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SMILE

The theoretical and application **S**tudy on a **M**etering and **I**ntelligent tool for **L**ow Voltage grid control **E**nhancement

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Zusammenfassung

Ziel des SMILE-Projekts ist, Algorithmen zu entwickeln und in einem intelligenten Messsystem GridEye (entwickelt durch die Firma DEPsys) zu integrieren und damit den Verteilnetzbetreibern (VNB) zu ermöglichen, ihre Netze zu analysieren und zu steuern. Diese intelligente Plattform bietet eine wirksame Kontrolle der Kosten und der störenden Auswirkungen auf das Verhalten des Stromnetzes (Überschreiten der Maximalwerte für Spannung, Strom, usw.), welche vor allem durch das vermehrte Einspeisen erneuerbarer Energien hervorgerufen werden. Romande Energie und DEPsys haben die Anforderungen an die Überwachung und Steuerung von Niederspannungsnetzen definiert, wobei über 30 verschiedene VNBs aus fünf Ländern befragt wurden. Aus dieser Erkenntnis wurde der Prototyp GridEye v2 mit spezifischer Softwarearchitektur entwickelt und in ein Live-Netz integriert. Ein besonderes Augenmerk wurde auf die Signalverarbeitung gelegt um eine hohe Messqualität unter Berücksichtigung der Einschränkungen eines kostengünstigen, integrierten Systems zu erzielen. Schlussendlich wurde ein Algorithmus zur Berechnung der Spannungsempfindlichkeitskoeffizienten entwickelt, welcher ohne die Kenntis der Netzparameter auskommt. Dieser Algorithmus kann zur dynamischen Steuerung (Droop Control) des Netzes, sowie für die Regelung eines expliziten Leistungssollwertes verwendet werden.

Résumé

Le but du projet SMILE est de développer des algorithmes à intégrer dans un outil de mesure intelligent appelé GridEye (développé par la société DEPsys), afin de permettre au GRD (Gestionnaire de Réseau de Distribution) de visualiser et de contrôler leurs réseaux avec une approche décentralisée. Cet outil intelligent fournit un contrôle efficace des coûts et des effets perturbateurs sur le fonctionnement du réseau électrique (violation de tension, courant, etc.) causée principalement par la croissance des DER (sources de production décentralisée). Pour réaliser ce projet, les exigences les plus importantes pour un GRD concernant la surveillance et le contrôle du réseau basse tension ont été définies par Romande Energie ainsi que par DEPsys (qui a interrogé plus de 30 GRD dans 5 pays différents). A partir de ces exigences, un prototype spécifique (appelé GridEye V2.0) ainsi qu’une architecture logicielle dotée d’une plateforme de visualisation ont été spécifiquement développés et intégrés dans un réseau électrique réel. Une attention particulière a été mise sur le traitement du signal afin de permettre d’obtenir de hautes performances de mesures tout en prenant en compte les limitations relatives à un système embarqué à faible coûts. Pour finir, un algorithme permettant de calculer le coefficient de sensibilité de tension sans paramètres de réseau a été conçu et testé avec les mesures réelles d'un réseau basse tension. Ce résultat sera utilisé pour la stratégie de contrôle par exemple droop control pour les onduleurs ou de pouvoir affecter des consignes précises en termes de puissance active et réactive pour les systèmes de production ou de stockages controllables (explicit power set point).

Abstract

The goal of the SMILE project is to develop algorithms to be integrated in an intelligent measurement tool called GridEye (developed by the compagny DEPsys), to allow DSOs (Distribution System Operator) to monitor and control their network with a decentralized approach. This smart tool provides an effective control of costs and disruptive effects on the functioning of the electricity grid (voltage violation, congestion, etc.) caused mainly by the growth of DER (Distributed Energy Resources).To realize this project, the most important DSO's requirements for a future monitoring and control system for the low voltage grid were defined. This information was provided by Romande Energie and by DEPsys (who asked more than 30 DSO's in 5 different countries).From these requirements a specific hardware prototype (called GridEye V2.0) and software architecture with a visualization platform were developed and integrated in a real low voltage grid. A particular attention has been set to find the best signal processing allowing a high performance measurement while taking into account the limitations of a relatively low cost embedded system. At the end, an algorithm allowing the calculation of the voltage sensitivity coefficients without grid parameters was designed and tested with real measurements of a low voltage grid. This result will be used for the control strategy e.g. dynamic droop control, explicit power set point, etc.

Table of Contents

1 Acronyms

DC	Direct Current
DER	Distributed Energy Resources
DESL	Distributed Electrical Systems Laboratory
DFT	Discrete Fourier Transform
DSO	Distribution System Operator
DSP	Digital Signal Processor
EPFL	Ecole Polytechnique Fédérale de Lausanne
GIS	Geographic Information System
HEIG-VD	Hautes Ecole d’Ingénieurie et de Gestion du Canton de Vaud
HV	High Voltage
HW	Hardware
IESE	Institut d'Energie et Systèmes Electriques
LV	Low voltage
MV	Medium voltage
NTP	Network Time Protocol
OPEX	operating expenses
PLL	Phase-Locked Loop
PMU	Phasor Measurement Unit
PV	Photovoltaic
RDDI	Remote Device Debug Interface
RSSI	Received Signal Strength Indicator
SW	Software
UHV	Ultra High Voltage

2 Starting Context

Although positive, the increase of distributed power generation (mostly renewable) causes the appearance of a bidirectional power flow in an infrastructure that was not designed for. This is causing many disruptive electrical phenomena that are increasingly difficult to manage by the Distribution System Operator (DSO). Stochastic production of renewable energy sources, production capacity and geographical location of the production sites are variable parameters that complicate the control of the distribution network. The task of the DSO is now complex: it should guarantee the stability of a distribution infrastructure without any control and monitoring system. In a period marked by a genuine energy revolution, this will certainly be a real technological challenge.

3 Goal of the project

The goal of the SMILE project is to develop algorithms to be integrated into GridEye, an intelligent measurement tool developed by the company DEPsys, to allow DSOs (Distribution System Operator) to monitor and control their network. This smart tool provides an effective control of the disruptive effects on the functioning of the electricity grid (voltage violation, congestion, etc.) caused mainly by the growth of DER (Distributed Energy Resources), thus reducing the related costs

The main scientific objectives are the development of a measurement tool able to monitor and control the low voltage grid-based on the estimation of the voltage sensitivity coefficient without any parameters of the grid and define a communication architecture able to minimize the data transmitted to a central point.

4 Requirement of DSOs

To design a solution near to the actual market and customers' needs in term of monitoring and control, the industrial partners, Romande Energie and DEPsys, have submitted the following DSO requirements.

1) **Grid parameters:** Most of the already existing optimal control procedures require an accurate knowledge of the feeder's topology and line/cable parameters. In low voltage grids, this assumption does not always hold in reality. In particular, DSO might have wrong data for the feeder parameters or in some cases, no information is available (especially in developing countries, see Figure 1b). Furthermore, there are factors, such as the temperature 12, aging or various impedance as fuses or connection resistance that can cause variations in the values of the resistances and/or impedances of the network branches, which are not (or with difficulty) taken into account in the computation of the admittance matrix. Therefore, a "model-less" approach shall be followed.

2) **Retrofit:** The system must be integrated into the actual DSO's infrastructure, which has not been designed to install this type of devices (see Figure 1a).

3) **Limitation of OPEX cost:** Especially in the low voltage grid, the topology is modified/adapted quite frequently (more or less each day for a network DSO with around 300'000 customers). Figure 2 shows the evolution of the chosen area from the beginning of the project (2014) and the end (2016).

   As shown in the example in Figure 3, in two years, the following main changes occurred:

   - Two solar plants (1x74kVA, 1x 5kVA) installed,
   - Three residential homes added,
   - One distribution cabinet added.

   The system must be as Plug&Play as possible to limit OPEX cost of the DSO in term of installation/ maintenance of the solution, due to the "fast" integration of decentralized sources and to the grid infrastructure evolution.

4) **Easy to install:** This kind of systems will be installed by an operator of distribution system who typically is not familiar with these electronic devices. Therefore, the system must be easy and quick to install, without requiring an engineer at each installation.

5) **Low voltage grid observability:** DSOs today have no vision of their LV network. To ensure quality and adequate supply mainly due to sources of distributed generation, it is necessary to increase the visibility of networks.

6) **Scalability and Modularity:** Smart-Grids are evolving, the legal framework is changing and varies in different countries. It is necessary to evolve in terms of control and monitoring, solution strategy may change over time and new laws for years to come. The system must be able to be updated by remote control.

Figure 1: a) example of a Swiss node on cabinet and b) a Chinese node on pole

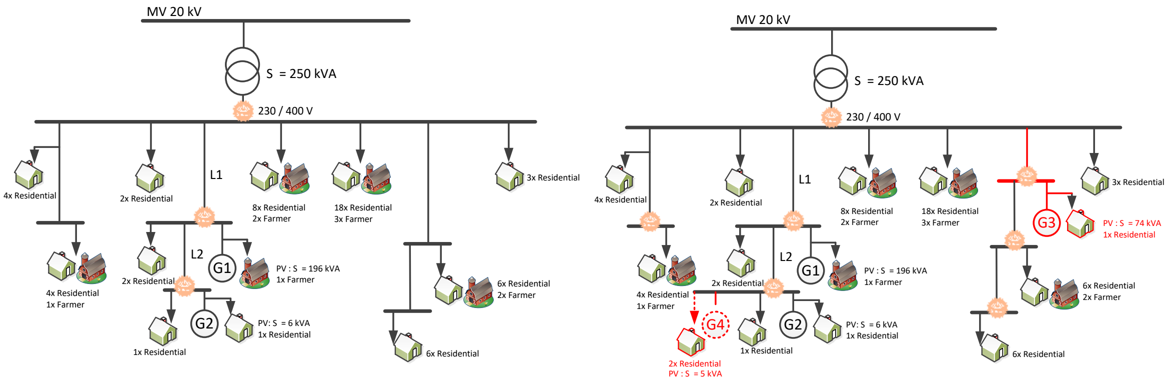

Figure 2: Example of the evolution of an LV grid infrastructure in 2 years: a) 2014 – b) 2016.

5 Concept – installation description

5.1 Hardware

A hardware prototype (called GridEye V2.0, see Figure 3) to be integrated into the LV grid has been specified and built. It was mainly composed of a DSP for signal processing of the four currents (three phases plus neutral) equipped with Rogowski coils and three voltages sensing, an ARM processor with an embedded Linux for the high-level processing and a GSM 3G for the communication and synchronization with an NTP protocol.

The possibility to buy an existing device was evaluated, but it was preferred to design a new one, mainly for the following reasons:

1) The most important constraint was to be able to integrate this type of devices in the existing infrastructure, especially in the distribution cabinet, where the available space is limited.

2) To be free to change the measurement algorithm (depending on the accuracy and dynamic of signals, see section 6.1), and to be able to update it by remote control depending on the need of the development during the evolution of the project.

Figure 3: GridEye V2.0

5.2 System Architecture

Compared to the conventional control system of the electrical network used for the transmission in HV, GridEye brings a new approach: **the decentralized intelligence.** The main idea is to have an autonomous control system in the LV area. The goal is to avoid the problems related to big data management. Indeed, the centralized control of (several) thousands of production/storage sources seems to be quite challenging and would require a lot of servers and computing units. Therefore, the two main objectives of GridEye are:

1) To avoid a big data infrastructure (limiting the costs of large infrastructure)
2) To avoid the single point of failure on control signal (limiting the risk of blackout)

Sometimes this unusual approach to the electrical grid control can scare the DSOs because no "human being" is behind to control system. However, considering that the system is designed for small LV areas, the risk and the consequence of a severe blackout are limited.

Figure 4 shows a typical example of the structure of an electrical grid, with the centralized control (as today) for the EHV, HV and sometimes MV and the decentralized approach to control the LV grid thanks to the GridEye solution.

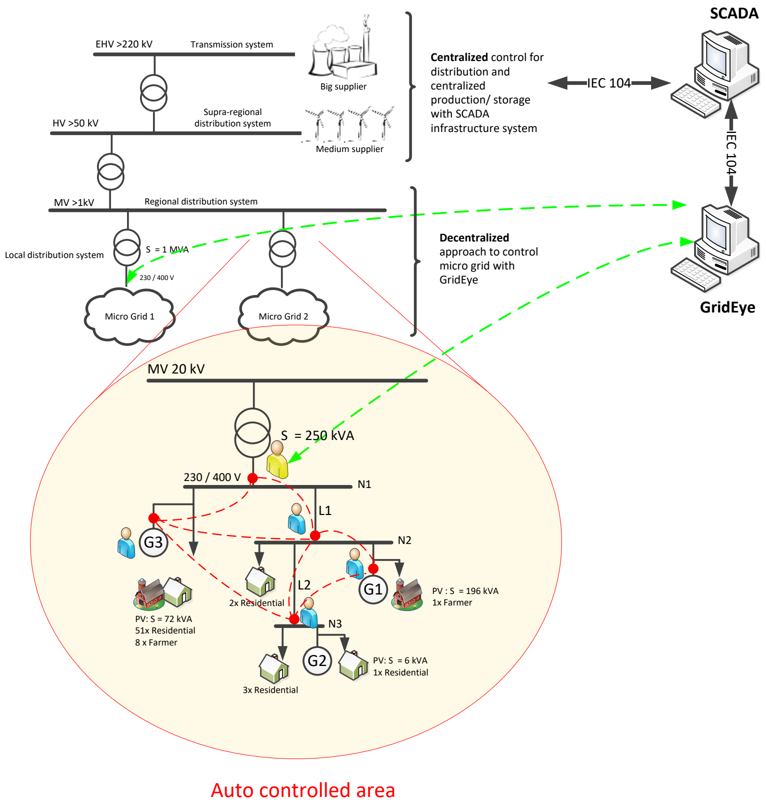

Figure 4: Structure of the LV auto controlled area

5.3 Communication, data acquisition and visualization

The GridEye V2.0 used for this project was designed only with a GSM communication. This choice was mainly driven by the easy implementation compared to other technologies (which was not the specific goal of this project). Therefore, a mesh communication as shown in Figure 4 was planned for the next version (V3) of the device GridEye. A specific CTI project was built to specially deal with this topic.

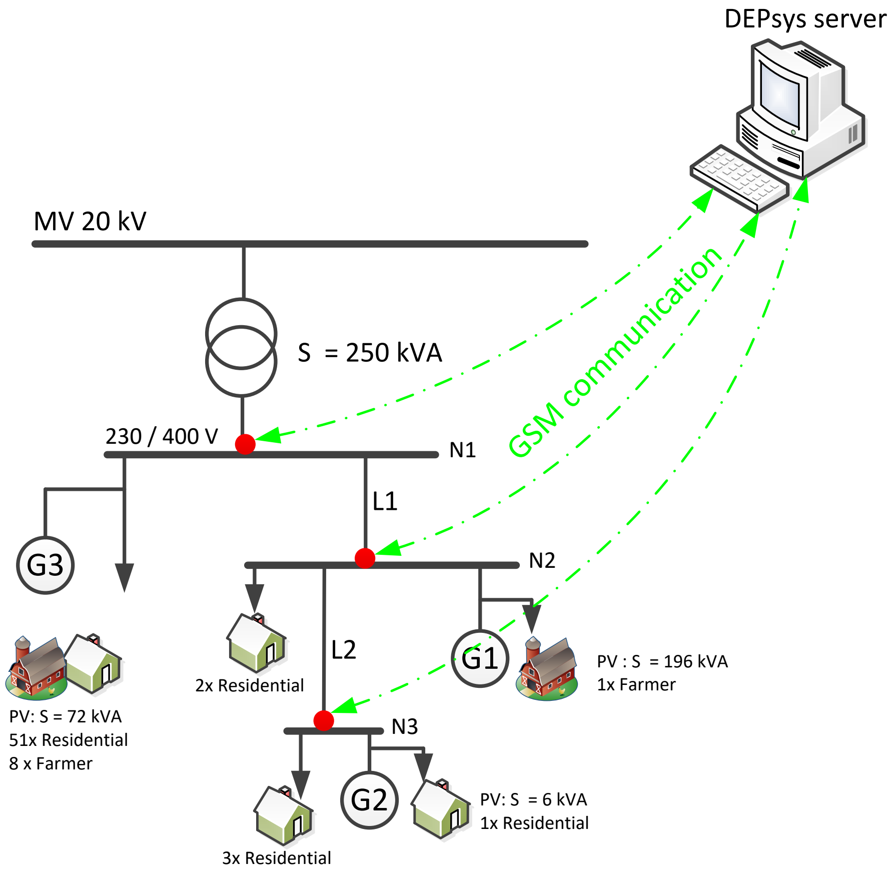

Figure 5: Communication system

The communication is bidirectional. From the devices to the server, the measurements of the magnitude of the voltage, the current and the phase difference for each module installed in the grid are sent to a server. The maximum refresh frequency is 1 per second. This value can be parameterized if slower frequencies can be accepted. The different modules measurements are synchronized with each other with an NTP protocol. From the server to the devices the communication allows to update the algorithm and set parameters (as for example the sampling frequency).

5.4 Web application visualizations and remote control

In order to visualize and download data for the calculation of the sensitivity coefficients with real measurement, it was necessary to design a specific application on the server (Figure 6).

Figure 6: GridEye web application

As specified at the beginning of the project, the DSO need more observability for a better understanding and to ensure a good quality of services in the low voltage grid. This platform was first of all developed for data collection needed to develop the “voltage sensitivity coefficient” (see section 7). In a second time, it allows also the DSO to analyze what’s happening on the grid in real time (e.g. alarm when a voltage violation appears), and be a useful tool for statistics of the low voltage grid (e.g. statistic evaluation of transformer loading, or maximum loading of cables, etc.).

In future it could be also used to participate in system planning, SCADA integration, or in balancing markets and/or balancing groups.

5.5 Testing area

The network used in this case study is an actual low voltage three-phase radial distribution feeder (230/400 V, 50Hz) selected by Romande Energie and located in a rural area (Chapelle-sur-Moudon, Vaud) in Switzerland, shown in Figure 7. This particular area is composed of 57 residential blocks, 9 agricultural buildings, and supplies in total 88 customers.

This system has been selected as it contains non-negligible injections from photovoltaic systems. The existing decentralized PV plants provide a maximum power of 274kVA divided respectively in three PV generators of 6kVA, 196kVA, and 72kVA. With the existing PV capacity, there are periods of times during which the production of power is larger than the consumption of the entire area. The associated power flows in these cases cause non-negligible voltage fluctuations, above the allowed limits. In particular, voltage variations of more than 9% larger that the network rated value are constantly observed, with consequent impacts on the power quality (see section 5.6).

The second reason why this grid was selected is because its network topology and components data are available and, therefore, it is possible to validate the various results obtained in this project.

Figure 7: Grid topology of used area

5.6 Field Test Condition

To simplify the use case for the development of this project, the goal was to concentrate the efforts on one radial feeder in the electrical grid selected by Romande Energie (Figure 5). The following figures show the installation of GridEye devices in the actual grid in Chapelle-sur-Moudon.

(a) Transformer: Device GridEye V2.0 installed in the transformer.

(b) Transformer: Rogowski coils for current measurement on LV side transformer.

(c) Cabinet: Romande Energy operator fixing a vertical switchgear in a cabinet to protect the measurement of the GridEye module.

(d) Cabinet: Rogowski coils for current measurement at the input of the cabinet.

Figure 8: Installation of GridEye devices in Chapelle-sur-Moudon

In the following, some cases are analyzed to highlight different phenomena related to photovoltaic distributed generation.

In Figure 9 we see that during high levels of solar productions, voltages near to injection points can reach critical levels, e.g. +9% of the nominal value of 230V (see Figure 9).. However, using conventional grid simulation software (e.g. "CYME") and making a load flow analysis based on theoretical data of the grid (i.e. data of grid available from the planning studies), the voltage variation of this node should not exceed 2.44% (see "DeltaU "in Figure 9).

Even making reference to a higher nominal voltage of 240V (instead of 230), the voltage variation is higher than 4.5% (250V). This means almost a factor of two with respect to the theoretical value (simulation). From the abovementioned observation, we can deduce that a great uncertainty lies between theoretically available data (based on the datasheet of the cables) and measured data in the field. Therefore, as mentioned at the beginning of this report, a "model-less" approach for controlling the network is the best option.

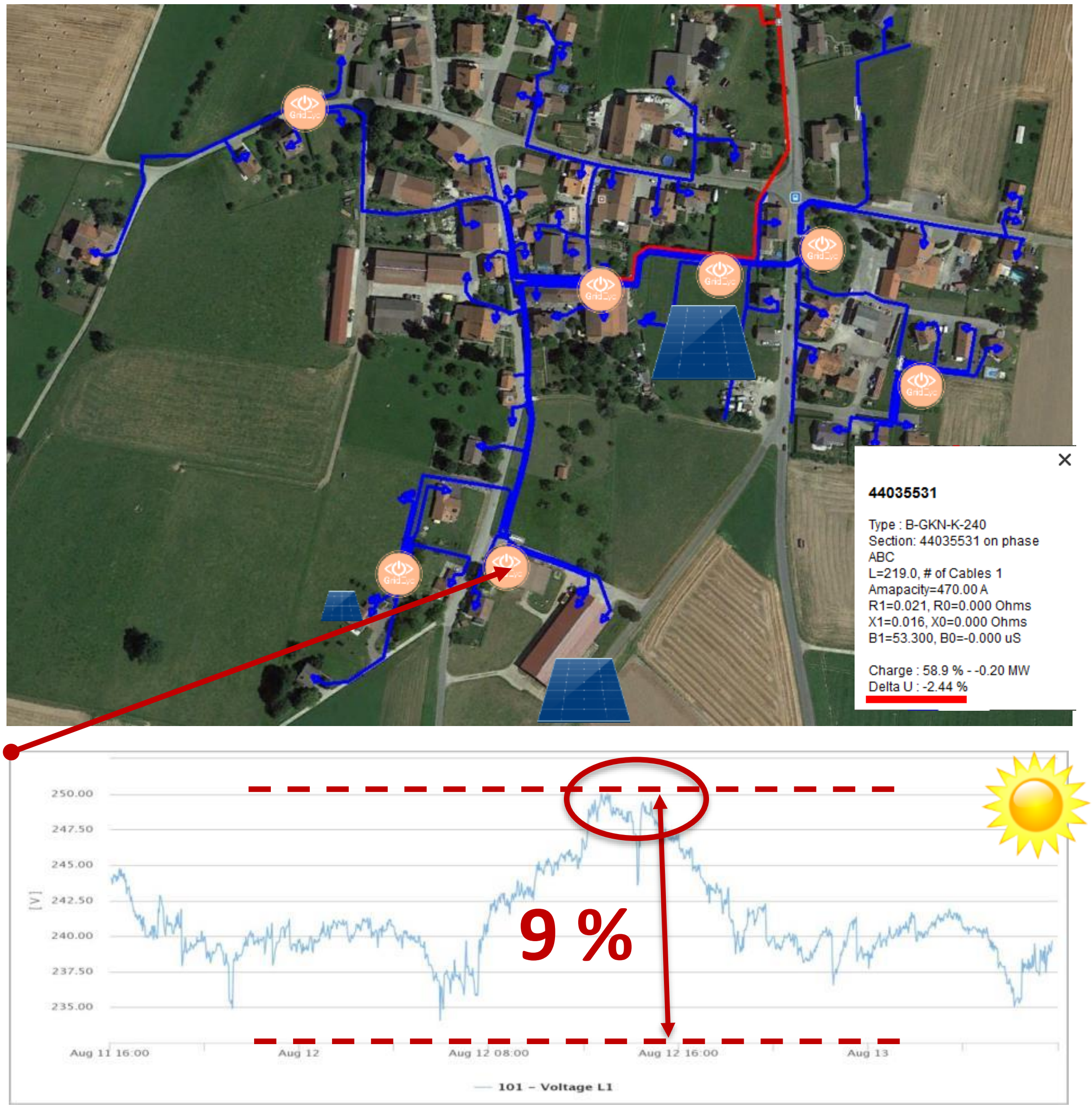

Figure 9: DER impact on the LV grid voltage variation

Figure 10 allows highlighting the high dynamics of PV generation sources, due to rapidly changing weather conditions, e.g. due to fast moving clouds. These variations directly affect the quality of services of the voltage on the overall LV grid. Another phenomenon also visible in this type of district is the "overproduction". As it can be seen in Figure 11, during certain periods an important quantity of the energy produced is directly fed back into the medium voltage network.

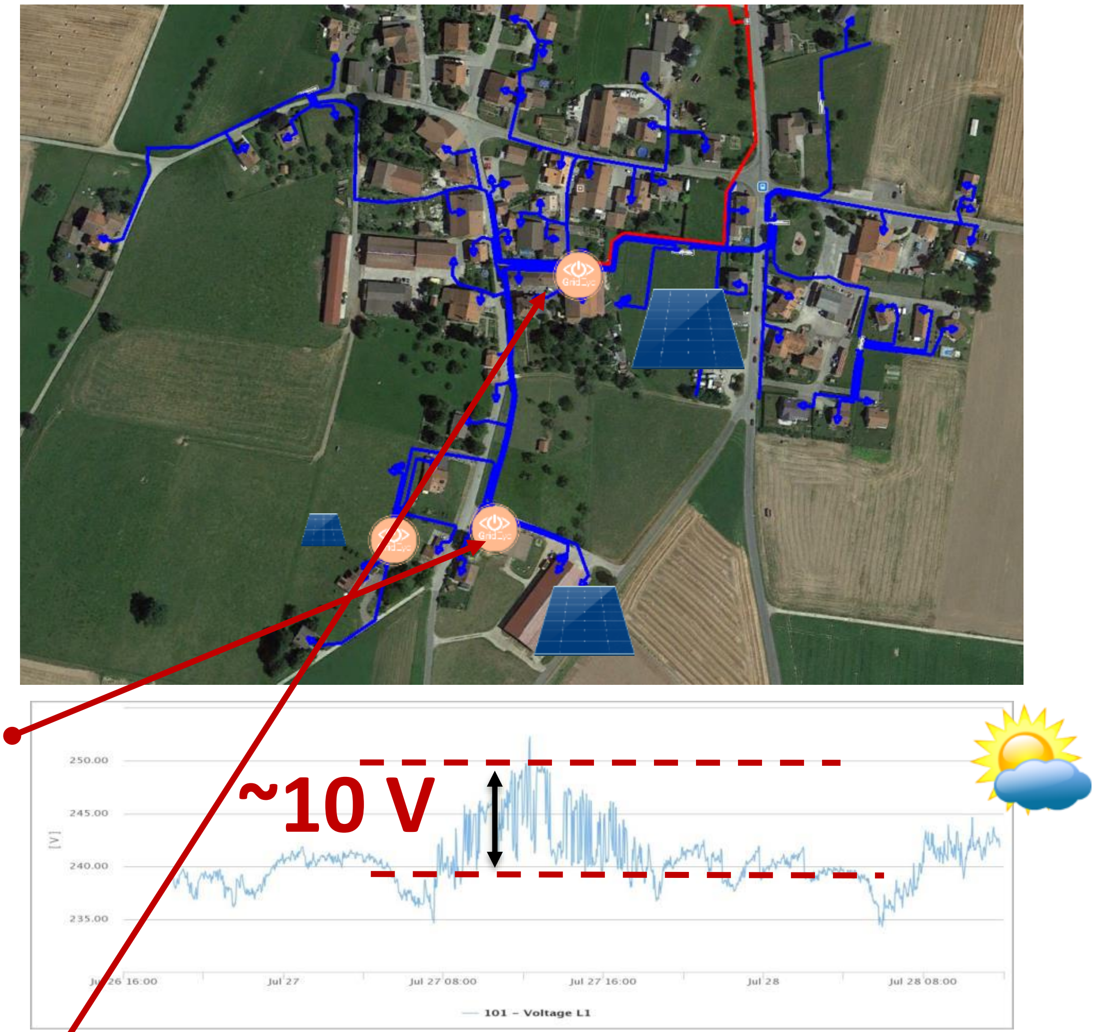

Figure 10: DER impact on the LV grid voltage variation

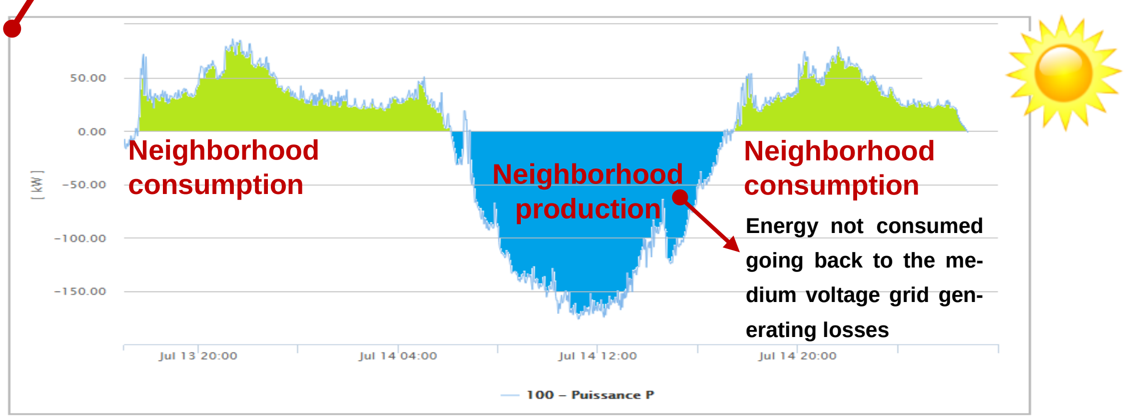

Figure 11: MV/LV transformer bidirectional power flow.

6 Procedure / methodology

6.1 Voltage and current calculation algorithm

The choice of generating an electrical network management system with a "model-less" approach induces specific constraints in terms of measurement specifications. The measurements affected are the voltage and current amplitude, and the phase shifting between the two.

The first system developed within SMILE was based on IEC 61000-4-30 standard. However, to achieve the accurateness of the measurement required by this application, a complete review of the procedure was necessary. The method previously used was quite good but a significant time window was necessary to ensure good results accuracy. In addition, in the case of a high dynamics network, the power factor calculation procedure was not stable enough. The presence of harmonics strongly perturbed the validity of the results and the fact that each value was calculated on a differentiated acquisition did not suit the needs of the new synchronization algorithm.

It was decided to continue research in the treatment of electrical measurement for the case of desired application. In order not to waste valuable time in a full hardware redesign, it was decided to keep the same basic hardware to meet these new requirements.

The use of a DSP with the average performance for digital acquisition and signal processing imposed the following main requirements to the new algorithms:

1. The values that the algorithm must process are: voltage, current and the dephasing for the three phases.
2. The current and voltages samples must be synchronous within a fixed time window.
3. The algorithm should be able to process the required values in a period of 60ms, to satisfy the network dynamics.

6.2 e-IpDFT algorithm

The choice fell on the e-IpDFT (Enhanced-interpolated DFT) algorithm used by the PMU developed by EPFL/DESL [2]-[4]. The main advantage of this algorithm is that it allows an extremely fast processing to determine the value of the fundamental frequency of the signal inside a fixed acquisition window. This eliminates the necessity of a PLL to synchronize signals and to process a fixed number of samples in a fixed time window. The proposed algorithm has several advantages. Besides the aspects considered above, it also eliminates the problems related to the harmonic. Moreover, the calculation of sensitivity coefficients requires the fundamental values to avoid skewing the results. In terms of HW resource, this algorithm turns out to be an excellent compromise. It requires a non-negligible storage for weighting tables but the real time computing resources are very limited, which is interesting for embedded systems applications.

The algorithm principles will be shortly summarized in the following.

The actual system allows the sampling of the analog signals at 30 kHz. The chosen acquisition window corresponding to three fundamental periods, so 1800 samples must be treated.

The DFT (Discrete Fourier Transform) is defined as:

$$s(n) = \tilde{s} + \sum_{m=1}^{M} A_m \cos(2\pi m f_1 n\Delta t + \varphi_m), \quad n = 0,1,\ldots,N-1 \ (1)$$

where

- f_1 fundamental frequency (a priori unknown)
- $\tilde{s}$ DC component
- N sampling number
- A_m amplitude of m-t h harmonics
- φ_m phase of m-t h harmonics.

The signal s(t) is sampled with a sampling period $\Delta t = 1/f_s$ on a time window $T = N\Delta t$. This time window is short enough for the signal to be considered as stationary.

To avoid problems resulting from the abrupt discontinuity at the ends of the truncated function, especially if the frequency is not exactly the nominal one, the samples are preliminarily processed through a weighting window. Among the various windowing techniques presented in literature, the Hann window, or "Hanning", also called "Raised Cosine window", has been chosen. This windowing technique allows for an acceptable compromise between the resolution of harmonic components of comparable value with similar frequencies and components of different values with different frequencies. The Hann window can be obtained as:

$$w(n) = \frac{1}{2}\left(1 - \cos\left(\frac{2 \cdot \pi \cdot n}{N-1}\right)\right)$$

DFT can then be calculated as

$$S(k) = \frac{1}{B}\sum_{n=0}^{N-1} w(n) \cdot s(n) \cdot e^{-jk\beta_n}, \ k = 0,1,\ldots,N-1$$

where

$$B = \sum_{n=0}^{N-1} w(n) \ \text{and} \ \ \beta_n = (2\pi n / N)$$

Separating real and imaginary parts

$$Re(S(k)) = \frac{1}{B} \cdot \sum_{n=0}^{N-1}\left(s(n) \cdot w(n) \cdot \cos\left(k \cdot \frac{2 \cdot \pi \cdot n}{N}\right)\right)$$

$$Im(S(k)) = -1 \cdot \left[\frac{1}{B} \cdot \sum_{n=0}^{N-1}\left(s(n) \cdot w(n) \cdot \sin\left(k \cdot \frac{2 \cdot \pi \cdot n}{N}\right)\right)\right]$$

6.2.1 Evaluation of the fundamental components

Taking into account that the frequency resolution is $\Delta f = f_s/N$, to calculate the whole DFT the calculations above should be repeated for each k [0, N − 1]. However, what is important in this application is a specific frequency k_1 near the utility nominal frequency. It is then possible to calculate only six values, required to interpolate the results, i.e.

$$Re[S(k_1-1)]\ ,Re[S(k_1)]\ ,Re[S(k_1+1)]$$

$$Im[S(k_1-1)]\ ,Im[S(k_1)]\ ,Im[S(k_1+1)]$$

We can define an additional parameter representing the ratio between the highest spectral lines of the DFT evaluated:

$$\alpha=\frac{|S(k_1+\varepsilon)|}{|S(k_1)|}$$

where:

$$\varepsilon=1\cdot sign\left(|S(k_1+1)|-|S(k_1-1)|\right)$$

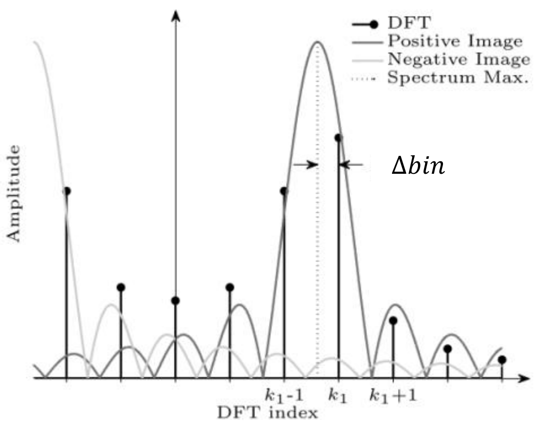

Figure 12: Definition of Δbin and qualitative representation of short- and long- range spectral leakage [2]

According to the hypothesis of adopting a sampling frequency that is much larger than the fundamental tone frequency, we can calculate

$$\Delta bin=\varepsilon\frac{2\alpha-1}{1+\alpha}$$

The result of this method allows determining the following relations for the amplitude, the phase as well as the frequency of the fundamental of the signal contained in the considered window as follows

$$A_1=2|S(k_1)|\cdot\frac{\pi\Delta bin\cdot(1-\Delta bin^2)}{\sin(\pi\Delta bin)}$$

$$\varphi_1=\angle S(k_1)-\pi\Delta bin$$

$$f_1=(k_1+\Delta bin)\Delta f$$

6.2.2 Tests Validation

The implementation of the e-IpDFT algorithm has been validated through tests on the field. The obtained results are within the requirement limits. In order to validate the results, a comparison of the phase voltage and the power factor between the GridEye device and a commercial reference-measuring power analyzer tool (Mavowatt 70) has been performed (Figure 13 and Figure 14).

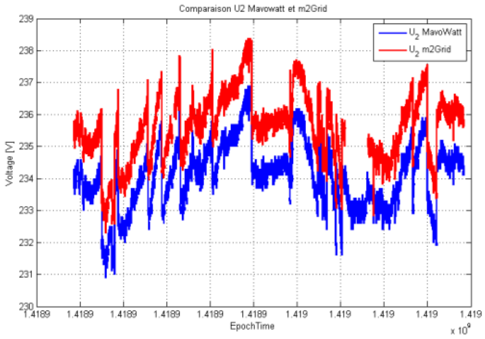

Figure 13: Phase voltage comparison.

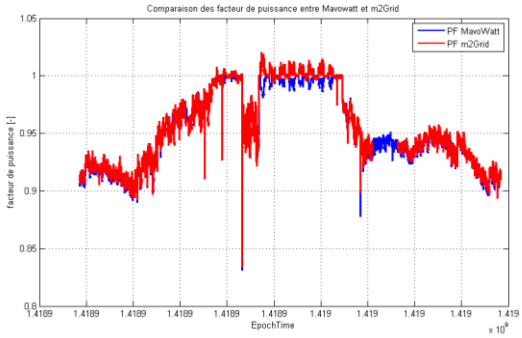

Figure 14: Power Factor comparison.

Analyzing the quality of the voltage, one can see that the line voltage measured by both systems is very similar. However, an offset of approximately 2V has been observed in the GridEye system, due the HW choices made on the GridEye measuring chain. This behavior is known and can be easily corrected by calibration.

As far as the phase is concerned, the developed system allows to directly discriminate between inductive and capacitive behavior, while the commercial network analyzer makes no difference when the inductive/capacitive power behaviour changes to the other one. This issue of the commercial network analyzer can be observed in Figure 14 near the unity factor.

The conclusion is that the DFT algorithm has been properly implemented, and has been installed by remote control on all the devices currently in the field.

7 A control approach based on voltage sensitivity coefficient

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7.1 Introduction

The distribution system operators (DSOs) have to ensure the technically secure operation of their grids. The customers would like to have access to reliable and economic power supply. Therefore, the secure and economic operation of distribution grids are essential for both customers and DSOs. These aspects should be guaranteed from the scheduling (e.g. day-ahead) to the real-time operation of the grid, specifically in the presence of intermittent renewables.

The voltage sensitivity coefficients of node voltages with respect to nodal power injections can be effectively used for optimal voltage control of distribution grids. The sensitivity coefficients provide a set of linear constraints that links the variations of nodal power injections to the variations of node voltages. These linear constraints can be effectively used for the optimal grid control, instead of the nonlinear and complex power flow equations. It efficiently decreases the computation time for calculating the optimal control decisions, which is very important specifically for the real-time optimal control applications.

The optimal control decisions are required in the real-time operation, scheduling, and planning of distribution grids. Note that the optimal control decisions can guarantee the security of the network, whereas the droop control methods based on local measurements result in sub-optimal states or even infeasible operating conditions.

Regarding the real-time optimal control, the DSOs can use the sensitivity coefficients for the voltage control (i.e. ensuring that the node voltages are within the allowed operation limits). In this respect, the coefficients can also be used for the deployment of demand response, demand side management, and activation of resources in balancing markets.

Furthermore, the DSOs can use the sensitivity coefficients for the optimal scheduling of resources with different objectives, like minimization of operation costs, losses minimization, etc., while maintaining the system within acceptable operating bounds in terms of voltage magnitudes.

The DSOs can also use the sensitivity coefficients for the system planning studies, like optimal grid reinforcement, optimal location/allocation of Energy Storage Systems, etc.

7.2 Sensitivity coefficients determination: problem formulation

In this section, we propose a method for the computation of voltage sensitivities relying solely on measurements, without using any information on the grid model.

In literature, the coefficients of interest are the voltage magnitude sensitivities of the i-*th* bus with respect to absorbed / injected power of a bus j defined as:

$$K_{P_{ij}} \triangleq \frac{\partial E_i}{\partial P_j} \qquad K_{Q_{ij}} \triangleq \frac{\partial E_i}{\partial Q_j} \tag{1}$$

The computed sensitivities allow for a local linearization of the voltage deviation as a function of the nodal power variations:

$$\Delta E_i(t) \approx K_{P_i}\Delta P + K_{Q_i}\Delta Q \triangleq \left(K_{P,Q}\Delta(P,Q)\right)_i \tag{2}$$

Where $K_{P_i} = [K_{P_{i1}}, \dots, K_{P_{iN}}], K_{Q_i} = [K_{Q_{i1}}, \dots, K_{Q_{iN}}]$, are the vectors of voltage sensitivities of bus i.

Such a linearized dependency can be used by the DSO to formulate an optimal control problem whose solution is optimal required nodal power adjustments, which lead to the desired operation set-point for voltage control (e.g.[4],[6]). Alternatively, their knowledge can be used for the on-line tuning of droop controllers of flexible resources.

The sensitivities of interest are typically acquired through an updated Jacobian matrix derived from the load flow problem, via methods based on the use of the so-called adjoint network or using analytical approaches that involve the solution of linear systems of equations (e.g., [6]-[14]). Despite their differences, all the aforementioned methods require the knowledge of the network admittance matrix. In this work, we use as a benchmark the coefficients computed using the method presented in [6].

In this work, in order to estimate the aforementioned voltage sensitivity coefficients using measurements only we rely on the following hypotheses:

- H1. The DSO has no knowledge of the network admittance matrix [Y] and system state, i.e., nodal voltage phasors.
- H2. A monitoring infrastructure is available providing the DSO with measurements at frequent time-intervals (i.e., 1s) of the voltage magnitude of each network bus i, $(\tilde{E}_i(t))$ and of the nodal power injections ($\tilde{P}_i(t)$; $\tilde{Q}_i(t)$)[1]. Note that we do not require the measurements to be highly synchronized as availability of PMUs is still limited in distribution grids and we rely on conventional metering devices.
- H3. The desired sensitivities do not vary significantly over a time window of duration τ during which an adequate number of measurements can be obtained for their computation.

The key idea behind the proposed method is to use the available measurements in order to compute variations of the voltage magnitudes and corresponding variations of the nodal power injections[2]. Then using the computed variations, a system of linear equations can be obtained starting from (2) that we can solve to obtain the desired coefficients.

In particular, between two consecutive sets of measurements available at time t and $t+\Delta t$ (for a small $\Delta t > 0$), we define $\Delta\tilde{P}_i(t+\Delta t) = \tilde{P}_i(t+\Delta t) - \tilde{P}_i(t)$ and $\Delta\tilde{Q}_i(t+\Delta t) = \tilde{Q}_i(t+\Delta t) - \tilde{Q}_i(t)$. Similarly for

[1] In what follows we denote with a tilde the quantities that correspond to measurements, e.g.,$\tilde{E}$.

[2] Note that the method described next is generic and can be applied to the case of unbalanced networks as it treats each phase of the network separately.

the voltages, the desired variation is computed as $\Delta\tilde{E}_i(t+\Delta t) = \tilde{E}_i(t+\Delta t) - \tilde{E}_i(t)$ If we have a large number of available measurements over a given time window $\tau = [t_1;\ t_m]$ and we make the assumption that the desired sensitivities do not vary significantly during this time period then we can construct the following system of linear equations for each network bus i:

$$\begin{pmatrix} \Delta\tilde{E}_i(t_1) \\ \vdots \\ \Delta\tilde{E}_i(t_m) \end{pmatrix} \approx \begin{pmatrix} \Delta\tilde{P}_1(t_1) & \cdots & \Delta\tilde{P}_N(t_1) & \Delta\tilde{Q}_1(t_1) & \cdots & \Delta\tilde{Q}_N(t_1) \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \Delta\tilde{P}_1(t_m) & \cdots & \Delta\tilde{P}_N(t_m) & \Delta\tilde{Q}_1(t_m) & \cdots & \Delta\tilde{Q}_N(t_m) \end{pmatrix} \cdot \begin{pmatrix} \mathrm{K}_{\mathrm{P_{i1}}} \\ \vdots \\ \mathrm{K}_{\mathrm{P_{iN}}} \\ \mathrm{K}_{Q_{i1}} \\ \vdots \\ \mathrm{K}_{\mathrm{Q_{iN}}} \end{pmatrix} \tag{3}$$

$$=> \Delta\tilde{E}_{i,\tau} = \Delta\big(\tilde{P},\tilde{Q}\big)_\tau K_{PQ_i} + \omega$$

The additional vector ω in (3) contains the errors from the measurements. These errors are a combination of the measurement errors for both voltages and powers. Among these two, we assume that the effect of the errors linked to the power measurements is negligible compared to the one of the errors in voltage measurements (see Figure 16). In order to take into account the voltage measurement noise, we first use a pre-filtering of the acquired measurements. In particular, for each time-step t, at least one value of the $\Delta\tilde{E}_i(t)$ among all the network buses should be higher than a pre-specified threshold. The value of this threshold is determined based on the uncertainty of the voltage sensors. To fix ideas, this threshold can be $3\sigma_E$, where $\sigma_E$is the variance of a type II uncertainty of a voltage meter. After the filtering, in order to maintain an acceptable number of values that will allow the solution of the problem, the filtered values are replaced by older measurements for which the specified criterion is satisfied for them.

Furthermore, in order to properly model the noise in (3), we take into account the correlation of the errors on the voltage measurements between consecutive time steps. The errors of the voltage measurements are considered Gaussian and independent and identically distributed (i.i.d.) with a standard deviation that reflects the accuracy of the GridEye metering equipment. However, in (3) we formulate the problem using voltage differences and therefore the noise term ω exhibits correlation between two consecutive time steps that cannot be neglected. In particular, the voltage measurement of bus i at time-step t is denoted as:

$$\tilde{E}_i(t) = E_i(t) + \epsilon_i(t) \tag{4}$$

where each $\epsilon_i \sim \mathcal{N}\ (o, \sigma_E)$.[3]

Using this notation the voltage differences for each bus i are expressed as:

$$\begin{aligned} \Delta\tilde{E}_i(t+\Delta t) &= \tilde{E}_i(t+\Delta t) - \tilde{E}_i(t) \\ &= E_i(t+\Delta t) - E_i(t) + \epsilon_i(t+\Delta t) - \epsilon_i(t) \\ &= \Delta E(t+\Delta t) + \omega_i(t+\Delta t) \end{aligned} \tag{5}$$

Where $\omega_i(t+\Delta t) \triangleq \epsilon_i(t+\Delta t) - \epsilon_i(t) \sim \mathcal{N}(0, \sqrt{2}\sigma_E)$ is still gaussian as the difference of 2 gaussian variables but exhibits correlation.

The correlation coefficient between two consecutive time steps is defined as:

---

[3] The errors associated with the voltage measurements are assumed i.i.d between different time steps and different buses.

$$\rho\big(\omega_i(t), \omega_i(t+\Delta t)\big) = \frac{cov\ (\omega_i(t), \omega_i(t+\Delta t))}{\sigma_{\omega_i(t), \omega_i(t+\Delta t)}} \tag{6}$$

Where

$$\begin{aligned} cov\ \big(\omega_i(t), \omega_i(t+\Delta t)\big) &= \mathbb{E}[(\omega_i(t) - \mathbb{E}[\omega_i(t)])(\omega_i(t+\Delta t) - \mathbb{E}[\omega_i(t+\Delta t)])] \\ &= \mathbb{E}\big[\big(\omega_i(t)\big)\big(\omega_i(t+\Delta t)\big)\big] \\ &= \mathbb{E}\big[\big(\epsilon_i(t) - \epsilon_i(t-\Delta t)\big)\big(\epsilon_i(t+\Delta t) - \epsilon_i(t)\big)\big] \\ &= \mathbb{E}[-\epsilon_i(t)^2] \\ &= -\sigma^2 \end{aligned} \tag{7}$$

Therefore:

$$\rho\big(\omega_i(t), \omega_i(t+\Delta t)\big) = \frac{-\sigma^2}{\sqrt{2}\sigma\sqrt{2}\sigma} = -\frac{1}{2} \tag{8}$$

Note that, due to the i.i.d and zero-mean assumptions on the errors ϵ_i, it holds that $\mathbb{E}\big[\big(\epsilon_i(t+k\Delta t)\epsilon_i(t+\mu\Delta t)\big)\big] = 0, \forall k \neq \mu$.

Therefore, the correlation coefficient of the errors ω_i between two non-consecutive time-steps is equal to 0 and the resulting correlation matrix has the following structure[4]:

$$\sum = \begin{pmatrix} 1 & -0.5 & & & \\ -0.5 & \ddots & \ddots & 0 & \\ & \ddots & \ddots & \ddots & \\ & 0 & \ddots & \ddots & -0.5 \\ & & & -0.5 & 1 \end{pmatrix}$$

Provided that $t_m > 2N$, we have formulated the problem as an over-determined system of linear equations that can be solved using a generalized least squares method to account also for the correlated errors. In such a case, the sensitivity coefficients are obtained analytically through the resolution of the following equations [14]:

$$\mathbf{K_{PQ_i}} = (\mathbf{\Delta}(\tilde{\mathbf{P}}, \tilde{\mathbf{Q}})_\tau^{\mathbf{T}} \mathbf{\Sigma}^{-1} \mathbf{\Delta}(\tilde{\mathbf{P}}, \tilde{\mathbf{Q}})_\tau)^{-1} \mathbf{\Delta}(\tilde{\mathbf{P}}, \tilde{\mathbf{Q}})_\tau^{\mathbf{T}} \mathbf{\Sigma}^{-1} \mathbf{\Delta} \tilde{\mathbf{E}}_{\mathbf{i},\tau}$$

It is important to note that when the pre-filtering described earlier is considered, then certain columns (rows) of the matrix $\Delta\big(\tilde{P}, \tilde{Q}\big)_\tau$ $(\Delta\tilde{E}_{i,\tau})$ are removed. In this case the correlation matrix needs to be adjusted by properly setting to zero the entries that do not correspond to measurements of consecutive time steps.

[4] Note that $\sum$ is correct for the ideal case where the errors in the power measurements are less dominant than those of the voltages. If both errors need to be accounted for, $\sum$ is not known a priori and its assessment might require a more sophisticated analysis.

8 Results

8.1 Sensitivity coefficient validation

In order to compare the performances of the proposed method with the formal analytical method proposed in [6], we need to have access to the actual parameters of the network and the real topological information corresponding to the obtained measurements. Therefore, the validation will be performed for this first step with a power flow analysis (approach explained on Figure 17).

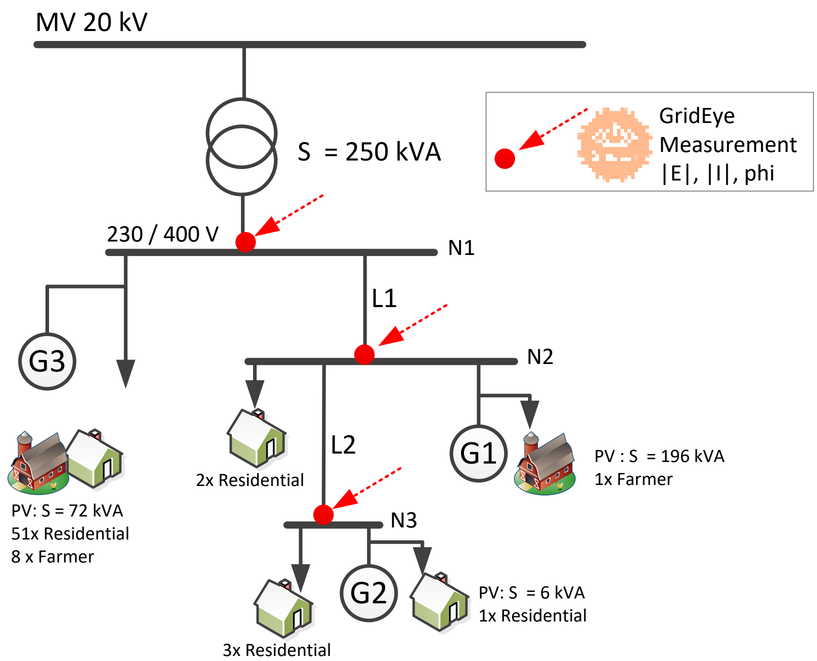


Figure 15: Real low voltage distribution feeder used for the performance evaluation of the proposed method.

To simplify the system to be analyzed, the validation will be held on a reduced part of the system shown in Figure 15. Table 1 and Table 2 summarize the characteristics and parameters necessary for the definition of the matrix YBUS (necessary to define the coefficients of accurate sensitivities in [6]).

	Cable Type	Length [m]	(R,X Ohm/km)	C uF/km
L1	1kV 4 x 240mm2 AL (B-GKN-K-240 AL)	219	(0.096, 0.072)	0.77
L2	1kV 4 x 150mm2 AL (B-XN-150 AL)	145	(0.2633, 0.078)	0.73

Table 1: Cable main data.

	Power	**Uin**	**Uout**	**Coupling**	**Ucc**	**X/R**
T1	250 kVA	20kV	230/400V	DYn11	4.1%	2.628

Table 2: Transformer main data

In the validation procedure we considered real and reactive power measurements at nodes 1, 2 and 3 of all phases (a,b,c), during a period of 9 hours 22 minutes, as provided by GridEye devices. The profiles are shown in Figure 16 (with a sampling frequency of 1 second).

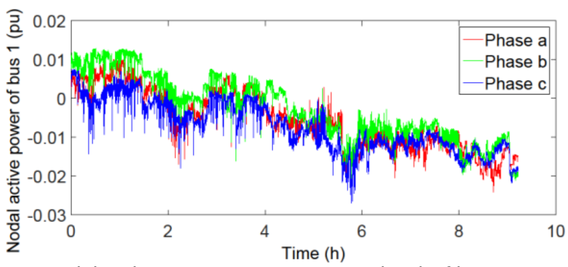
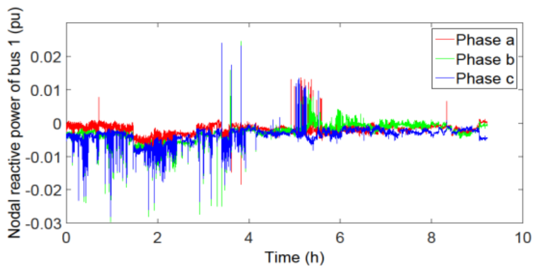
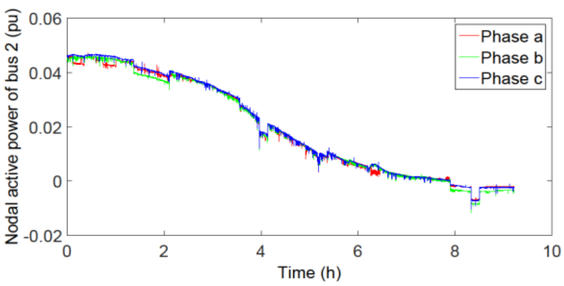
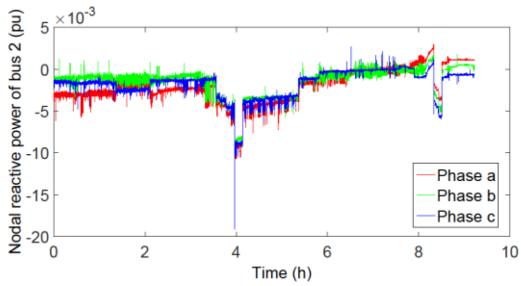
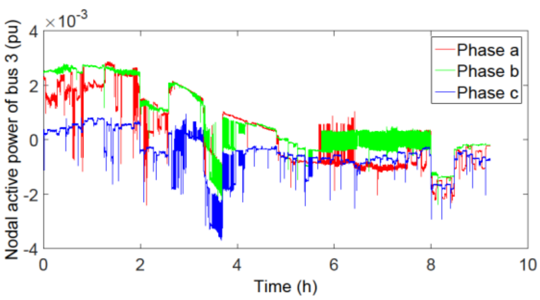
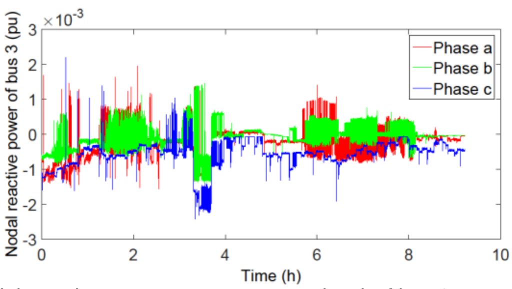
	Real Power	**Reactive power**
Node 1	 Nodal active power measurements (p.u.) of bus 1.	 Nodal reactive power measurements (p.u.) of bus 1.
Node 2	 Nodal active power measurements (p.u.) of bus 2.	 Nodal reactive power measurements (p.u.) of bus 2.
Node 3	 Nodal active power measurements (p.u.) of bus 3.	 Nodal reactive power measurements (p.u.) of bus 3.

Figure 16: Real and reactive power profile

The flowchart of the validation procedure of the algorithm is shown in Figure 17.

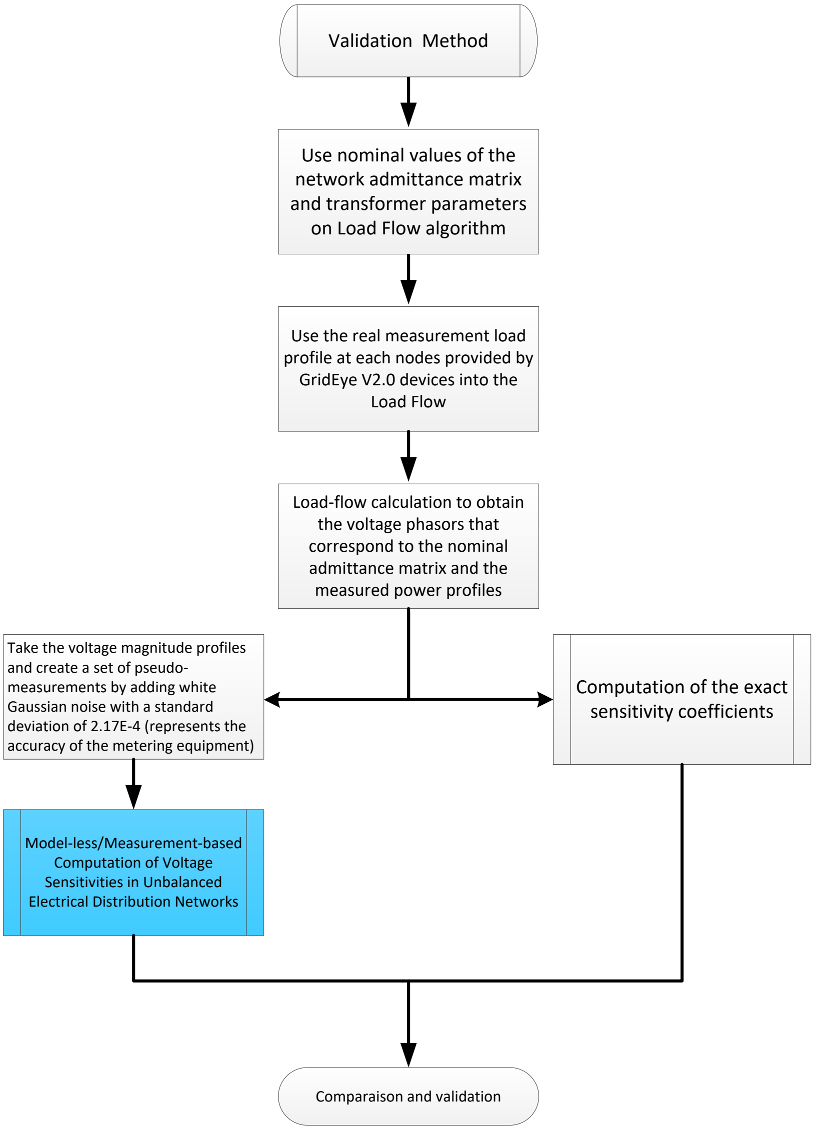


Figure 17: Flowchart of the validation procedure of the decentralized sensitivity coefficients determination algorithm.

For the sake of brevity, only a few coefficients will be shown for each part of the validation process. Note that cross-phase coefficients are not shown in the following. These coefficients are zero in this case study as the grid topology is symmetric, despite the unbalances in the network loads. In Figure 18 and Figure 19, we emphasize the importance of the size of the time window used for the estimation. The red solid line represents the actual voltage coefficients of phase “a” of bus 3 with respect to the active power injection of phase “a” of the same bus. The blue and green curves depict the corresponding measurement-based coefficients using a time window of 200 s and 1000 s respectively, whilst the red curve corresponds to the true coefficients computed using [6] .

It is worth observing that even though both the blue and green curves are quite close to the actual coefficients in the first 1h, the blue curve exhibits large variations in the last 1.5h. The reason for this is that the least squares problem that needs to be solved is badly conditioned. This is shown in Figure 19 where it can be observed that with a time window of 200 s, the condition number of the matrix that needs to be inverted increases significantly and consequently the quality of the estimated coefficients becomes worse compared to the case of a 1'000s time-window.

Therefore, in what follows we choose to estimate the desired coefficients using a measurement time-window of 2'000s. Figure 20 and Figure 21 show the exact voltage sensitivities in red line, the measurement-based sensitivities without the noise pre-filtering technique described in section 3 - Decentralized sensitivity coefficients determination; in green and the measurement based sensitivities using the noise pre-filtering in blue.

In particular, Figure 20 shows the sensitivity of phase "c" of bus 2 w.r.t. active power of phase c of bus 2, Figure 21 shows the sensitivity of phase a of bus 3 w.r.t. active power of phase "a" of bus 3 and Figure 22 shows the sensitivity of phase "b" of bus 3 w.r.t. reactive power of phase "b" of bus 3. In all cases, the measurement-based estimates of the coefficients are close to the exact values computed using the analytical method in [6].

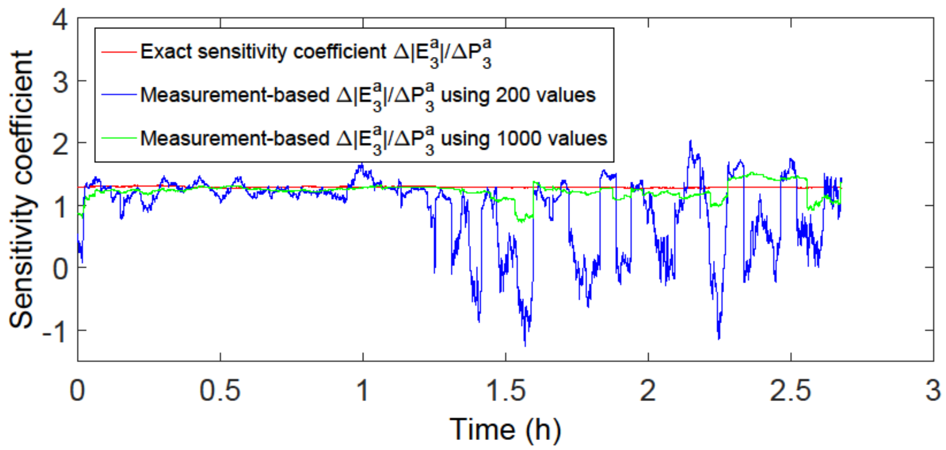


Figure 18 : Exact and measurement-based voltage sensitivity coefficients of bus 3 phase a with respect to the active power of bus 3 phase « a » using different window sizes.

However, it is worth noting that in some cases not using the pre-filtering of the noise (green curves) results in significant peaks in the estimated coefficients (Figure 21) that can also lead to values of the sensitivities that are very far away from the actual coefficients (for instance negative values in Figure 22). This behavior is observed when the network state does not vary significantly from one time step to the next, and therefore the matrices corresponding to the voltage and power differences are essentially composed of noise and lead to an ill-conditioned system (time 3:2 h in Figure 21 or time 9:1 h in Figure 22). In this case, using the pre-filtering technique described earlier leads to much better estimates of the sensitivities as evidenced by the blue curves in Figure 21 and Figure 22 which are much closer to the exact coefficients and do not exhibit large variations across the time-steps.

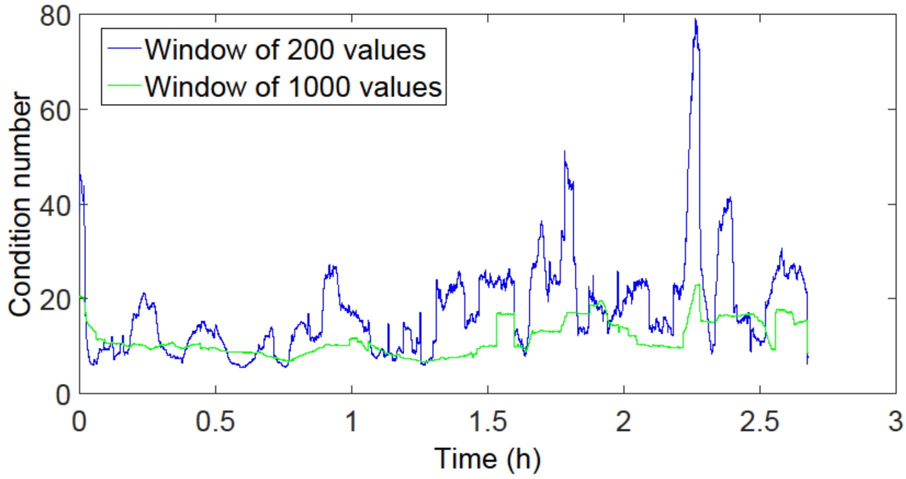


Figure 19: Condition number of the matrix used in the least-squares problem for different window sizes.

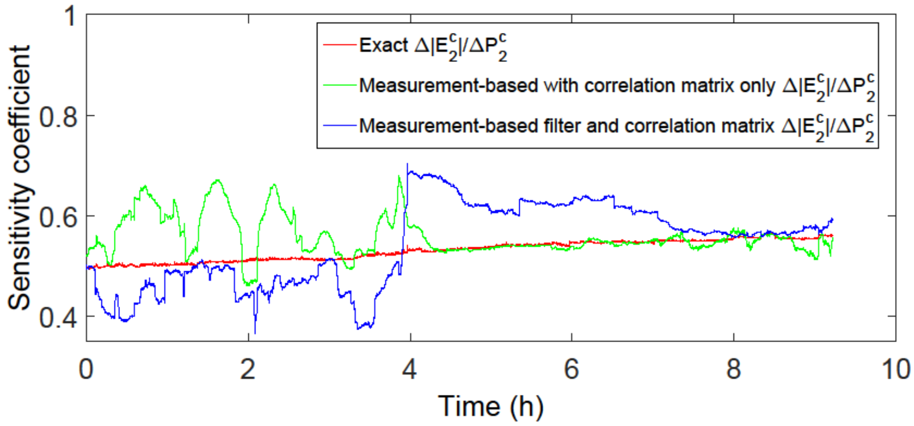


Figure 20: Exact and measurement-based voltage sensitivity coefficients of bus 2 phase c with respect to the active power of bus 2 phase c using solely correlation or noise pre-filtering and correlation.

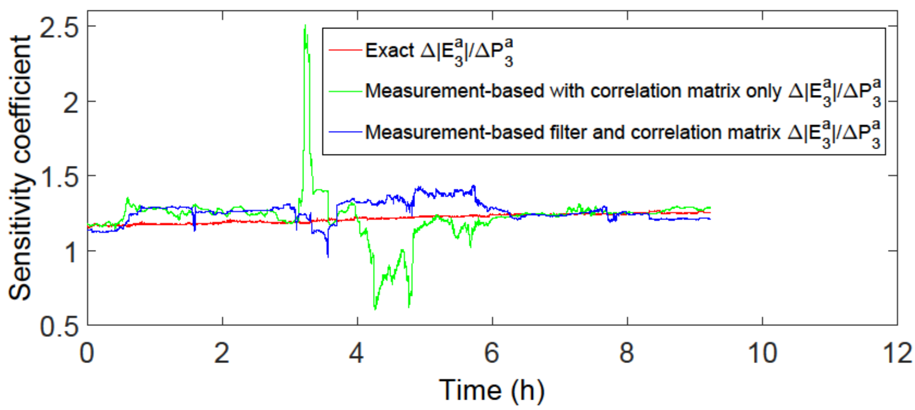


Figure 21: Exact and measurement-based voltage sensitivity coefficients of bus 3 phase a with respect to the active power of bus 3 phase a using solely correlation or noise pre-filtering and correlation.

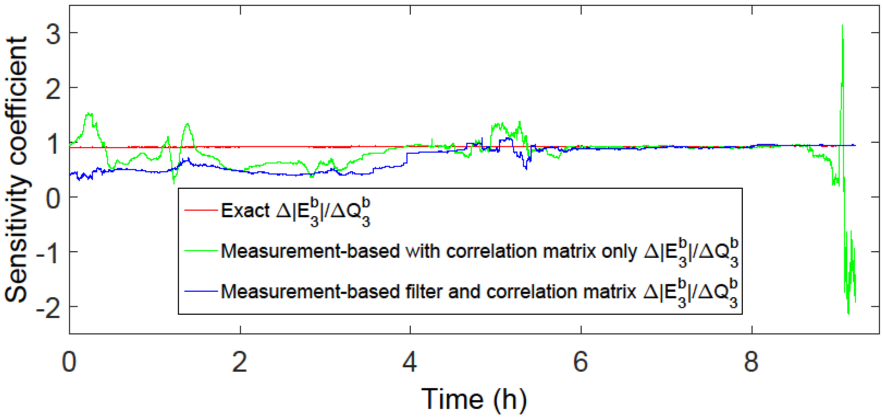


Figure 22: Exact and measurement-based voltage sensitivity coefficients of bus 3 phase b with respect to the reactive power of bus 3 phase b using solely correlation or noise pre-filtering and correlation.

9 Discussion / evaluation of results / learning

9.1 GridEye Installation in electrical grid

9.1.1 Procedure and timing

The installation of the GridEye device requires an operator having the competence and authorization to perform the work under voltage. Depending on the internal security rules of the DSO, two persons are required. All the installations can be done under voltage without interruption of supply.

Tasks	**Time [min]**
Preparatory work	3
Fixing devices	2
4 x Rogowski coils fixed on cable	2
Fixing the vertical switchgear and breaker and making voltage connections	5
Testing communication and data validation	3
	Total : ~15min

Table 1: Total time for installation of one device by one person.

The total time to add a new module to the electrical grid is around 15 minutes for one person.

9.1.2 Good points and possible improvement

The remarks in Table 2 are acquired from the discussions with the grid operators from Romande Energie. The feedback aims to have the best practical point of views and to improve the design of the next version of the device.

Good points	**Improvement points**
• Easy to install for one person (with all protection equipment). • No need of power cut. • Short installation time. • No need for long training or specific knowledge for installation.	• Smaller diameter of Rogowski coils can be better for cabinets. • Mobile app for live visualization in field. • Only 4x current measurement, no possibility to have a double or more connection.

Table 2: Operator feedback

.

9.2 GSM: M2M communication

The test of the GSM communication is performed with the company Swisscom (the main operator in Switzerland).

9.2.1 Communication test

During the entire pilot projects, several measurements were made to analyze the quality of the GSM signal of the different GridEye modules (with an antenna of +3dB) on the pilot project of Chapelle-sur-Moudon (rural area).

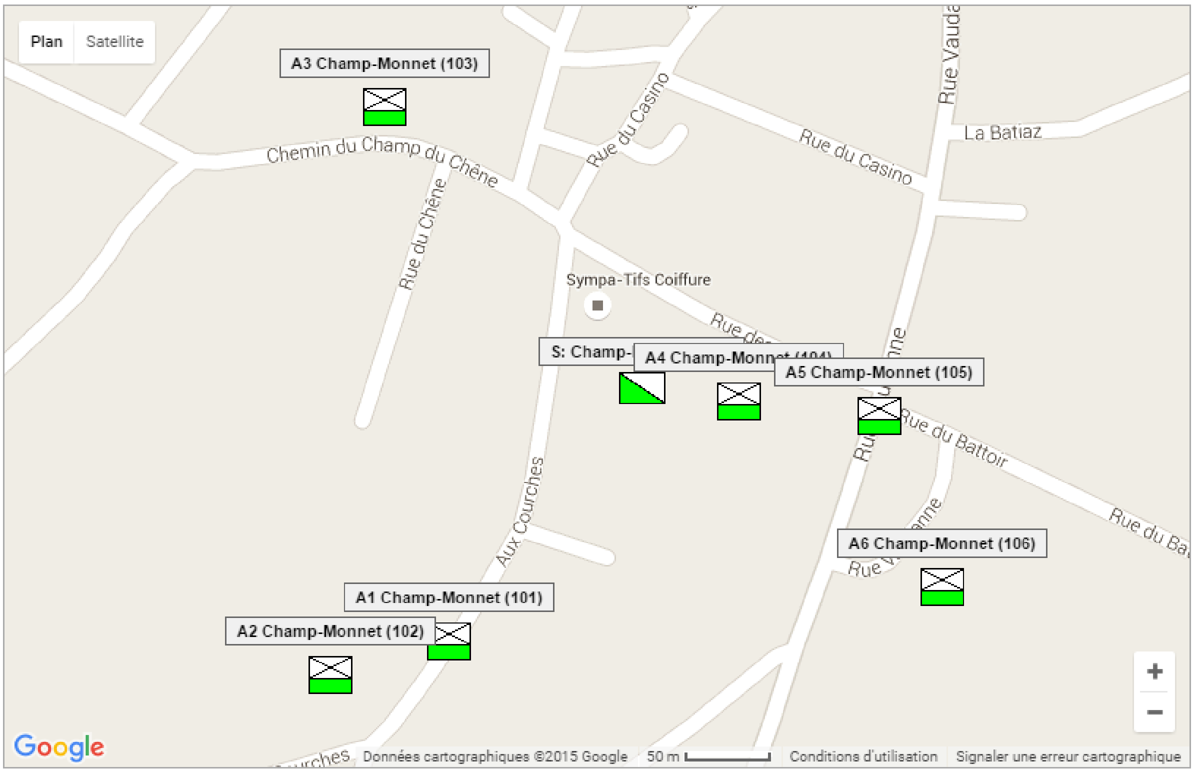


Figure 23: Location of the modules in the field.

The presented results in Table 3 show the average measurement of the quality of the signal on the GridEye devices during the whole project.

Module's number	RSSI dBm	Analyse[5]	Connection loss
100	-103	Marginal	NO
101	-83	Good	NO
102	-85	OK	NO
103	-101	Marginal	NO
104	-95	Marginal	NO
105	<-109	Marginal	Sometimes
106	-67	Excellent	NO

Table 3: Quality of GSM signal measurement.

All the devices are located within an area of 250 square meters. Nevertheless, the results of Table 3 show that the quality of the GSM signal can change a lot, depending where the devices are located.

<u>Sufficient value of "RDDI dBm" without risk of loss of connection:</u>

-103 dBm

The required value for the installation of the devices should not be less than -103 dBm to ensure a good quality of communication.

9.2.2 Good point and possible improvement

Good points	Improvement points
• Quality of services, the number of outage is very low. • The number of data per month and per module is quite low (max: 100Mo/month).	• No possibility to have access to the statistics of the communication outages by Swisscom platform management: need to be visualized on next version. • Need to save data measurement in case of communication outage. • Increase the antenna sensitivity. • Dependence of the signal quality on the location of the module. • Communication cost

Table 4: M2M, good points and possible improvement

[5] detail information http://m2msupport.net/m2msupport/atcsq-signal-quality/

Save data: During all the test phases a few disconnections were detected. However, in the version 2.0 of GridEye, the data can’t be saved during the loss of connection. This point should be considered for the next version.

The quality of the signal: To ensure that the device has enough connection signals, it would be interesting to send the information of the quality of the signal to the server (db) and show it with a led on the casing if the dBM is lower than -103 dBm.

It is observed that in some cases the signal is very low and it can cause the communication outage. It can be better to increase the sensitivity with a better antenna. But in any case, after the loss of connection, the reconnection procedure is working well and none of the devices were lost during the entire project.

Reconnection procedure: The reconnection procedure is working well but it needs a global reboot of all devices which is not really efficient. Before rebooting all the Linux systems, the application of the GSM management must try to reconnect it. The time of the reconnection procedure (to find the network) must be longer. The actual time is 20 seconds and a better value is 60 seconds).

Time Synchronization: The time synchronization of the devices with NTP protocol is enough for the estimation of the sensitivity coefficients.

Remote control: The SSH on GSM to perform a software update on the GridEye application is working well. All the improvement of the GridEye application can be made by remote control without problem on ARM processor.

9.3 Hardware Modifications

The hardware of the GridEye device is under modifications by DEPsys and HEIG-VD on the CTI project "GridEye: Outil de gestion d'un réseau électrique basse tension, destiné à la prise en charge des injections massives non-contrôlées des sources de génération décentralisées" (new design on Figure 24) .

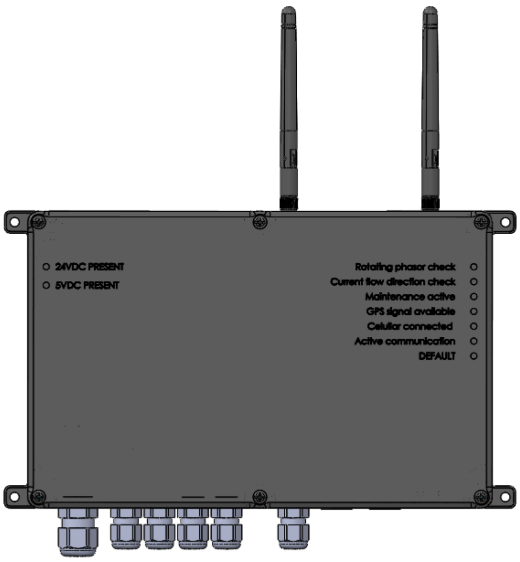


Figure 24: GridEye V3.0

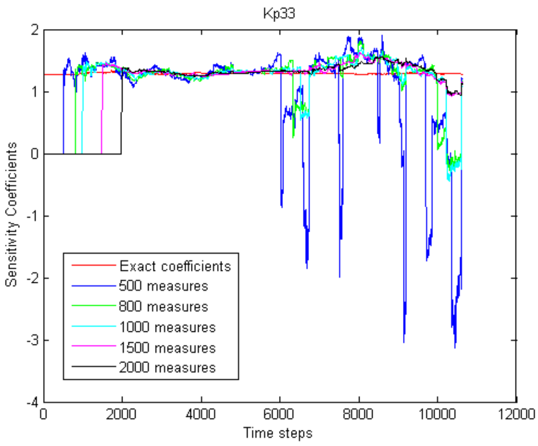
In order to determine the minimum hardware requirements of the GridEye device for a successful implementation of the decentralized sensitivity coefficients estimation, the most important influential parameters are analyzed, as following:

- Influence of the number of measurements for the estimation (memory of devices)
- Voltage absolute maximal error
- Current absolute maximal error
- Phase absolute maximal error

A summary of these requirements is shown in Figure 25.

<table>
<tr>
<td>

Number of measurement:



a.

</td>
<td>

<u>Test conditions:</u>

N mes = Variable

Error V = 0%

Error I = 0%

Error φ = 0°

<u>Result:</u>

The appropriate number will be more than 1’500 values

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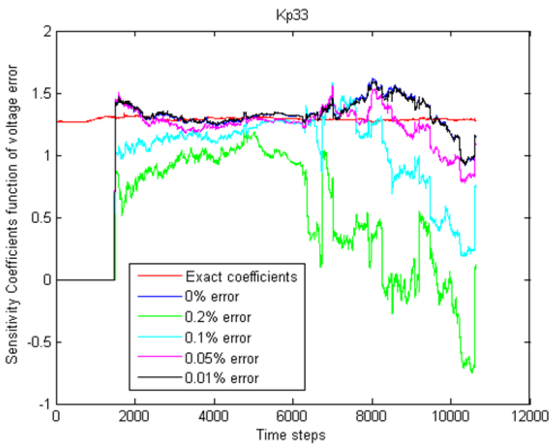
Voltage accuracy:



</td>
<td>

<u>Test conditions:</u>

N mes = 1500

Error V = Variable

Error I = 0%

Error φ = 0°

<u>Result:</u>

The coefficient is really sensitive to the accuracy of the voltage. The best will be 0.05%

</td>
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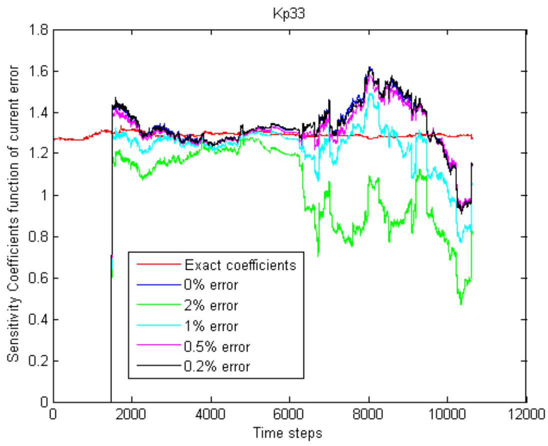
</table>

Current accuracy:



<u>Test conditions:</u>

N mes = 1500

Error V = 0%

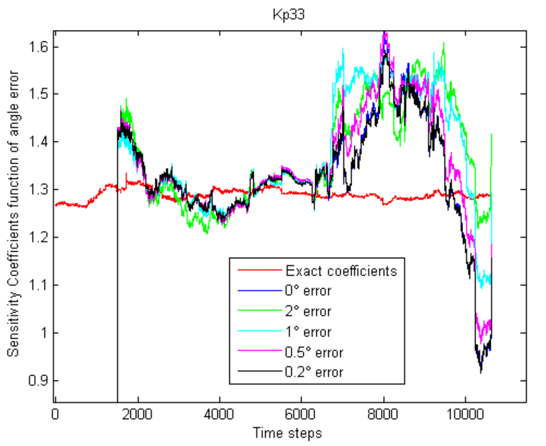
Error I = Variable

Error φ = 0°

<u>Result:</u>

The coefficient is not really sensitive to the accuracy of the current. Accuracy about 1% is enough

Phase accuracy:



<u>Test conditions :</u>

N mes = 1500

Error V = 0%

Error I = 0%

Error φ = Variable

<u>Result:</u>

The coefficient is not really sensitive to the accuracy of the phase. Accuracy about 1° is enough.

Figure 25: Most important factors analysis.

10 Conclusions

The estimation of the voltage sensitivity coefficients without the model of the grid showed very good results, as summarized in section 8. However, to validate and test it in a real application, some improvements, especially in term of measurement accuracy, are required. These features will be made available in the new version of GridEye V3 (see section 9.3 and next section 11). Moreover, it would be necessary to have a low voltage microgrid available, where all physical parameters and power injections are accurately known. This requirement is due to the difference between the simulation with theoretical data of the cables (even if they are well known) and the real measurements, which can result in errors up to 50%, as mentioned in section 5.6. All these aspects will be assessed in the new microgrid “ReIne” under development at the HEIG-VD (see next section 11).

The prototype of GridEye (V2) allowed validating the majority of requirements defined by the DSO at the beginning of the project (see section **Erreur ! Source du renvoi introuvable.**) .

- **No need of grid parameters:** As specified above, the method proposed in this project allows the estimation of the voltage sensitivity coefficients without the need of the grid parameters.
- **Retrofit & easy to install:** The fast installation of the devices on the field by the operator (Section 9.1) proves that the GridEye V2 prototype is well designed. The operator needs only 15 minutes for every device installation.
- **Low voltage grid observability:** The platform of the GridEye allows the DSO to analyze what is happening in the low voltage grid without dealing with big data management. This platform can be also used in the future for system planning, providing balancing services, etc. depending on the needs of the DSO.
- **Limitation of OPEX cost:** At the beginning of the project, only three devices were installed in the grid. Then, in order to have more information and also due to the addition of a new PV power plant, all the cabinets of the LV grid have been equipped. The cost for the DSO was only the installation time of the devices on the cabinet, and no other parameters / work were needed.
- **Scalability and modularity:** All modifications of the firmware of the devices could be done by remote control directly from the GridEye platform.

Another point which was not defined by the requirement of the DSO is the life cycle and the robustness of this type of “new electronic” devices. The GridEye V2 prototypes have been working for around two years on the field with quite extreme conditions (temperature more than 35°C and lower than -10°C) without any fault. The estimated life cycle is around 10 years.

The choice of a GSM communication provided by Swisscom was a good choice for this project. This technology is well known, robust and the network coverage in Switzerland is very good, from both geographical availability and quality of the signal. Concerning a large-scale deployment, it would be necessary to analyze other possibilities as PLC, RF or other technologies in order to reduce the communication cost (today GSM technology is quite expensive).

11 Outlook, later stages (after the project)

In order to improve and validate the developed methods of this projects, there are some ongoing projects.

CTI PROJECT : "GridEye : Outil de gestion d'un réseau électrique basse tension, destiné à la prise en charge des injections massives non-contrôlées des sources de génération décentralisées". A CTI project was started by HEIG-VD, with DEPsys as an industrial partner, to develop the new hardware platform (GridEye V3). The goal of the project is to have a preindustrial device and testing an alternative communication possibility to the GSM (in order to reduce the communication cost).

DEPSYS PILOT PROJECTS: DEPsys has started (or will start soon) some pilot projects with 8 Swiss DSOs to utilize the GridEye V3 and validate the application of the developed method in this project for differents grid topologies.

New microgrid "ReIne": The HEIG-VD is building a new laboratoire, ReIne (Réseau IntElligent, Intelligent Grid), a micro grid in scale 1:1. This new laboratory allows testing the limits of the GridEye system in a safe environment, and to validate the estimation of sensitivity coefficients.

SFOE SMILE-FA: The HEIG-VD submitted a new research project to SFOE to test the limits of the GridEye system in the laboratory ReIne (see previous point). The goals of the project are: to validate the estimation sensitivity coefficients thanks to the known parameters of the grid in the laboratory, to define and test the utilization strategy of GridEye, and to define and test a cybersecurity strategy for this type of monitoring / control systems.

SCCER-FURIES ROLLE Demonstrator: The GridEye system is planned to be part of SCCER-FURIES demonstrator of Romande Energie to test the compatibility and interaction between several technologies developed in SCCER-FURIES project (e.g. PMU, GridSense).

12 Annexes

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13 Annexes

13.1 Patent

Joël Jaton, Guillaume Besson, Michael De Vivo, Mauro Carpita, Mario Paolone, Konstantina Christakou, Carl Mugnier, “Method for determining mutual voltage sensitivity coefficients between a plurality of measuring nodes of an electric power network”, Patent EP16166721.7, 22.04.2016.

13.2 Paper

K. Christakou, C. Mugnier, J. Jaton, M. Carpita and M. Paolone : «*Model-less/Measurement-based Computation of Voltage Sensitivities in Unbalanced Electrical Distribution Networks*,» 19th PSCC, Power Systems Computation Conference, June 20-24, 2016, Genoa, Italy.