BENEFITS OF PHASOR MEASUREMENT UNITS FOR DISTRIBUTION GRID STATE ESTIMATION : PRACTICAL EXPERIENCE FROM AN URBAN DEMONSTRATOR

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ABSTRACT

This work shows how a distribution grid state estimator combined with the deployment of a limited number of PMU's in the medium voltage grid can help to increase observability, and highlights what is needed to attain sufficient accuracy. A real-time demo platform was setup in an urban area on three different MV-grids to evaluate the concepts in a real-life situation. The demo platform showed that real-time state estimation using the measurements available today is possible, up to some level. The lack of power measurements in the distribution grid in general can be assessed with pre-defined load patterns, but the calculations of direction of power flow and the balance between active and reactive power flow in the feeders still contain significant error in some cases. A selective integration of power measurements on some feeders improves the accuracy. An intelligent management of input data to the state estimator, with priorities between the different measurements, helps to avoid numerical over-determination of the system. The integration of PMU's has shown to improve the accuracy regarding the HV-grid behaviour calculations, and grid instabilities caused by decentralized power generation can be tracked. PMU-measurements were used to assess the quality of necessary HV-grid measurements and calculations provided by the TSO.

INTRODUCTION

Power flows in distribution grids and between distribution and transmission grids become less predictable. At the medium voltage level, the implementation of more decentralized generation complicates the matter even further. Daily operations become more critical because of the increased complexity in planning the medium voltage grid, and often only a poor view on the active and reactive power flow is available for dispatchers. [1]

Therefore more observability in the distribution grid is clearly needed. Mass installation of additional power and voltage measurements in the grid bares huge costs and incredible data challenges. One solution is to integrate selectively new advanced grid measurements combined with an intelligent state estimation software. [2]
Is reliable state estimation in distribution grids with the available measurements today possible ? Can selective PMU integration improve the accuracy of the state estimator and help facing future challenges in daily operations ? No standard solution exists today for the different types of distribution grids.

SETTING UP AN ADVANCED DEMO STATE ESTIMATOR

The main goal of this task is to examine if it is possible to build a state estimator with the available assets today, and how accurate this system could be made. Next to that, also which are the needed extra measurements to be installed to attain the wanted accuracy.
The demo state estimator was built on a mainframe at the DSO's premises, using a commercial grid calculations software, NEPLAN®, using the load-flow calculation module. The software uses a model, which describes the grid topology and the characteristics of all grid elements (cables, transformers, switches,…) as well as a default value of the loads, which acts as a starting point for the calculations. The principle of operation of the proposed state estimator is to inject measurement data into the model, so the software will adapt the individual load values in a way the model achieves the best correspondence with the injected measurement data. [4] This functionality is depicted as 'load balance' (see Figure 1). Next, an external program was written to actively inject measurement data in the model, repeat the load flow calculation every 10 minutes, and manage the data output of the calculation.
Two vital elements (grid model + complete initial state of the grid) are present at the different DSO's, which are the initial building blocks for establishing a state estimator. The type and quality of the input data injected in the model in time greatly determines the accuracy of the state estimation. In general three different configurations were looked into. (Figure 2)

Scenario 1 : The basic configuration

The basic configuration takes into account the injection of feeder RMS-current values in the model and the position of the breakers. At each feeder the individual load values are adjusted to achieve the best correspondence with the load current measured at the feeder connections in the substations. The loads are scaled linearly according to the predefined default values in the model. Since only RMS-values of the current are passed to the model, the power factor of the loads stays equal to the default value entered in the model. Voltage deviations at the MV-busbars up to 10 % were noticed, active power deviation up to 10 % and reactive power deviations up to 50 %.

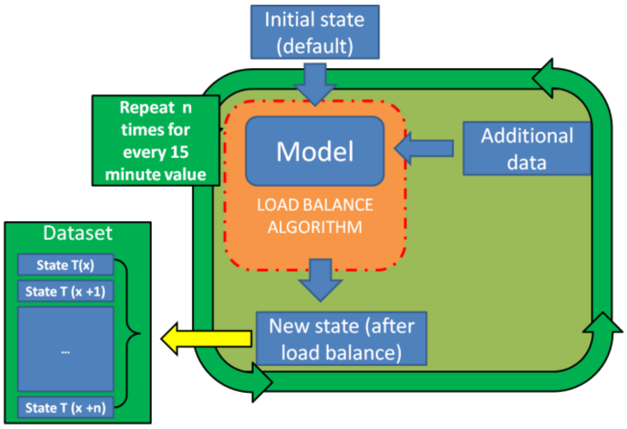


Figure 1: Working principal of the real-time demo state estimator.

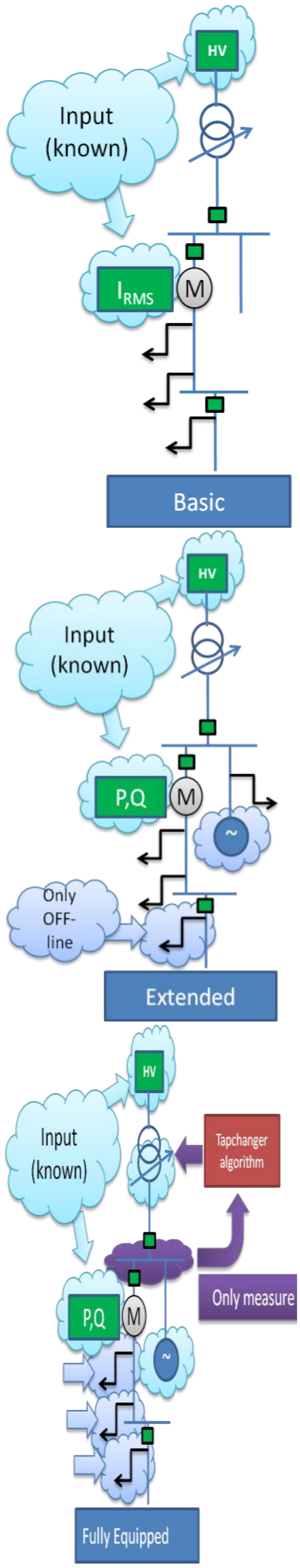
This was mainly due to the fact that no information on the power factor is passed on to the model, nor on the tap position of the OLTC at the transformer. The relative deviation of 50 % needs to be put into perspective with the absolute values, which is dependent on the loads at the different feeders. In this area, most feeders have a power factor higher than 0.95 which means that the deviation of 50 % corresponds in reality to small absolute values of some 100 kVArs.

Scenario 2 : The extended configuration

This scenario is split up in two sub scenario's, hence the input and output columns are split up in two sub columns. The extended configuration employs P,Q feeder data (column 1) or signed RMS-current values (column 2), and the addition of some loads and decentralized production units. The individual loads are balanced on the power factor as well. Voltages are calculated with less than 5% of error (compared to SCADA). The tapchanger position remains unknown. Active and reactive power balance at the busbar can be calculated with less than 5% of error. Integration of the loads tends to lead to more precise results in the different feeders. The configuration was tested for a rural case, with off-line provided data from a case-study, yet no PMU's were employed in this case. Integrating the sign of the feeder currents is needed to keep deviations to the same level, when bi-directional power flows are present. With abundant decentralized production the sign is important.

Scenario 3: The fully equipped configuration

The fully equipped configuration employs P,Q feeder data and P,Q load data at all locations, combined with the injection of the tapchanger position into the model. It is expected that this version attains the same accuracy as the provided input data. Today with the existing assets, this is impossible to realize, but can be approached if more knowledge is gathered on the unmetered loads in the grid. The unmetered loads could be replaced by predetermined load profiles, according to different meta-data (location, type, distributed generation, MV/LV transformer data,…)



Scenarios →	Basic (Sibelga)	
Observables	Input	Output
U HV	X	Identical
Φ HV (*)	X	Identical
U MV busbar		8 %
Φ MV busbar (*)		~ 1-2 °
Tapchanger pos.		~ 4 %
P (transformer)		< 10 %
Q (transformer)		> 50 %
I feeder	X	< 10 A
I sign		unknown
P feeder		< 10 %
Q feeder		> 50 %
U MV nodes		8 %
Switch states	X	Identical
P loads		unknown
Q loads		unknown

Scenarios →	Extended (TBC)			
Observables	Input		Output	
U HV	X		Identical	
Φ HV (*)	X		Identical	
U MV busbar			< 5 %	8 %
Φ MV busbar (*)				
Tapchanger pos.				
P (transformer)			< 5 %	< 5%
Q (transformer)			< 5 %	< 50 %
I feeder		X	< 10 A	
I sign		X	Identical	
P feeder	X		< 5 %	< 10 %
Q feeder	X		< 5 %	> 50 %
U MV nodes				
Switch states	X		Identical	
P loads				
Q loads				

Scenarios →	Fully Equipped	
Observables	Input	Output
U HV	X	
Φ HV (*)	X	
U MV busbar	X	
Φ MV busbar (*)		
Tapchanger pos.		
P (transformer)		
Q (transformer)		
I feeder		
I sign		
P feeder	X	
Q feeder	X	
U MV nodes		
Switch states	X	
P loads	X	
Q loads	X	

Figure 2: Schematic overview of a grid model and injection of data in the fully equipped version – overview of observables and accuracies after comparison between the data sets: (top) basic version, (middle) extended version, (bottom) fully equipped version.

Next to that, a tap changer algorithm based on the voltage measurements at the MV- busbar could be established to calculate the tap changer position.

EXPERIENCES OF PMU'S IN DISTRIBUTION GRIDS

It is clear that knowledge of the voltage angle could be a vital source of information for daily operation, especially in the urban region of Brussels, since a lot of parallel couplings in the MV-grid take place in the exploitation of the grid. [1][3] Nine devices were installed in the field, measuring the voltage phasors. The results were compared to the available information from SCADA and other measurement sources.

Description and performance of the PMU-system

The PMU – system consists of the following components:

- The PMU-devices, physically installed in the substations, synchronized by GPS
- The communication system between the devices and the PMU-data server, employing mobile GPRS communication
- The PMU – data server

The PMU-device has the ability to calculate the voltage phasors, and was built on a cRIO® data acquisition platform (National Instruments) by Laborelec. The GPS-module has the ability to synchronize the devices up to 100 ns precise, and contains an internal quartz clock to cover brief loss of synchronization. This second feature proved to be indispensable when using PMU's in urban areas. Antenna manufacturers prescribe a clear open sky view for the antenna to guarantee the well-functioning, which is a challenge in urban areas that often cannot be met. The communication system is often susceptible to loss of connection. To cope with this, the data rate was increased to significantly higher samplings than what is normal for distribution grid measurements. In this project, a sampling rate of 10 second-values was attained in a stable way. In the best cases, 95 % of data could be retrieved daily. The worst cases, where the antenna placement proved very challenging, represented a successful daily data rate of 80 %.
The different devices where installed in three different MV-grids in the Brussels area. It was chosen to install the devices at the substations, both on the MV and HV-side of the feeding transformers. Also, PMU's were installed at different switching stations in the MV-grid.
In normal operation, the MV-grids are operated independently from each other, but are sometimes coupled in parallel to allow the transfer of load between the substations during interventions in the grid.

Application of PMU measurements

The data of the PMU-system was used to calculate time series of phase angles and voltages at different locations. This data was compared to other available data.
The voltage time series can be represented in absolute values, namely the voltages at the busbars. The angle time series are always represented relative to a chosen reference point. An example is given in Figure 3.

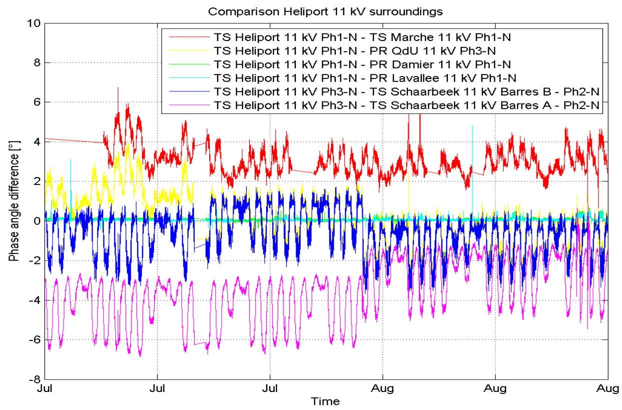


Figure 3: Phase angle differences time series between the different substations in the Brussels region.

It can be noticed here that the phase angle difference shows an repetitive variation, which is related to the load at the substations. Phase angle difference tend to become greater when the load at the substations increases compared to the load at the reference substations. Also, a change in exploitation of the MV-grid has a significant impact on the phase angle difference, as can be seen to occur at the beginning of august during the measurement campaign. In this case a switching substation was re-routed to another feeding substation. Next to that, it was noticed that, due to the nature of the grid which is quite strong in the Brussels region, phase angle differences inside a MV-grid zone tend to be quite small.
Due to the increased data rate, it was also possible to distinguish single events from the operation of the grid. An example of such an event is shown in Figure 4, which depicts a brief parallel coupling between two substations. It can be seen that this action provokes a sudden collapse of the angle difference between these substations, while the angle difference with another neighboring substation increases.
Secondly, the on-load tap changer (OLTC) position at the MV-side can be calculated thanks to the highly sampled HV and MV voltage profiles. This information is normally not available at the dispatcher, nor logged by the DSO, since it is an act of a local voltage controller. In Belgium, these OLTC's are even the property of the TSO. The results are shown in Figure 5. The algorithm for detection of a tap change, counts on the fact that a sudden voltage change is seen at the secondary side, and not at the primary side. This way, it can make a distinction between the act of a FACTS device in the grid (such as a capacitor bank) or a tap change in the high-voltage grid, and a real tap change at the secondary side of the HV/MV-transformer. PMU-measurements have in this case a direct application for the grid operator, since it is an aid for the prediction and follow-up of complex grid

operations, which cannot be estimated with the present measurement capabilities.

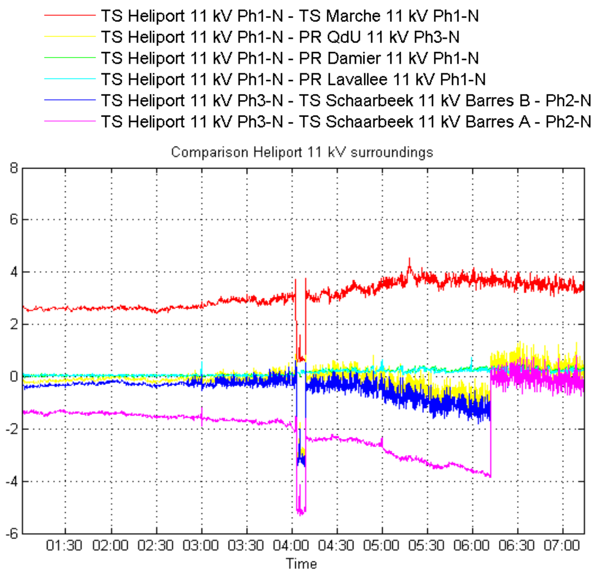


Figure 4: Phase angle differences time series between the different substations in the Brussels region (zoom).

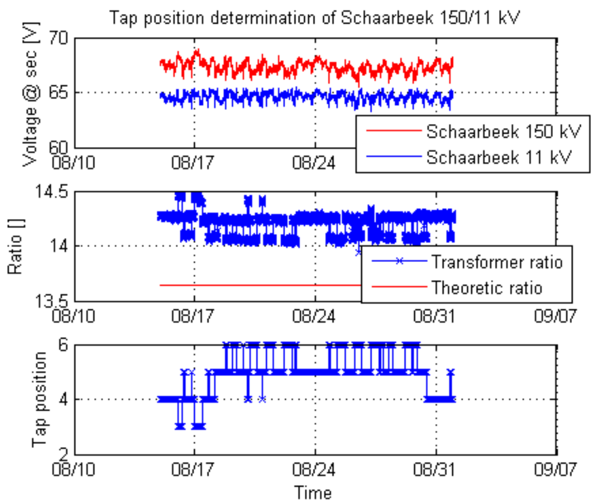


Figure 5: Calculation of the on-load tapchanger position time series: (top) absolute voltage profiles at the secondary side of the voltage measurement transformers, (middle) evolution of the transformer ratio, (bottom) result of the tap-position evolution calculation.

Comparison of the different data sets

The comparison was made between the following data sets: the output of the state estimator of the TSO, measurement data of the DSO SCADA, PMU measurements done in the demo platform at the DSO, output from the demo state estimator at the DSO. The comparison was done on a common data point, namely the MV-grid busbars at the transformer substations.

ΔV median [kV] Location	TSO state estimator	DSO SCADA	DSO PMU	DSO state estimator
Heliport 11 kV	0.8	0.1	0.1	0.1
Schaarbeek 11 kV	0.3	1.7	0.3	1.7
Marché 11 kV	0.5	0.1	0.1	0.3

Δφ median [°] Location	TSO state estimator	DSO SCADA	DSO PMU	DSO state estimator
Heliport 11 kV	0.6	NA	0.1	0.1
Schaarbeek 11 kV	0.1	NA	0.1	0.1
Marché 11 kV	0.3	NA	0.1	0.1

Figure 6: Differences between data sets: (top) voltage differences [kV] (median), (bottom) angle differences [°] (median).

Figure 6 shows that in general, the voltage differences between the different data sources remain beneath 300 V (2.7 %), with the exception of the output of the TSO state estimator which has the worst offset at 800 V (7.3 %) with respect to the other data sets. The reason here is that the TSO state estimator does not contain MV-grid voltage measurements on all locations, and that tapchanger information is not passed to the state estimator regarding the OLTC at the MV-grid level. Hence the estimation of the MV-grid voltage contains a certain mismatch with reality. A second large offset was seen at one of the substations, where a voltage difference up to 1.7 kV was seen. This unusually large offset was due to a faulty measurement converter at the substation. Since this data was also fed to the demo state estimator, this resulted in the same deviation on the output. Regarding the angle differences, it appears that the angle calculations are quite accurate. The most accurate data set is in this case the PMU-system. Due to the fact that the active power transit through the HV/MV – transformer is taken into account in the TSO state estimator, the estimation of the MV-grid angle by the TSO is quite accurate. An angle difference below 1° of error is considered to be accurate in this case.

CONCLUSIONS

The presence of the two vital elements (model + initial states) at the DSO's, allowed to set up a basic state estimator. From a first experience, a basic version of a state estimator gives satisfactory results without significant investments on measurement devices in the MV-grid. Also the injection of HV-grid data is a requirement, which was a success thanks to the sharing of this data between TSO and DSO. In general, the comparison of the different data shows that the differences stay rather limited. A point of attention is the voltage differences with the TSO state estimator output, which could be improved by increasing the detailing of modeling of the MV-grid. An alternative for this can be data provided by a PMU installed at the substation. The demo platform shows that even in challenging urban regions, data rates above 80 % are attainable.

In general, the lack of power measurements (P,Q) is the biggest bottleneck for improving the accuracy. Also the voltage (and angle) measurements at the busbars are highly recommended for checking the results of the calculations. The first priority here is placing these measurements at the MV-feeder connections in the substations. This type of measurement could be of great benefit in determining a more accurate averaged power factor inside an MV-grid zone. This way the initial state could be improved significantly. The second priority is placing the measurements at some strategic loads in the MV-grid, to be able to study the MV-grid load profiles more in detail.

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BIOGRAPHIES

Stijn UYTTERHOEVEN graduated at Katholieke Universiteit Leuven as civil electromechanical engineer, option electrical energy. Since 2008, he is employed at Laborelec as specialist on electrical power systems. His main activities are in the field of electrical networks and power quality and power line communication investigation. His main interests are power electronics, smart grids and power quality analysis.

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