer are calculated from the LV measurements and the transformer losses. For testing the DSE algorithm, data retrieved over a total period of 6 months have been used (this corresponds to about 26,000 different operating points).

Load data corresponding to the maximum demand (in MW) of each secondary substation of the network are available in the network database. They are used to build the pseudo-measurements required by the DSE algorithm.

The state estimation algorithm is therefore run "off-line" for different operating points of the network and taking different sensors' configurations as input data.

METHODOLOGY USED FOR ASSESSING THE DSE PERFORMANCES

<u>Statistical approach used to estimate the real network value</u>

When testing the performances of the DSE algorithm through simulations, the "real-value" of state variables is provided by a network simulator. Sensors' measurements are modeled by applying Gaussian errors to the simulated values. These modeled sensors measurements are then used as inputs by the DSE algorithm. The performances of the algorithm are then obtained by comparing the DSE results (state variable estimates) with the network simulator data ("real-value" of state variables) [3].

However, when testing the performances of the DSE algorithm with field sensors data, the real-value of state variables is unknown, as sensors always give an erroneous measurement compared to the real value. It is therefore required to find a methodology to assess the state variable value with which DSE results can be compared.

The first idea could be to compare DSE results with sensors data. However, this is not appropriate as the DSE algorithms use sensors data as inputs and try to improve the knowledge of state variables given by sensors measurements. Therefore a statistical method has been used in order to assess the "real-value" of network state variables. It is based on fitting multivariate Gaussian mixtures to a given data set with a clustering analysis. In other words, the 26,000 different operating points obtained over 6 months of network monitoring, are clustered with a mix of Gaussians in order to define some families of operating points to which each of the 26,000 operating points belong to. Each of the Gaussian is then centred on a value which is supposed to be the "real value" of the corresponding operating point. The standard deviation of the Gaussian is supposed to be the error corresponding to the sensors errors and the errors due to the calculation of the MV data with MV/LV transformers parameters.

To apply this statistical method, the MIXMOD software was used. It is a publicly available software distributed for different platforms (Linux, Unix, Windows). It is an object-oriented package which is interfaced with the widely used mathematical softwares Matlab and Scilab. It was developed jointly by INRIA, the Besancon Math Laboratory and the Heudiasyc Laboratory at Compiegne [4].

To be consistent, this method requires a large number of data sets with a large number of operating points incorporated in a single Gaussian.

Use different sensors' configurations for assessing DSE performances

The main aim of this first off-line experiment is to validate the theoretical models developed and conclusions drawn so far by EDF R&D on both the choice of state estimation algorithm and the impact of sensors placement on the performance of the estimation.

To do so, different case studies are performed, each of them using a different configuration of sensors as inputs of the Distribution State Estimation. For example, the impact of voltage sensors on the performance of DSE's results is analyzed with the following case studies:

- Firstly, for both feeders, state estimations are performed using only the voltage sensors and the P/Q sensor at the HV/MV substation. Pseudo-measurements are used at all MV/LV substations.
- State estimations are then run based on the same sensors configuration with an additional voltage sensor in an MV/LV substation.
- Sensors are added progressively as inputs of the DSE.

Studying the impact of different sensors' configuration is a pre-requisite: since DSE performances are very dependent on sensors' configuration, it is important to choose an adapted system of measurements to the development of a Distribution State Estimation. Such investigations can then lead to an optimized instrumentation of the MV network at minimum cost.

PRESENTATION OF RESULTS

Each measurement series, obtained from each sensor, is analysed with the Mixmod software. As previously described, the latter helps determine the corresponding "real values" assumed for each measurement. These "real values" are used in order to calculate the relative errors obtained for each corresponding state estimates. Thus, different performance curves have been built: they provide a percentage of measurements (among all total measurements) under different relative errors given.

The performances are determined both for the primary and secondary variables related to the instrumented nodes. Three configurations of sensor are used:
config 1 : only the voltage and the P/Q measurements at the HV/MV substation are provided to the DSE.
config 5: corresponds to the conf 1 where all the voltage measurements available are provided to the DSE.
config. 10: corresponds to the conf 5 where all the P/Q measurements available are provided to the DSE.

Thus for each instrumented node of each feeder considered, three curves related to the DSE performances are given and compared. The results obtained for each instrumented node are similar.

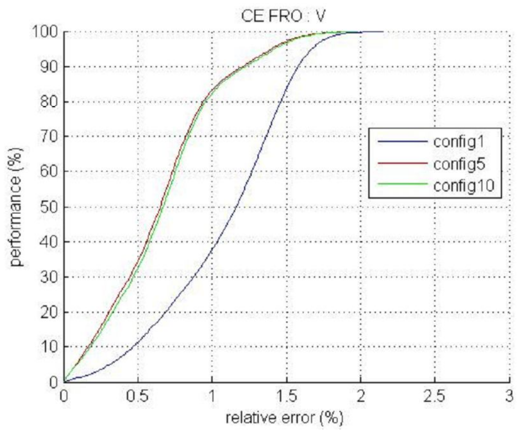

Figure 2: Voltage amplitude estimates for different sensors configurations

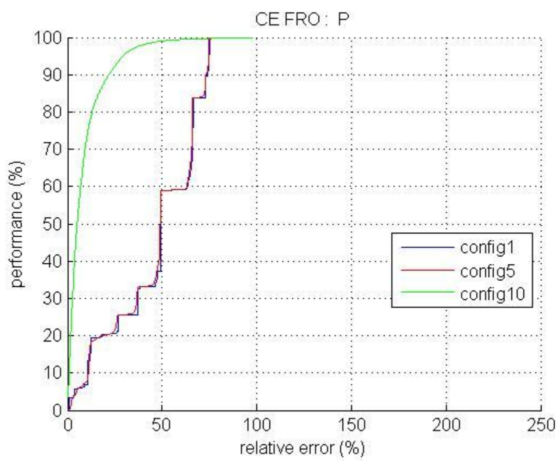

Figure 3: Active power estimates for different sensors configurations

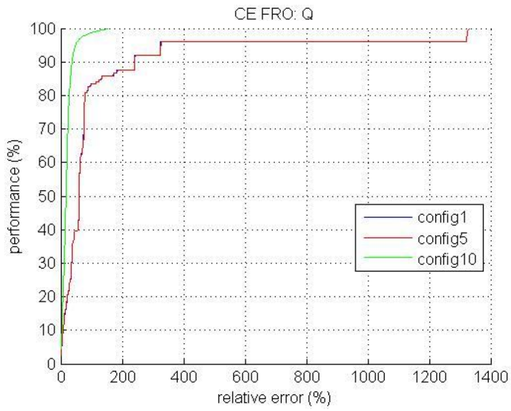

Figure 4: Reactive power estimates for different sensors configurations

Figures 2, 3 and 4 illustrate the results related to the secondary substation CE FRO:
for the primary variable (Voltage amplitude): the performances for the configurations 5 and 10 are identical.
for the secondary variables (P/Q): the performances for the configurations 1 and 5 are identical.

As a result, for the voltage amplitude estimates, the sensors P/Q have no influence while the voltage sensors added enhance the DSE performances. For the secondary variables, voltage amplitude sensors have no influence and only the replacement of the pseudo- measurements by P/Q sensors improves the P/Q state estimates. Moreover, unlike for voltage sensors, the influence of P/Q sensors is only local.

Concerning the DSE performances, the results must be taken with care since it is based on Mixmod measurements filtering performances. For instance, one of the Mixmod requirements is to gather several measurements related to each operating point. It is not the case for the P/Q measurement, which could explain the bad performances obtained for P/Q estimates.

CONCLUSIONS AND PERSPECTIVES

This paper describes a first experiment of a Distribution State Estimation algorithm with sensors installed in ERDF's network. This work enabled us to verify the following properties, which were identified through simulations in [1]:

- The voltage magnitude sensors have a global impact on DSE primary state estimates whatever their placement. This means that adding one of them impacts the precisions of both the voltage magnitude and phase angle at each node.
- For the secondary variables, no types of sensor have a global influence on the MV/LV power flow estimates. Only the replacement of the pseudo-measurements by active and reactive power sensors at each MV/LV substation leads to an improvement of the MV/LV power estimates.

Moreover, several implementation constraints have been pointed out for the future integration of the DSE in the existing Distribution Management System (DMS) of ERDF:

1) Measurements must be made on the MV side of secondary substations. Due to the unbalance of the LV network and due to the lack of precision of secondary transformers data, calculating MV voltages from LV measurements would lead to inaccurate inputs for the DSE.
2) In order to estimate voltages for a voltage control function dealing with MV and LV connected Distributed Generators, voltage sensors must have an accuracy of 1% or less.
3) The network database must contain precise data on feeders' parameters (resistance, inductance, etc…).
4) Assessing the performances of the DSE algorithm requires more sensors than usually required in order to have a redundancy of measurements to carry out different tests.

This work is a pre-requisite towards the implementation choices of new DMS functions in ERDF real-time distribution network control system. Such DSE function is needed to be able to run new centralized voltage control functions in presence of Distributed Generation [2]. The next steps are to industrialize the existing DSE algorithm and integrate the function into ERDF control centre tools described in [5]. Then on-line experiments of the real-time state estimation function will be performed.

Acknowledgments

This work is part of the French REFLEX project. Therefore, the authors would like to thanks the TENERRDIS competitivity initiative in France in which the REFLEX project is hosted.

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