SOGNO

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Description of initial interfaces & services for grid awareness

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Abstract
This document includes the description of the services developed in the SOGNO project for providing situational awareness to the distribution grid operators and support them in the management of the distributed energy resources available in the grid. The report details the techniques for these features and contains an overview of the interfaces required in the Virtualized Substation to enable the coordinated operation of the services.

Keyword list
Distribution grid monitoring, State estimation, Power control, Power quality, Distributed generation, Distributed energy resources

Executive Summary

Improving the existing situational awareness allows grid operators to evaluate the real-time operating conditions of the system, to efficiently manage the network and to identify possible automation and control solutions and settings to be deployed for improving the grid performance. In the past situational awareness was not critical for operating a distribution system, due to the passive and relatively simple operation of these grids. Today, with the growing penetration of renewable generation and other distributed energy resources, the availability of situational awareness has become essential also at distribution level.

The objective of WP2 is the development of the hardware and software components needed to provide advanced situational awareness to distribution system operators by means of cost-effective solutions and virtualized substation intelligence. This report provides the description of the grid awareness services developed in the project, namely state estimation, power control and power quality. The document provides the technical details of the concepts and models building the foundation of the algorithms running in these services, together with specific interfaces needed for the integration of the services in the cloud environment hosting the virtualized substation automation.

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1. Introduction

The project *Service Oriented Grid for the Network of the Future (SOGNO)* is funded by the Work Program H2020-LCE-2017-SGS. It has officially started in January 2018.

1.1 Related Project Work

This report is based on the work done in the tasks T2.1, T2.2 and T2.5 of Work Package WP2. The first two tasks (T2.1 and T2.2) deal with the design of the main techniques for grid awareness. In particular, T2.1 focuses on the State Estimation service, which is the service allowing the real-time monitoring of the operating conditions of the distribution system, while T2.2 develops the techniques for the management of the power electronic components associated to the distributed generation (Power Control service), providing control and awareness of the behavior of the system with a large share of renewable energy sources. Task T2.5 discusses the development of low-cost measurement units needed to enable both state estimation and power control. The Advanced Power Measurement Units (APMUs) designed in SOGNO also allow monitoring different power quality parameters, as part of the Power Quality Evaluation service, offering an additional degree of situational awareness for the distribution system operators regarding the quality of the power supply in the grid. Last but not least, T2.5 includes the activities for identifying the interfaces needed to integrate the above-mentioned grid awareness services in the cloud platform for the virtualization of the substation intelligence.

Figure 1 shows the overall structure of SOGNO. The grid awareness services designed in WP2, together with the specifications on required interfaces, are provided as input to WP4 for integration in the Virtualized Substation (ViSA) before deploying the services in the field (WP5).

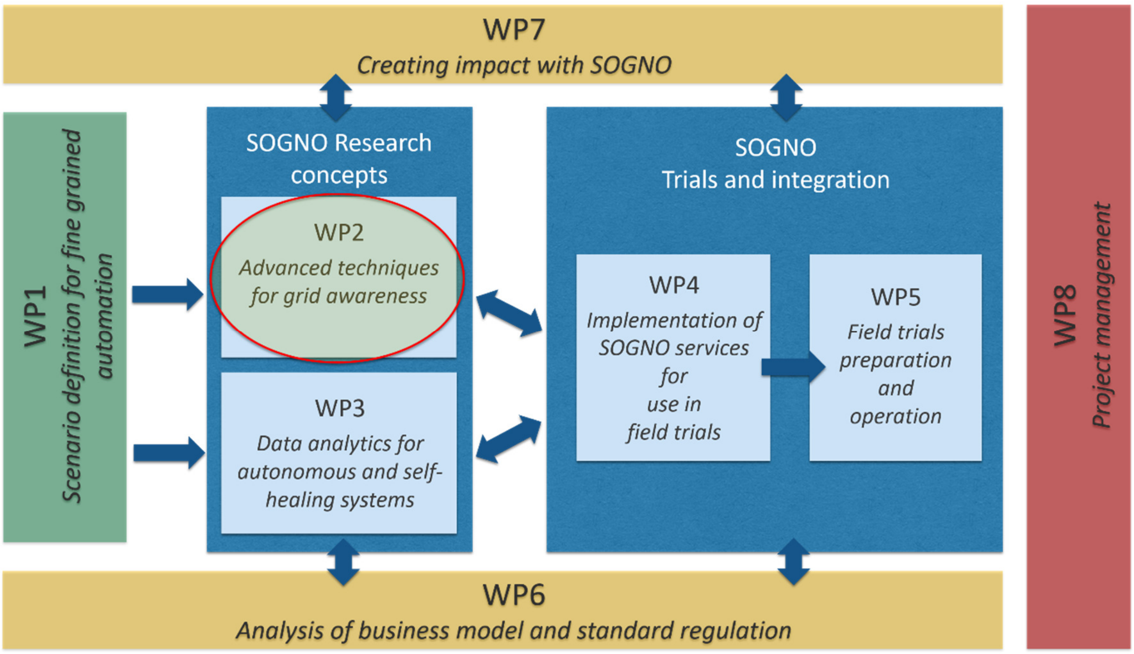


Figure 1: Overview of SOGNO activities.

1.2 Objectives of the Report

This report covers two main objectives: first, presenting the algorithms used in grid awareness services developed in the project (namely State Estimation, Power Control and Power Quality Evaluation), and second specifying interfaces needed to enable to operate these services on the cloud platform hosting the Virtualized Substation (ViSA). The presentation of the grid awareness services will not only focus on the description of technical details relevant for the design of the service itself, but also on the specific solutions adopted in the SOGNO project to deal with the main challenges in the distribution grid scenario. Moreover, this section will also introduce and present the main innovations added in the design of these services compared to state-of-the-art solutions.

1.3 Outline of the Report

The report consists of two main parts covering the service design and the identification of the required interfaces. The first part (Chapter 2) introduces three services developed for grid awareness, namely State Estimation, Power Control, and Power Quality Evaluation. Chapter 2 will provide the details on the mathematical framework behind the algorithms and other technical aspects. The second part of the report (Chapter 3 below) provides a list of interfaces required for integrating the services in the Virtualized Substation, including an overview of the hardware and software components developed for the final deployment on the field.

1.4 How to Read this Document

This report can be read as a standalone document. However, other deliverables can be helpful to get a better view of the concepts advanced in the SOGNO project and to have more details on the grid awareness services. In particular, other deliverables closely related to this one are:

- D1.1 – Scenario & architectures for stable & secure grid (M12): it includes a description of power system scenarios investigated in the project, with motivations for the services presented in this deliverable for current and future distribution grids.
- D2.1 – Detailed description of 5G-based ICT concepts for supporting grid awareness (M22): it discusses the role of 5G communications for fostering the deployment of the grid awareness services presented in this deliverable.
- D2.3 – Validation of techniques for grid awareness including interfaces and related services (M22): it presents the results of off-line tests performed as a first validation for the designed services, also indicating the potentially achievable performance.

2. System awareness services

This chapter presents the services developed in the SOGNO project for providing system awareness to the Distribution System Operators (DSOs). These services are:

- State Estimation (SE)
- Power Control (PC)
- Power Quality Evaluation (PQE)

For each service, the chapter provides the main objectives and the technical details related to the models or mathematical basics of the underlying algorithms. Moreover, the section includes the specifications for the sensors needed to collect measurement data in the field as input to the services. See deliverable D1.1 for more details on the power system and ICT requirements, as well as the mapping of component, information, communication and function layers of each service using the Smart Grid Architecture Model (SGAM).

2.1 State estimation

State Estimation (SE) is a mathematical tool aimed at processing the real-time data gathered from the measurement devices available in the field in order to determine the most probable operating conditions (i.e. the state) of the electricity grid at a given instant of time. SE techniques were developed in the 1970s for transmission systems, but they have been recently extended also to distribution systems to give a better insight in the real-time operation of Low Voltage (LV) and Medium Voltage (MV) networks. This becomes particularly important in scenarios with increasing penetration of distributed generation, since reverse power flows and highly dynamic conditions can occur due to the intermittent behaviour of the renewable energy sources.

Different from the transmission systems, where the adopted SE techniques are now mature and consolidated, the application of SE at distribution level still presents several challenges, mainly due to the poor coverage of measurement instrumentation on the field, but also because of the very large size of MV and LV networks and their specific characteristics, including high resistance of the lines, and an unbalanced nature of the loads [1]. These conditions call for the design of SE solutions that combine good accuracy performance even with a low number of measurement devices in the field, with high efficiency and light computational burden.

Keeping these main requirements in mind, the following section first provides the specifications of the sensors to be used in the measurement chain for the collection of real-time data, since the characteristics of the sensors play a key role for the accuracy performance achievable by the SE algorithms. Then, the section presents two different techniques investigated in the SOGNO project for distribution system SE. The first one is a modification of the classical Weighted Least Squares (WLS) method, which has been adapted to fit scenarios where only few measurements are available in the grid and no information about the historical or statistical data of power consumption/generation at the nodes can be used. The second one is a more innovative approach based on the use of Artificial Neural Networks (ANN), which is also designed to face the problem of poor availability of measurement information in the network. The development of these solutions specifically aims at achieving accuracy performance as good as possible even in presence of few measurement devices in the field. To deal with the large size of the distribution networks, specific SE architecture solutions have been devised to distribute the computational burden among different LV and MV estimators. The proposed solution, presented in the final part of this section, allows multiple SE instances operating in parallel, with fast harmonization processes for refining the SE accuracy performance, and permits coordinating the SE process among different grid levels.

2.1.1 Sensor specifications

Accurate distributed measurements are fundamental for the implementation of the state estimation service on energy distribution lines: the maximum composite error of the complete measurement chain must be lower than 1% both in voltage and in current signals. During the H2020 FTI project named "ADMS" the topic was investigated further by RWTH ACS institute as well as by the UniBo Measurement Department: the results of RTDS simulations and of laboratory calibration tests have both confirmed that 0.5% is the maximum contribution of voltage and current sensors to measurement uncertainty. Moreover, the sensors must keep the accuracy class in a wide range of primary current (I_{PR}) and voltage (U_{PR}) values to lead to a correct estimation of the state of the grid even in abnormal conditions.

In January 2018 new standards on passive sensors were published: IEC 61869-10, relevant to Passive Low-Power Current Transformers (LPCTs) and IEC 61869-11, covering Passive Low-Power Voltage Transformers (LPVTs). Among the accuracy classes reported in the IEC Standards, "0.5" is the one associated to errors lower than 0.5%. Furthermore, this accuracy performance must be guaranteed also in faulty conditions, i.e. over a very wide dynamic range for the current and down to very low levels of voltage. To cover such an application, the suffix "P" (Protection) is added to the current accuracy class, and "S" (Special) is added to the voltage accuracy class.

The tables below show the limits of ratio error and phase displacement for voltage and current sensors in accuracy class "0.5 S" and "0.5 P" respectively. Max U_{PR} and I_{PR} are the maximum voltage and current values to be properly transduced; these parameters will be determined to cover fault conditions in FLISR service specifications.

	0.02 U_{pr}	0.2 U_{pr}	0.8 U_{pr}	U_{pr}	Max U_{pr}
Ratio Error ± [%]	2	1	0.5	0.5	0.5
Phase Error ± [mrad]	24	12	6	6	6

Limits of ratio error and phase error for voltage sensors of 0.5S accuracy class (IEC 61869-11)

	0.01 I_{pr}	0.06 I_{pr}	0.2 I_{pr}	I_{pr}	Max I_{pr}
Ratio Error ± [%]	1.5	0.75	0.5	0.5	0.5
Phase Error ± [mrad]	27	13.5	9	9	9

Limits of ratio error and phase error for current sensors (IEC 61869-10)

IEC Standards on Current and Voltage Instrument Transformers report that the accuracy class is kept in the real operation temperature range (e.g., -40 °C to +60 °C for outdoor sensors), for small variations of the fundamental frequency, for small variations of the output burden (± 5%), once that the equipment is installed in a three phase configuration.

Moreover, it is worth noting that the customers can also add special requirements, such as to maintain the accuracy under the rain, over time, on the measurement performance for power system harmonics, etc. depending on the set of services to be enabled together with state estimation.

2.1.2 WLS-based state estimation approach

2.1.2.1 WLS formulation

The SE approach presented in this section is based on one of the most commonly used techniques to perform state estimation, namely the Weighted Least Squares (WLS) method [2]. The WLS-based SE technique applies the following measurement model:

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

where $\boldsymbol{z}$ is the vector containing the measurements at a given instant of time, $\boldsymbol{x}$ is the vector of the variables representing the state of the electric grid, $\boldsymbol{h}(\boldsymbol{x})$ is the set of measurement functions expressing each measurement in $\boldsymbol{z}$ in terms of the state variables used in $\boldsymbol{x}$, and $\boldsymbol{e}$ is the vector of the errors associated with the measurements in $\boldsymbol{z}$.

In State Estimation for transmission systems, the state variables representing the electrical system are typically the voltage magnitudes and phase-angles at the different nodes of the grid.

However, it is possible to use different parameters in the state vector, such as rectangular voltages [3] or branch currents either in polar or rectangular coordinates [4], [5], [6], and these alternatives offer specific advantages for distribution system SE. See [7] for a detailed example; the measurement vector includes different types of measurements. Typical measurements adopted for SE purposes are the voltages at the nodes, the currents at the branches of the grid or injected at the nodes, and the active and reactive power flowing in the branches of the grid or injected at the nodes.

Based on the model in eq. (1), the objective of the WLS method is to minimize the following weighted sum of the measurement errors:

$$J = min\left(\sum_{i=1}^{m} w_i[z_i - h_i(x)]\right) \tag{2}$$

where m is the number of measurements in the vector $\boldsymbol{z}$, and w_i is the weight associated to the *i*-th measurement. Note that, to maximize the accuracy of the WLS method, the weight has to be chosen as the inverse of the overall measurement variance, which has to be derived from the uncertainty characteristics of the components present in the measurement chain such as sensors and measurement units.

Converting the minimization in (2) into a matrix form, the WLS objective function can be written as:

$$J = [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})]^T \boldsymbol{W} [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] \tag{3}$$

where $\boldsymbol{W}$ is a weighting matrix having the weights w_i in the elements of its diagonal. Under the assumption that the measurement errors are statistically independent, the other elements of the weighting matrix are equal to zero and, therefore, $\boldsymbol{W}$ is a diagonal matrix.

The WLS minimization can be performed using the iterative Gauss-Newton method, which leads to the following equation system solved at each iteration k:

$$\boldsymbol{G} \cdot \Delta\boldsymbol{x} = \boldsymbol{H}^T \boldsymbol{W}\left(\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x}_{k-1})\right) \tag{4}$$

where $\boldsymbol{x}_{k-1}$ is the state vector estimated at the iteration $k-1$, $\Delta\boldsymbol{x} = \boldsymbol{x}_k - \boldsymbol{x}_{k-1}$ is the vector computed to update the estimation of the state vector $\boldsymbol{x}$, $\boldsymbol{H}$ is the Jacobian matrix having the derivatives of the measurement functions $\boldsymbol{h}(\boldsymbol{x})$ with respect to the state variables in $\boldsymbol{x}$, and $\boldsymbol{G} = \boldsymbol{H}^T\boldsymbol{W}\boldsymbol{H}$ is the so-called Gain matrix.

Due to the fact that the measurement functions are usually non-linear, the equation system in (4) has to be solved iteratively until a certain convergence criterion is satisfied. Usually, the convergence criterion is set as:

$$max(|\Delta\boldsymbol{x}|) < \varepsilon \tag{5}$$

where ε is a convergence threshold arbitrarily chosen (for example, a typical value for polar voltage based state estimators is $\varepsilon = 10^{-6}$). Note that the smaller the convergence threshold, the larger the number of iterations required by the WLS algorithm to converge and, consequently, the larger the execution time of the algorithm.

After the convergence of the iterative procedure, the last computed value of the state vector $\boldsymbol{x}$ represents the final estimation of the state of the grid. The WLS method is known to be the maximum likelihood estimator in presence of measurement errors with Gaussian distribution, as often assumed in the SE context [2]. Under these conditions, the WLS provides the best possible accuracy performance achievable through the given set of input measurements. An additional benefit given by the WLS method is the possibility to determine the uncertainty associated to the estimated states. The covariance matrix of the estimated states can be calculated as the inverse of the Gain matrix $\boldsymbol{G}$, from which it is thus possible to derive the uncertainty (in terms of variance) of the estimated states (diagonal elements of the covariance matrix) and the covariance among the different estimated variables (terms out of the diagonal in the covariance matrix). As Section 2.1.4 will show, the information on the uncertainty of the estimates is highly important for properly designing the harmonization steps in distributed approaches and to enable proper coordination in multi-level SE architectures. Last but not least, note that, once the vector of the state variables has been estimated, the other quantities of the grid can be derived by using classical power system equations. Consider this example: if bus voltages in the state vector represent the state of the grid, the estimation of currents and powers, both the flow at the branches and the consumption or injection at the nodes, can be obtained from the estimated bus voltages. Moreover, the uncertainty of the indirectly computed quantities such as currents or powers in the example above can be also computed by applying the law of propagation of the uncertainties, which is:

$$\boldsymbol{U}_{\boldsymbol{y}} = \boldsymbol{H}_{\boldsymbol{y}} \boldsymbol{U}_{\boldsymbol{x}} \boldsymbol{H}_{\boldsymbol{y}}^{T} \tag{6}$$

where $\boldsymbol{y} = \boldsymbol{h}_{\boldsymbol{y}}(\boldsymbol{x})$ represents the set of electrical quantities calculated from the state variables $\boldsymbol{x}$, $\boldsymbol{H}_{\boldsymbol{y}}$ is the Jacobian matrix with the derivatives of the mathematical functions $\boldsymbol{h}_{\boldsymbol{y}}(\boldsymbol{x})$ with respect to $\boldsymbol{x}$, $\boldsymbol{U}_{\boldsymbol{x}}$ is the covariance matrix associated with the estimated states $\boldsymbol{x}$, and $\boldsymbol{U}_{\boldsymbol{y}}$ is the covariance matrix of the newly computed electrical quantities in $\boldsymbol{y}$.

2.1.2.2 Measurement inputs

SE approaches usually rely upon a set of redundant real-time measurements for their operation. The condition necessary for applying the WLS method is that the system is overdetermined, that is the number of available measurements must be larger than the number of state variables to be estimated, and that the Jacobian matrix $\boldsymbol{H}$ has full column rank. Under these conditions the system is said to be observable and the SE tool allows filtering out the errors unavoidably present in the collected measurements, thus providing an accurate and reliable picture of the operating conditions of the grid.

In the distribution systems, one of the main obstacles for applying SE is the lack of a sufficient number of real-time measurements to obtain the grid observability. Most of the approaches proposed in scientific literature bypass this issue by introducing pseudo-measurements such as forecast measurements derived from historical or statistical data about the power consumption (or generation) at the different nodes of the grid. If pseudo-measurements are available for all load and generation nodes, then a real-time voltage measurement (for example at the main substation) is enough to guarantee the observability of the system. In the WLS model, pseudo-measurements are handled exactly in the same way as real-time power injection measurements, but a quite large uncertainty is assigned to them to reflect the poor reliability of their information. The use of data with low accuracy also degrades the accuracy of the SE results, but such an approach is essential to deal with the lack of measurement instrumentation in the field and to allow the operation of the SE tool.

While the use of pseudo-measurements is reasonable when the number of real-time measurements is not sufficient to ensure system observability, the generation of forecast information associated with the pseudo-measurements requires the availability of historical or statistical information on the customer behavior connected to a particular node. Such information is sometimes owned by DSOs, but in many cases there is no a priori knowledge available on the possible consumption or generation characteristics of the grid buses. The WLS method considered in SOGNO also addresses this worst scenario, and considers, for all nodes with unknown characteristics, the nominal power of the connected customer (or substation) as starting point for the definition of the power consumption (or injection) at the node. As there are no particular assumptions on the power consumption value, a uniform probability distribution is considered between the minimum and the maximum power values that can be present according to the nominal characteristics of the load or generator. Note that the use of a uniform probability distribution still allows deriving the associated standard deviation to be considered for defining the measurement weights in the WLS model. However, such an approach will lead to very large uncertainties associated to the values adopted in the state estimator as “nominal” measurements. As a matter of fact, these large uncertainties will also propagate to the SE results, and for this reason it is important that the few measurements deployed on the field have very good accuracy and are placed in strategic positions of the network.

Figure 2 summarizes the main sources of measurement information for the design of the SOGNO SE service. Real-time measurements are the most important source of information, and they will be considered with a Gaussian-distributed uncertainty according to the accuracy characteristics of the components involved in the measurement chain. If available, pseudo-measurements based on historical or statistical data will be then used to enlarge the set of measurements and these will be considered with a Gaussian-distributed uncertainty according to the level of confidence of the available information. Finally, for the nodes for which it is not possible to define pseudo-measurements, “nominal” measurements with uniform distribution of the uncertainty between a minimum and a maximum threshold will be considered.

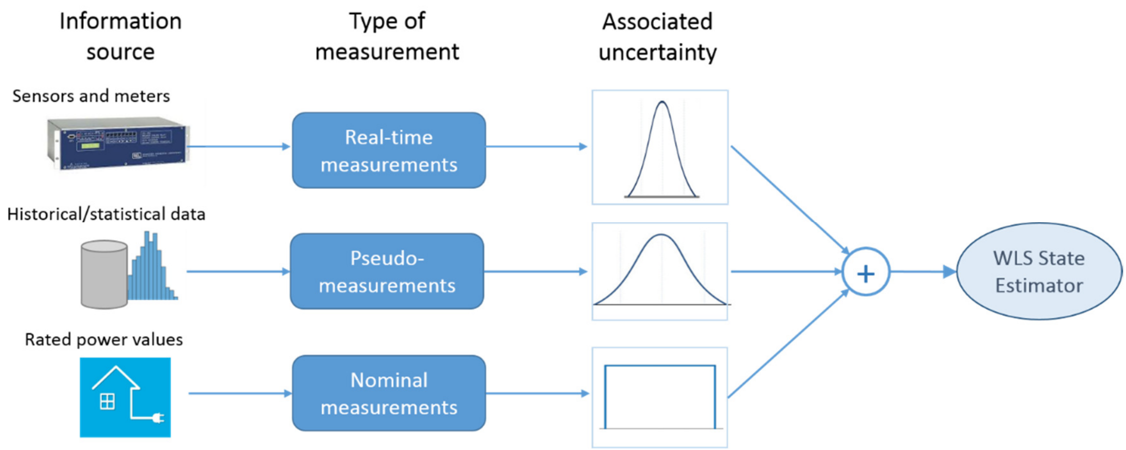


Figure 2: Overview of input measurements to the WLS estimator

2.1.2.3 Bad data detection functionalities

Conventional state estimators provide important functionality to detect and identify possible bad data based on the WLS approach. The successful execution of this task is strictly dependent on the availability of a redundant set of input measurements.

In distribution systems, due to the low number of accurate measurements provided by real instrumentation on the field and the low reliability of the other measurements (such as pseudo-measurements) used to enable the SE procedure, applying efficient bad data detection and identification routines is hardly achievable. For implementing a WLS-based SE service a filtering module will be used to remove clearly invalid data such as voltage values with negative signs, and a bad data detection and identification block based on the largest normalized residuals theory (see [2]) will be integrated to evaluate the achievable performance depending on the specific characteristics of the field trial and the adopted measurement configuration.

2.1.2.4 Integration of topology changes

Implementing the mathematical framework for the WLS algorithm relies on the knowledge of the grid data, namely the topology of the network and the impedance characteristics of the main components (lines, transformers, etc.). Since the topology of the grid can change, depending on the reconfiguration actions performed by the DSO in response to specific automation schemes, it is important that possible modifications of the grid topology are detected and communicated to the state estimator. The state estimator needs to be able to adapt the WLS model according to the information received. For this reason, the implemented state estimator will also include a topology processor module, which is responsible for modifying the models used by WLS in case of topology changes.

2.1.3 Data-driven state estimation approach

In alternative to classical WLS estimation approaches, data-driven approaches can also be used to perform the state estimation in distribution grids. To build data-driven monitoring models, the main requirement is the training data which represents the behaviour of the entire grid (states) found in the power distribution system depending on the current topology (which needs to be known). The training data can be obtained from load flow data, either from DSO load flow data or from a power flow simulation tool. In this context, Artificial Neural Networks (ANN) are exploited as a data-driven technique to perform the state estimation. To this end, an ANN is trained in such a way that it can map the system input (or measured grid variables) to the states (voltage magnitude and voltage angle) of the distribution system. In fact, ANN consists of several layers, each containing a certain number of neurons. The ANN architecture used in the SOGNO monitoring system includes three layers: an input, a hidden and an output layer.

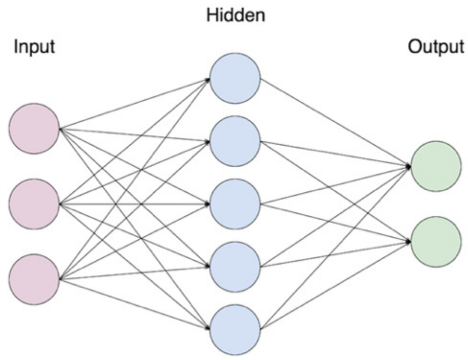


Figure 3: Artificial neural network architecture

The neurons in these layers are connected to each other through weights and biases that are synthesized by performing a training algorithm so that the ANN can learn to capture the non-linear correlations between input and output data sets. By providing training data (input and output data sets, which in the SE context correspond to starting measurements and grid state, respectively) the weights and biases are adjusted so that the distance between actual and predicted values would be below a specific threshold.

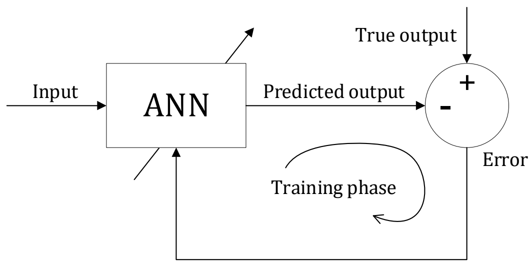


Figure 4: Artificial neural network training process

Compared to the WLS-based approach, the computational cost for performing state estimation in the data-driven monitoring approach is low as it does not involve matrix inversion operations. In runtime, upon receiving the measured values (input data), the ANN-based estimator very quickly calculates the grid states so that these can be immediately processed in other distribution automation functions.

2.1.4 Distributed implementation for distribution grids

One of the major challenges for applying distribution system SE is the size of the distribution networks. In fact, MV grids are significantly larger than the power networks at transmission level and this scenario becomes even worse when considering also the monitoring of the LV grid. As a matter of fact, the design of distributed solutions is almost compulsory for dealing with the large size of the distribution system. For this reason, in the SOGNO project, an implementation based on a distributed architecture will be taken into account for the SE service. In particular, two types of distribution network partitions will be considered, as shown in the example grid in Figure 5.

- Vertical partition: the division of the network is according to the voltage level of the grid. As an example, in the system shown in Figure 5, the MV and the LV grid represent two different vertical layers of the SE architecture. In general, different vertical layers can exist within the same MV or LV levels, if different voltages are used and those grids are connected.
- Horizontal partition: the division of the grid belonging to the same vertical layer (having the same rated voltage) is according to topological or other specific criteria. In the system shown in Figure 5, LV grids are characterized by multiple feeders departing from the main substation. A possible partition criterion could be to consider each feeder separately. Note that multi-feeder configurations are quite common in radial distribution grids, both at MV and LV level, and this example reflects a realistic scenario.

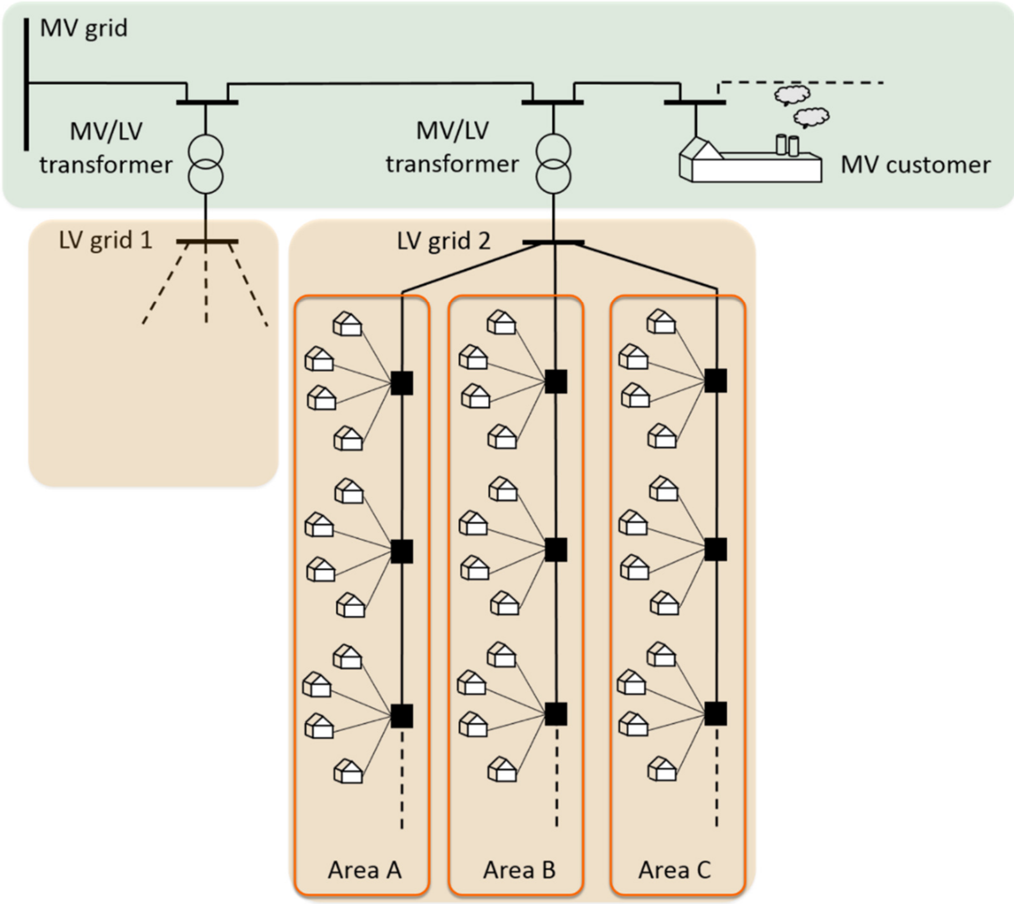


Figure 5: Partitioning of a distribution grid in multiple areas

The partition of the grids in multiple areas allows splitting the SE service into smaller sections that can be performed independently. However, the low number of measurement devices in the field calls for appropriate solutions to maximize the SE accuracy, and ad-hoc coordination procedures are used in SOGNO to merge the SE results of different areas to improve the final accuracy of the estimation results. In particular, different coordination procedures are devised to harmonize the results of SE instances belonging to the same vertical layer (different areas of the same grid) or to exchange the SE results between different layers.

Figure 6 shows the interactions between the SE instances associated to the grid partition presented in Figure 5. First of all, it is possible to observe that the coordination between different vertical SE layers follows a bottom-up approach. In fact, SE results obtained at the lower layers of the SE architecture are forwarded to the upper layers of the architecture. In particular, the SE results useful to be integrated at the upper level of the grid are those at the interconnection point, namely the voltage and the power consumption (or injection) seen at the substation. In a scenario where all the LV grids are monitored by a SE tool, this type of coordination ensures that voltage and power measurement are available input to the MV grid SE for each MV/LV substation. Consequently, this solution does not only allow dividing the SE problem between grids operated at different voltage levels, but also supports propagating information coming from the lower SE layers to the upper layer, improving its measurement redundancy and, eventually, the achievable SE accuracy. Note that, in order to enable this type of coordination, the SE process has to be executed sequentially starting from the lowest layer of the architecture. In the case shown in Figure 5 and Figure 6, the MV grid SE can be performed only after the SE process is completed for the LV grids. Since this type of coordination implies the use of some SE results given by the lower layers as equivalent measurements in the upper SE level, observe that the forwarded estimated values need to be provided together with associated information on their uncertainty. In the case of WLS-based SE, this can be easily carried out by using eq. (6) to compute the estimation uncertainty for electrical quantities provided to the upper layer SE.

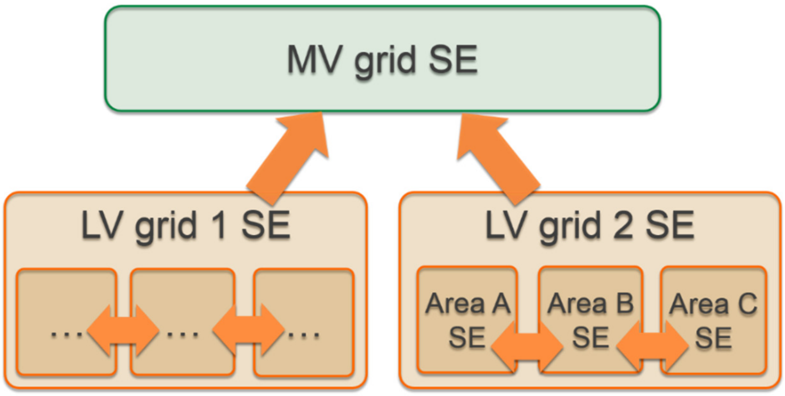


Figure 6: Logical coordination of different local SEs

Concerning the harmonization of SE results for different areas belonging to same SE layer, this is done in a two-step process, following the same philosophy presented in [8]. In the first step, the SE process is performed independently on each local area. In the second step, neighbouring areas share the SE results at the overlapping zones and the results achieved by the different local estimators are post-processed in order to refine the estimation results (see [8] for more details).

Overall, the distributed framework for the implementation of the distribution system SE service provides the following important benefits.

- Thanks to the vertical partition of the distribution grid in multiple SE layers, upper layers can exploit the results achieved at the lower level to improve their measurement redundancy and their SE accuracy performance. Such a solution prevents a massive installation of measurement units at the upper layers of the grid to obtain specific accuracy targets.
- The horizontal partition of the grids allows parallelizing the execution of SE on different areas, leading to a significant reduction of the overall execution times for the SE service. This will help to increase the execution rate of the SE service, thus leading to a more fine-grained monitoring of the distribution network, as required due to the highly dynamic conditions present in distribution grids.
- Input data (such as grid data, real-time measurements, etc.) are sent to and managed by different SE instances. Each one of these instances only need to take care of the relatively smaller amount of data associated to their area, thus implying that also the storage and communication requirements are distributed among the different SE instances.
- The proposed architecture ensures a higher degree of reliability, since a problem on a specific area does not affect the whole system but only the interested zone. In fact, if a problem occurs and a specific SE instance cannot run its SE, only this area will remain unmonitored, while the other areas at the same SE layer, as well as all the other layers, can continue to work without a significant SE accuracy degradation.
- The distributed solution goes in the direction of having scalability of the SE service by design. Theoretically, a large number of areas can exist in the same layer of the grid and this does not affect the overall SE set-up, since each area operates independently from the other ones and only requires a low communication interaction during the harmonization process with few neighbouring zones. Similarly, several vertical layers of SE can exist and this does not affect the overall SE structure, since each layer operates independently and only exchanges data with the immediately lower and upper layers (for receiving and sending the SE results, respectively).
- The distributed architecture can take great advantage using fast communications enabled by 5G and the associated availability of the Edge Cloud. In fact, each SE instance associated with a particular area can be deployed on the Edge Cloud and the use of 5G communication infrastructure can significantly improve the coordination process between SE instances or SE layers.

2.2 Power control

The Power Control (PC) service aims at obtaining the optimum management of the distribution grid power flows (at both MV and LV level) for preventing possible contingencies (e.g. violation of the voltage limits, overloading of grid components, etc.) and to foster a more efficient and reliable system operation. This is obtained through the smart control of the active and reactive power injected (or consumed) by converter-based components connected to the grid. While converters available today in the market do not guarantee this feature, this requirement can be considered as realistic in future scenarios where the availability of communication capabilities will allow to enable the smart grid.

The PC service is based on the monitored grid state as provided by the synchronously running SE service. Taking into account the requirements and aims of current grid codes, the possible limits for the active control of Distributed Energy Resources (DERs) by means of coordinated schemes are investigated to develop an exemplary algorithm that enhances the performance for a specific objective. The output of the PC service is the pair of active and reactive power set points for each converter-based component in the grid.

2.2.1 Grid codes and state of the art power control

Grid codes, standards and guidelines define the DER grid interconnection and operation including grid support. These standards include a multitude of requirements with respect to the control of DER or the behavior during faults. This includes several aspects with respect to voltage support, frequency support, dynamic grid support and direct grid management of the DSO.

Table 2-1: Definition of grid support functions from DER [9]

Requirement/ Function	Description	IEC TR 61850-90-7
Operational frequency range	Defined frequency range, where the generator has to operate normally.	N/A
P(f) at over frequency	Reduction or limitation of the active power at over-frequency in the grid	FW21/FW22
Q/cosφ range	Defined reactive power or cosφ to be provided by the generator	N/A
Cosφ(P)	Reactive power control mode: Cosφ as function of active power	WP41/42
Q(U)	Reactive power control mode: Q as function of grid voltage U	VV11/12/13
P(U)	Reduction or limitation of the active power at over-voltage in the grid	VW51/52
External control of P	Set point or limitation of the active power through an external signal	INV2/4
External control of Q	Set point or limitation of the reactive power through an external signal	INV3
External trip/disconnect	Disconnection of the generator from the grid through an external signal	INV1
LVRT	Low voltage ride through	(TV31)
HVRT	High voltage ride through	N/A

The automatic frequency support is enabled by a P(f) control that reacts to an over-frequency with the reduction of active power after the frequency exceeds 50.2 to 50.5 Hz. The voltage can be automatically supported by means of a cosφ(P) control or a Q(U) control. Both of these control paradigms change the reactive power to control the voltage. The cosφ(P) mode controls the power factor cosφ of the generator’s output as a function of its active power output to calculate the reactive power set point. A change of the reactive power infeed affects directly the voltage. The Q(U) mode controls the reactive power output as a function of the voltage. For evaluating the voltage, one of the following methods shall be used:

- positive sequence of the symmetrical components;
- average voltage of a three phase system;

- voltage of every phase to determine the reactive power for each phase independently.

The characteristic curve according to Figure 7 has to be configurable for both control modes considering the minimum and maximum value (typically equivalent to cosφ = 0.95 inductive or capacitive) and 3 connecting lines as the defining quantities. This curve is realized by a local controller that imposes the droop control for the set points of the DER taking into account the operational limits.

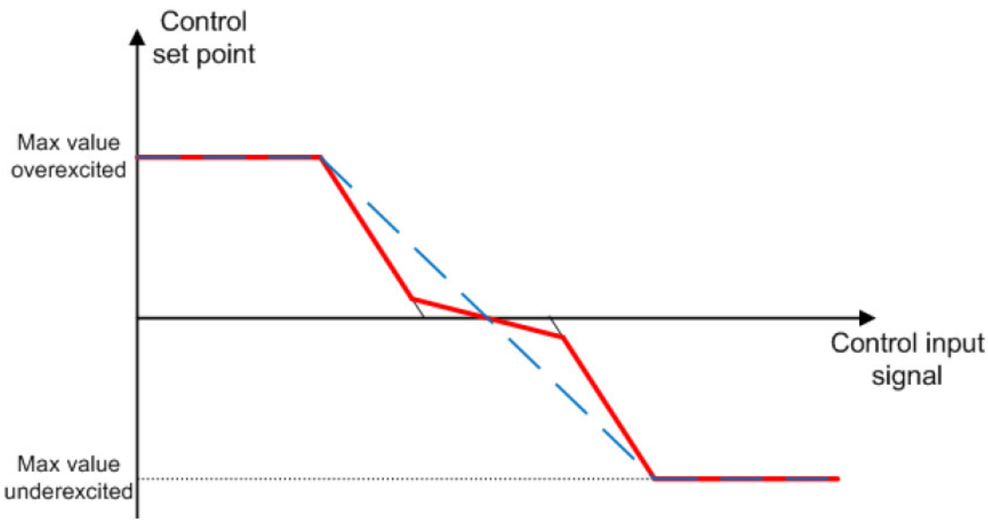


Figure 7: Example characteristics for Q control according to CLC/FprTS 50549-1:2014

Another option to restore the voltage is a P(U) control that limits the active power at over-voltages in the grid. However, this control acts only to avoid the disconnection of the generating unit. Due to the high impact of the active power on the distribution grids this counteracts a rising voltage. The implementation depends solely on the manufacturer.

The dynamic grid support is concerned with the behavior during faults in the form of fault ride through tests. The requirements for low voltage ride through and high voltage ride through test the capability of the generator to stay connected to the grid during a fault and the contribution to the short circuit current. However, these phenomena are typically in the area of milliseconds or a few microseconds and hence, not considered for PC and its management.

Grid codes among the European countries include a subset of these functions differently depending on the voltage level and the nominal power of the respective DER. Table 2-2 and Table 2-3 show the grid codes for some countries of Europe and the EU grid code for the Requirements for Generators (RfG) and additional guidelines on European level for the connection to a LV grid and a MV grid. Almost all of the featured functions are considered as mandatory requirements for MV grids. For the LV side, several norms and guidelines require the cosφ(P) control and the Q(U) control and some prescribe the external/ direct control of active and reactive power set points.

Table 2-2: Overview of grid support requirements for DER connected to LV grids [9]

DER connected to LV grids								
Country	**NC RfG***	**Europe (≤16 A)**	**Europe (>16 A)***	**Germany**	**Italy**	**Austria**	**France**	**Spain**
Function	2016	2013	2015	2008/2013	2016	2016	2013	2011/2014
Operational frequency range	Yes (Type A)	Yes	Yes	Yes (all)	Yes (all)	Yes	>100 kVA	No
P(f) at over frequency	Yes (Type A)	Yes	Yes	Yes (all)	Yes (all)	Yes	Yes*	No
Q/cosφ range	No (Type A)	Yes	Yes	>3.68kVA	Yes (all)	>0.6 kW	No	No
Cosφ(P)	No (Type A)	Yes	Yes	>3.68kVA	Yes (all)	>0.6 kW	No	No
Q(U)	No (Type A)	Yes	Yes	No	>11.08 kW*	>0.6 kW	No	No
P(U)	No (Type A)	No	Optional	No	Optional	>0.6 kW	No	No
Direct control of P	No	No	Yes	>100kW	Yes (all)	>100kVA	No	No
Direct control of Q	No	No	Optional	No	>11.08 kW	>100kVA	No	No
Remote trip/disconnect	Yes (Type A)	No	Yes	No	Yes (all)	No	No	No
LVRT	No (Type A)	No	Yes	No	>11.08 kW	No	No	No
HVRT	No (Type A)	No	Yes	No	No	No	No	No
Reference	(EU) 2016/631 (NC RfG) [2]	EN 50438 2013 [7]	CLC/TS 50549-1:2015 [8]	VDE AR N 4105: 2011 [13]	CEI 0-21:2016 [17]	TOR D4: V2.3 2016 [16]	Arrêté du 23 avril 2008 [19] * Enedis-NOI-RES_13E 11/07/2016	RD 1699/2011 [22] 206007-1 IN:2013 [23]
Remarks	* non exhaustive requirements subject to implementation in national codes		* technical specification only – not mandatory	VDE AR N 4105 currently under revision	* Additional lock-in/-out function			

Table 2-3: Overview of grid support requirements for DER connected to MV grids [9]

DER connected to MV grids							
Country	**NC RfG**	**Europe**	**Germany**	**Italy**	**Austria**	**France**	**Spain**
Function	2016	2015	2008	2016	2016	2013	2010/2014
Operational frequency range	Yes (BCD)	Yes	Yes	Yes	Yes	Yes	No
P(f) at over frequency	Yes (BCD)	Yes	Yes	Yes	Yes	No	>2/10MW
Q/cosφ range	Yes (B*CD)	Yes	Yes	Yes	Yes	Yes	>2/10MW
Cosφ(P)	*	Yes	Yes	Yes	Yes	No	No
Q(U)	*	Yes	Yes	Yes	Yes	No	No
P(U)	*	Yes	No	Yes	Yes	No	No
Remote control of P	*	Yes	>100kW	Yes	>100kW	No	>2/10MW
Remote control of Q	*	Optional	No	Yes	Yes	No	No
Remote trip/disconnect	Yes (BCD)	Yes	optional	Yes	No	No	No
LVRT	Yes (BCD)	Yes	Yes	Yes	Yes	>5MW	>2MW
HVRT	No	Yes	No	Yes	No	No	No
Reference	(EU) 2016/631 (NC RfG) [2]	CLC/TS 50549-2:2015 [9]	BDEW MV Guideline (2008) [14] Amendment 4, 2013 [15]	CEI 0-16:2016 [18]	TOR D4: V2.3 2016 [16]	Arrêté du 23 avril 2008 [19]	P.O.12.3:2006 [21]; P.O.12.2:2005 [24] RD1565:2010 [25]; UNE 206007-2 IN:2014[22]
Remarks	* non exhaustive requirements subject to implementation in national codes					Specific requirements for island networks (Corsica and DOM-TOM).	

The previous control algorithms that are based on characteristics curves as in Figure 7 are realized by means of a local controller. Following the measurement of the voltage, frequency or active power, the set points for active and reactive power of the DER are calculated directly following the characteristic curve.

The possible usage of external input signals for the DER provides a new dimension. Instead of automatic controllers, or in addition, external set points for active and reactive power may be directly imposed by the DSO overwriting other set points (Figure 8). The increasing requirement in LV grid codes (and already prevailing MV grid codes) for DER to be able to use external control signals rises the possibility for more controllability and flexibility for the system operator. This potentially enables the DSO to react to commands from the Transmission System Operator (TSO), e.g. the request for active power limitation to avoid a congestion, or act based on the observed system state, e.g. to avoid an emergency situation.

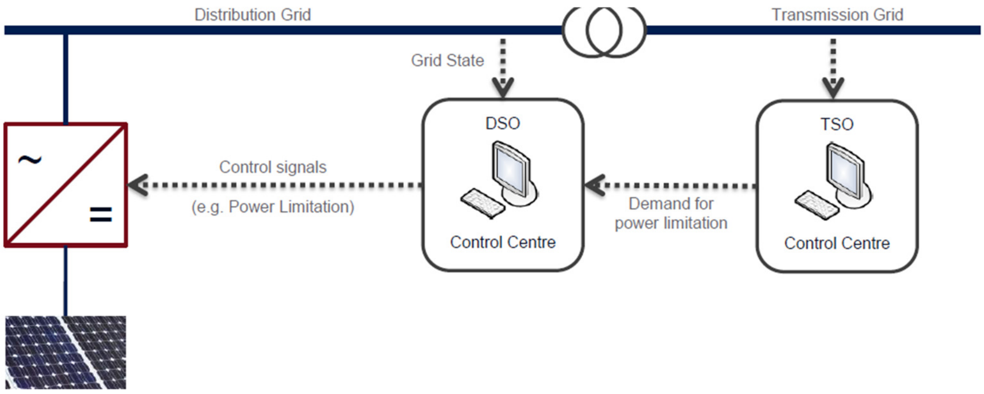


Figure 8: External control of active/reactive power set points by system operator [9].

However, the options are not limited to this kind of scenario. The DSO can use the external control signals to adjust the power flow in the distribution in its favor. The DSO may send active and reactive power set points to keep the voltage of a feeder within the limits during generation peaks. The full reactive power capacity could be utilized before any active power has to be curtailed. Or the losses in the grid may be minimized using a coordinated voltage control scheme for the grid. This kind of approaches could allow minimizing the power curtailments for distributed generation based on renewable energy sources, thus fostering their operation in the distribution system.

The execution of such approaches requires additional computational power to run algorithms that can provide an optimal power flow for the grid or a system state within the operational limits. Moreover, the value of these algorithms increases with the reliability, flexibility and speed of the communication since the response time to any kind of event or desired action is lowered and the operational safety margin can be reduced. The SOGNO solution that is based on the ViSA together with a 5G communication to the controllable devices provides the computational power in the cloud and a flexible communication cost-efficiently, as it requires a minimal amount of hardware. This leads to the possibility to look into possible algorithms that can potentially lead to a better management of DER and the distribution grid.

2.2.2 New power control approaches

In general, the PC service solves an optimal power flow (OPF) problem for different objectives with operational restrictions. These objectives may be to prevent possible contingencies (e.g. violation of the voltage limits, overloading of grid components, etc.), to increase the efficiency (e.g. minimizing active power losses, reduce amount of active power curtailment, etc.) or to improve specific power quality factors (e.g. minimizing voltage unbalances in the three phase system). A first approach for a PC algorithm considers only the violation of preferred voltage limits and the enforcement of these limits at all times as a form of voltage support for a LV or MV grid. This approach may be extended to a multi-objective approach at a later stage. The decision variables are the set points for the active and reactive power injected by controllable resources. Typically, these resources are converter-based components in the grid belonging to DER (PV plants, wind turbines, etc.) and possibly energy storage units. The operational restrictions encompass several restrictions tied to the power flow: voltage levels have to stay within limits (these may differ from the desired voltage band levels in the objective), the active and reactive power limits of the DER must be kept, lines cannot be overloaded, etc.

The PF service takes the voltage profile at all buses as the input, and this is directly provided by the SE service. The algorithm acts if any of the voltages is exceeding the respective limits V_{min}/V_{max}. The voltage sensitivity of the buses with voltages beyond the thresholds are calculated based on the voltage sensitivity matrix S which is the inverse of the Jacobian matrix as obtained in the SE service.

$$\begin{bmatrix}\boldsymbol{\delta}\\ \boldsymbol{V}\end{bmatrix} = \begin{bmatrix}S_{\delta P} & S_{\delta Q}\\ S_{VP} & S_{VQ}\end{bmatrix}\begin{bmatrix}\boldsymbol{P}\\ \boldsymbol{Q}\end{bmatrix} \qquad with\ \ S = \begin{bmatrix}S_{\delta P} & S_{\delta Q}\\ S_{VP} & S_{VQ}\end{bmatrix} = H^{-1} \tag{7}$$

The vectors $\boldsymbol{P}$ and $\boldsymbol{Q}$ represent the injected active and reactive power at each bus and the vector $\boldsymbol{V}$ the magnitude of the voltages at each bus. The voltage sensitivity matrix S_{VQ} expresses the impact of the change of any reactive power injection on all bus voltages. The voltage sensitivity for the bus voltage V_i that exceeds the limits the most is sorted in descending order for the reactive power injection. This results in a list of reactive power injections weighting the impact on this voltage. Considering the controllable devices and their locations in the grid, this list is filtered to contain only injections that can be influenced. This is represented by the modified sensitivity vector $\tilde{\boldsymbol{s}}_{V_iQ^{con}}$. The higher a controllable reactive power is in this vector, the higher is the preference to use the associated inverter for the control of the bus voltage. The reactive power infeed of the first inverter Q_j is changed to counteract the voltage violation based on the corresponding impact according to the Jacobian matrix.

$$\Delta Q_j = h_{Q_jV_i}\Delta V_i \qquad with \;\; \Delta V_i = V_{max} - V_i \tag{8}$$

If the remaining reactive power capacity of the first inverter in the list is not sufficient to apply the needed changes of reactive power, ΔQ_j is limited to the highest amount possible and already reducing the voltage difference ΔV_i partially. In this case, the next element of $\tilde{\boldsymbol{s}}_{V_iQ^{con}}$ is chosen to reduce the remaining voltage difference further. This ensures that the least amount of reactive power has to be controlled to restore the voltage limits. This procedure is followed until the remaining voltage difference is zero or if no controllable devices have any reactive power capability left to support the voltage. If the voltage support by means of reactive power is not sufficient to support the voltage, the active power has to be curtailed. This is done following a procedure similar to the presented reactive power approach, starting with the voltage sensitivity matrix S_{VP} and then following the same steps.

A new run of the state estimation can confirm that the resulting power flow after the application of all set point changes would stay within all operational limits before the set points are physically applied on the controls. It has to be noted that the simple iterative approach to obtain the set points is tailored to the typical structure of a feeder in radial grids, e.g. a LV grid. Otherwise, the parallel solution of the underlying OPF problem may be needed.

Since the PC algorithm relies fully on the results of the SE service, its accuracy depends directly on the accuracy of the SE service. Specific accuracy requirements to enable the PC service do not exist in the scientific literature and will be investigated during the SOGNO project. Similar to the case of SE, a critical challenge for the application of PC at distribution level is the large size of the distribution grids. This calls for the design of distributed approaches where PC algorithms act on small areas, possibly sharing some data with an upper level controller to ensure the coordination of the power control strategy in the whole grid. This leads to the identical setup for the logical architecture of PC as shown in Figure 6 and section 2.1.4.

2.3 Power quality evaluation

The SOGNO Power Quality Evaluation (PQE) service provides continuous real-time situational grid awareness to the electricity grid operators about the quality of the power supply in their grid and, in case anomalies are detected, triggers suitable countermeasures to prevent asset stress or failures, and outages. The produced power quality information can be used as input for more complex management and SOGNO control functions by the DSOs to efficiently operate their grid. In this regard, control or optimization functionalities built based on the PQE service can lead to:

- reduced costs by reducing outages and their associated regulator fines;
- reduced asset failures due to low power quality;
- reduced time to identify outages related to poor power quality;
- improved service quality and efficiency of the power delivery.

The SOGNO PQE service is provided by the Advanced Power Measurement Unit (APMU) device that is being developed by MAC, as shown in the following:

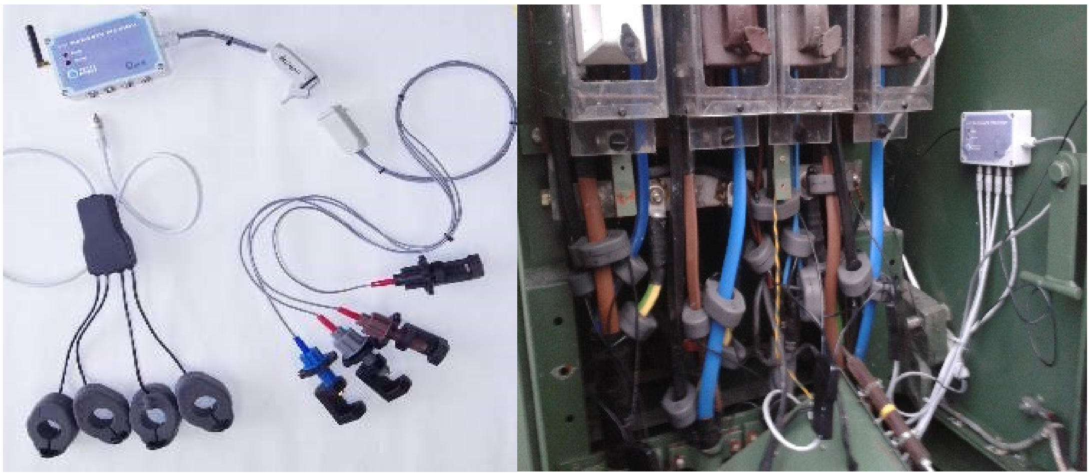


Figure 9: APMU deployed on a 4-Feeder LV Network.

On LV and MV lines, the APMU measures:

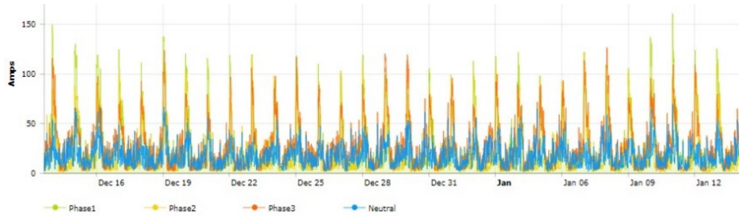
- Classical electrical quantities, including voltage, current, power and frequency.
- Advanced power quality parameters, including current flow direction, harmonics, reactive power, power factor, energy, unbalanced phases, earth fault currents, voltage sags & dips.
- Smart event monitoring, such as over-voltage, over-current, and overload detection, using algorithms that run in the APMU and are dynamically updated for local grid-edge intelligence.

The algorithms are updated as required depending on the operational/business monitoring objectives of the DSO for specific parts of their networks or issues that they are encountering. There could be straightforward changes to Over-Voltage/Current thresholds or as complex as defining new PQ indices or potential fault conditions to be monitored.

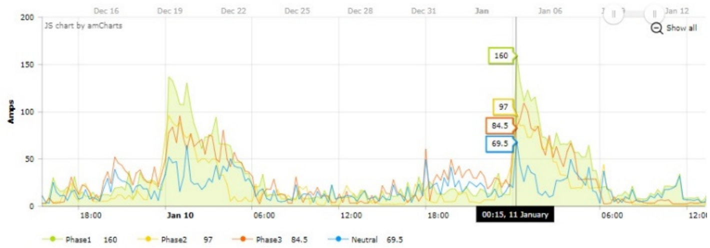
While current power quality monitoring units that compute PQ parameters already exist in the market, the innovative added value of the SOGNO solution is the implementation of innovative functionalities including: (a) providing grid-edge processing and dynamic DSO-defined algorithms, (b) using a low-cost device that enables mass deployed network monitoring to generate real-time data, even in very large distribution grids at MV, but particularly at LV, and (c) integration into the SOGNO ecosystem and all of its other services. The information directly provided by the APMU can be optionally complemented by the results of SE or by additional post-processing algorithms implemented in the SOGNO ViSA cloud platform for the computation of other power quality indicators.

The PQE outputs of the APMUs are communicated in real-time to the ViSA and, finally, transmitted to the grid operators to give them awareness on the current status of the power quality in the grid. The different power quality indicators can be constantly shown in the visualization tool of the DSO or could trigger specific alarms if the related values exceed specific thresholds. For instance the following figure shows some typical examples of SOGNO PQE service user interface parameters from MAC's cloud-based visualisation platform at http://gridwatch.cloudapp.net

- Currents of 3 phases & Neutral from one Feeder



- Current detail showing Neutral current



- Voltages of 3 phases from one Feeder

- Active Power for 3 phases from one Feeder

- Frequency for 3 phases from one Feeder

- Power Factor for 3 phases from one Feeder

Figure 10: PQE Service User Interface examples of monitored parameters.

Being a monitoring service, the SOGNO PQE runs continuously with a reporting rate of the monitored parameters to the control centre, typically well below a minute. However there are no strict requirements on the reporting rate with which the APMUs in the field provide the power quality parameters to DSOs.

2.3.1 PQE Algorithms

The PQE service's APMU devices continuously monitor and provides standard power quality parameters, including:

- Current (A) - Phase 1, Phase 2, Phase 3, Neutral Current, Flow Direction.
- Voltage (V) - Phase 1, Phase 2, Phase 3
- Power - Active Power (Kw), Apparent Power (VA), Reactive Power (VAr)

- Energy - Active Energy (kWh), Reactive Energy (kVArh)
- Frequency
- Power Factor
- Harmonic Distortion (up to 50^{th} current & voltage) THD & Individual harmonics

The SOGNO PQE Service dynamically loads algorithms that run in the APMU devices for local grid-edge intelligence. The algorithms are updated as required depending on the operational/business monitoring requirements of the DSO for specific parts of their networks or issues that they are encountering. So for instance in some substations, or parts of the grid, the operations staff may be concerned about, one or more of the following use cases:

- Imbalance across your 3 phases (leading to stresses on some phases),
- Excessive earth fault currents leakage and possible safety issues,
- Too high a reactive power or low power factor resulting in reduced delivery capacity,
- Potential harmonics due to certain loads.
- etc

The algorithms could be straightforward changes to Over-Voltage/Current thresholds or as complex as defining new PQ parameters or potential fault conditions to be monitored, such as:

- Over-voltage, over-current, and overload detection
- Excessive earth fault currents
- LV outage detection
- Persistent unbalanced phases
- Voltage Sag and Flicker Detection

However, it is expected that future algorithms will be more complex by defining more sophisticated grid parameters or potential fault conditions to be monitored, exploiting the security and low-latency features of 5G to better meet the operational needs of DSOs. For instance, the following have already been suggested by DSOs and are looking promising:

- Using LV monitoring to determine MV voltages.
- Using LV monitoring to detect MV lines down or fuse blown.

The SOGNO PQE dynamically loaded algorithms will enable sophisticated distributed real-time intelligent monitoring and grid-awareness right to the grid edge, in low-cost mass-deployed APMU devices to provide the PQE service data to:

- DSOs' operational field staff who "need to know urgently" about events on the grid as they occur on their mobile devices to help them prevent asset stress or failures, and outages.
- The DSO's backend SOGNO services, and Distribution Management System, at all times.

2.3.2 Sensor specifications

Voltage and current sensing in MV networks are usually done by transformer, but they are often unappropriated for power quality metering, due to their poor bandwidth (few tens of Hertz). The higher-frequency components (e.g., harmonics components generated by solar inverters) are attenuated, and the power quality is overestimated.

To provide a high-bandwidth voltage sensing, Low-Power Voltage Transformers (LPVTs) are often used. This technology, based on a passive capacitive or resistive divider, can provide a bandwidth up to hundreds of kilohertz, vs. less than a hundred hertz for voltage transformers.

Regarding current sensing, Rogowski coil technology is particularly suited for power quality measurements as it achieves an outstanding bandwidth, hundreds of times the current transformer ones. Current sensors based on Rogowski principle belong to passive Low Power Current Transformers (LPCTs).

The new standard IEC 61869-6 defines the bandwidth requirements for LPVTs and LPCTs to be used in Power Quality applications, in particular the table below regards the "0.5 S" accuracy class:

Table 2-4: Requirements for Power Quality applications

	[0.1,1] kHz	[1,1.5] kHz	[1.5,3] kHz
Ratio Error ±[%]	5	10	10
Phase Error ±[°]	5	10	20

Each APMU supports up to 4 feeders (6 in phase 2 of the project) and is powered from one of the voltage lines being monitored. In the WP5 pilots, for LV networks MAC's Planar Magnetic Current Sensors and industry standard voltage G-Clamps are used, and for MV networks ALTEA's high voltage sensors are deployed. More details on the sensors and measurement units deployed in the SOGNO field trials are provided in Deliverable D5.1. Existing voltage sensors deployed by the DSO can also be facilitated if available.

3. ViSA components and interfaces

According to the SOGNO vision, the system awareness services described in Section 2 will be integrated in a Virtualized Substation (ViSA) environment where all the distribution grid intelligence will be working. One of the main benefits of the ViSA solution is the possibility to flexibly interconnect several components to guarantee interoperability between the different services. Several components and interfaces are necessary in the ViSA platform to ensure the receiving of measurement data from the different devices on the field, the persistence of data in the databases, to manage the communications between services and the sending of results to the graphical user interface. The identification of these components and of the associated interfaces is important to guarantee the complex communication between the services. In this Chapter, the specification of the main components and interfaces needed to enable the system awareness services will be provided. The detailed description of their implementation and of the specific software solutions adopted is instead provided in Deliverable D4.2. The following figure illustrates the communication between the components

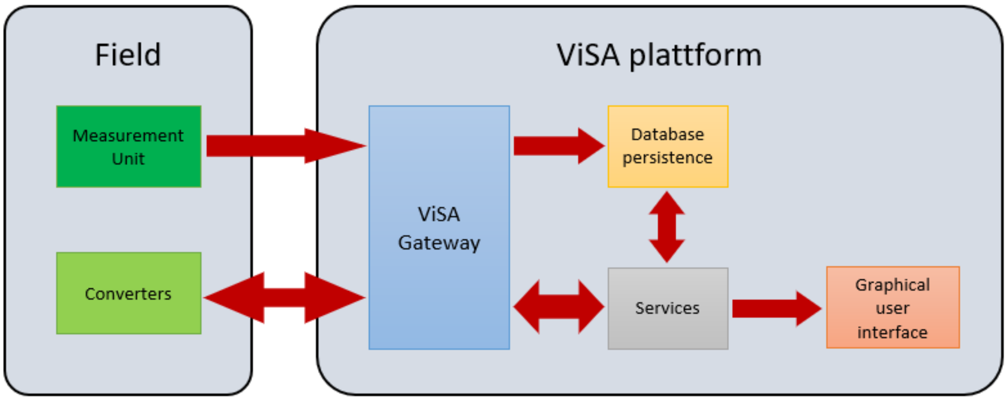


Figure 11: Communication between the components.

Figure 11 shows a high-level and schematic view of the main components involved in the operation of the different services. In the following, the components will be described according to their logical role and the specification of the needed interfaces will be provided in relationship to the services described in Section 2.

3.1 Field components

Measurements and converters are the components on the field providing the data needed to enable the described services. The SOGNO solution allows accommodating different types of measurement devices and can enable the bi-directional communication towards components on the field, as required for example by the Power Control service. While in SOGNO the focus is on the development of low-cost measurement devices that can also be easily customized, in general, the ViSA platform can interact also with meters and components available in the market. No specific modifications are needed for the components in the field to talk with the ViSA: their only requirement is to have real-time data communication capabilities. All the intelligence needed to handle the communication, to translate the specific protocols used by the field devices and to extract the needed data for the services is directly embedded into the ViSA platform. Such a solution is thus able to guarantee the interoperability among different devices and hardware manufactured by different vendors.

3.2 ViSA Gateway component

The ViSA gateway is the component allowing the communication between measurement devices or other possible components deployed on the field and the intelligent services in the cloud platform. This component need to be able to receive the measurements (or send control commands) in different formats or protocols according to the languages supported by the devices on the field. Moreover, since the system awareness algorithms have to work in (near-) real-time, the gateway has to ensure that the data communicated by the instrumentation on the field are immediately transferred to the services for their prompt processing. To ensure this, different interfaces are needed in the gateway, as described below. Figure 12 gives a schematic view of the interconnections among the different interfaces in the ViSA gateway described in the following, with the indication of the direction of the communication flow: It is worth noting that the same operation logic, and therefore also the same software interfaces, are needed in the gateway to enable both the system awareness services presented in this Deliverable and the self-healing automation services presented in Deliverable D3.4.

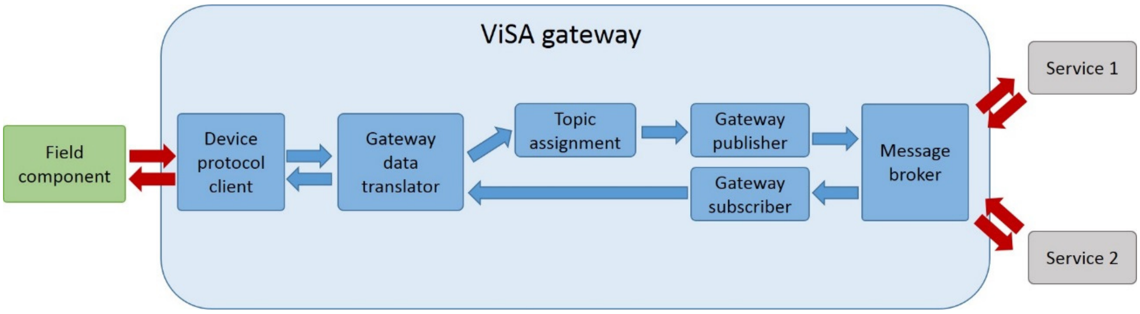


Figure 12: Schematic view of the software components in the ViSA gateway.

<u>Device protocol client:</u> this is in general the interface for the communication with the field components. Communication clients need to be available for each one of the communication protocols used by the devices on the field so that the communication with them can be correctly activated. For example, in case of the SE service, measurement devices can send their measurement data via IEC 61850 protocol or with the PMU IEEE C37.118 synchrophasor format: a client able to listen to these communications is therefore needed in the ViSA gateway as direct interface towards these measurement components.

- **<u>Gateway data translator interface:</u>** the ViSA platform needs to handle internally different data, which are coming from the measurement units on the field, from the outputs of the service algorithms, and so on. For this reason, specific internal transport protocols and data formats will be used within the ViSA, which will be in general different from the data formats used by the communication protocols of the field components. A data format translator is thus needed to ensure the correct translation of the data from/to field components to/from the ViSA platform. When the data flow is from the field devices to the ViSA, the data format translation interface takes care of the extraction of the relevant data provided by the device protocol clients and it converts them into the data format used within the ViSA. As an example, JSON (JavaScript Object Notification) format is a lightweight and flexible format that can be used for data interchanging within the ViSA. On the contrary, if the data flow is from the ViSA to the field devices (for example, in case of the PC service, for sending an actuation command to the DERs), the data format translator takes care of the conversion from the ViSA data format to the specific format needed in input to the associated device protocol client. Obviously, since different communication protocols can be used by the devices on the field, specific data format translation interfaces can be needed for each one of the communication protocols to be supported.

- **<u>Topic assignment interface;</u>** this is an interface that is used only for managing the communication flow from field components to ViSA. In general, data coming from the field can be different (measurements, switch event notification, etc.) and they can be required by different services according to their nature. In the ViSA, the routing of the data to the different ViSA components is performed using topics. The logic is that each ViSA component can subscribe to receive the data communicated under a certain topic, so that only the information of interest is received. To guarantee the coordination of the communication according to this logic, a topic assignment interface is therefore needed on the ViSA gateway for assigning the desired topics to the specific data arriving from the field devices. This interface is thus responsible for assigning the correct topics to the payloads from the data streams in order to forward them to the correct services.

- **Gateway publisher interface:** in order to guarantee the real-time communication of the data from the field component to the services, a publish/subscribe mechanism is used within the ViSA as communication paradigm. Data are always published using a specific topic, while the ViSA components can subscribe to different topics for getting only the data that are important for their operation. Different communication protocols can support the publish/subscribe mechanism, and MQTT (Message Queue Telemetry Transport) is an example of widely used protocol based on this solution. The main task of the gateway publisher is to wrap the data received from the data format translator and topic assignment interfaces with the decided publish/subscribe communication protocol and to forward these data to the message broker (described later).

- **Gateway subscriber interface:** since the ViSA gateway has to ensure the bi-directional communication between cloud platform and field, a subscriber is needed to get the data (for example the output of the PC service, since this needs to be sent to the DERs in the field) that need to be forwarded to the field components. The gateway subscriber has thus to subscribe to the relevant topics and needs to forward the received data to the data format translator interface for enabling the sending to the field components.

- **Message broker:** the message broker is a key component in the publish/subscribe communication paradigm. It is the actor responsible for getting the data published by the information producers and for forwarding them to the right components according to the received topic subscriptions. As a matter of fact, this is therefore the key component allowing the proper coordination of the data routing and guaranteeing that data are forwarded as soon as available, thus guaranteeing their (near-) real-time communication. The message broker plays a vital role for enabling the bi-directional communication between field components and ViSA services. In fact, data from the field are published through the ViSA publisher interface and then forwarded (via the message broker) to the relevant services. On the other hand, for the sending of actuation commands from the services to the field components, the services will publish the command and this, via the message broker, will be forwarded to the ViSA subscriber interface. In this way, the bi-directional communication between field and ViSA services can be enabled and guaranteed in (near-) real-time. It is worth noting that, in the developed solution, the message broker will not be only responsible for the coordination of the communication between field and ViSA services, but also for the re-routing of all the communication internally to the ViSA. As an example, according to what described in Section 2.2, the output of the SE service is needed in input to the PC service. The coordination of this communication happens thanks to the message broker. In particular, the SE service will publish its results as soon as available and the PC service (which needs to be subscribed to the topic associated to the SE results) will receive these data via the message broker.

3.3 Database persistence component

This component stores all possible information in a database so that network operators have the possibility to access historical data and service results. To ensure this, data produced from the measuring devices, services and the network model will be stored directly here. In the case of system awareness services described in this deliverable, both the results of the SE service and power quality parameters provided by the PQE service will be stored in the database for possible a posteriori analysis. In general, two different types of database will be used within the ViSA platform.

- **Static database:** this database is specifically set-up for the storage of all those data that are static and are not going to change during time. All the information about the grid data, the measurement devices characteristics and other field component characteristics will be thus stored in this database. In particular, as for the grid data, the Common Information Model (CIM) will be used. This format makes easier the exchange of data among different applications and platforms and allows a comprehensive modelling of the grid information. The CIM is object-oriented and consists of classes, attributes and relationships among them to describe the behaviour of the electrical system components. These data are essential inputs for both the State Estimation and the Power Control algorithms, but in general for all the services requiring any kind of knowledge on the grid model.

- **Time series database:** both live measurement data and the results of the services will be stored in this database, which is specifically conceived to manage in an efficient way large time series of data. This database must be highly scalable and resilient to satisfy the requirements of the network operators.

In SOGNO, the access to the database is handled in a different way, depending on whether a request/response action is performed to get, write or modify some data or if the purpose is to write the real-time data coming from the field devices or in output from the services (like SE and PQE).

In the first case, Application Programming Interfaces (API) will be available for the user or for specific services to access the data when these are needed, or to write them in the database (these interfaces are in any case on the user or service side). For the part of real-time data storing, instead, a publish/subscribe mechanism is implemented. According to this logic, the database will be equipped with:

- **Database subscriber:** it is the software interface through which all the live data that have to be stored can be received via the message broker in the ViSA gateway. It is worth noting that, if different databases are implemented for storing different classes of real-time data, then each one will be equipped with a database subscriber that only subscribes to receive the live data of interest. In this way, it will possible to distribute the storing data process among different entities fostering the scalability of the solution.
- **Database recorder:** it is the software component in charge of extracting the relevant information obtained through the Database subscriber and of writing it in the time-series database.

Figure 13 provides a view of the database persistence component and of the needed interfaces, according to the considerations reported above.

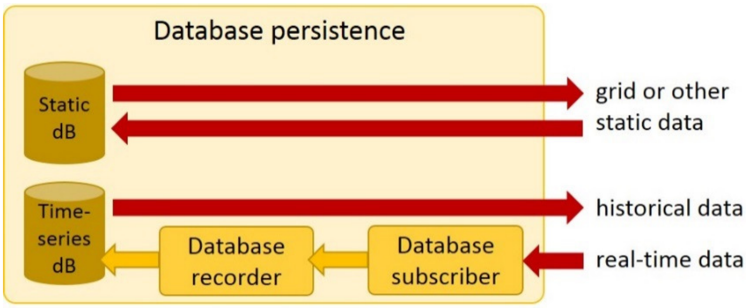


Figure 13: Schematic view of the software components in the ViSA database

3.4 Service component

The system awareness services need to receive data from the field components as well as the grid data for their operation. Once the service runs and produces results, those results need to be made available within the ViSA for triggering other possible services, for actuating some commands in the field, or simply for storing them in the database or visualizing them in the DSO user interface. As a result, specific interfaces are needed to enable the input/output communication of the service within the ViSA.

While relying upon different inputs, the State Estimation and Power Control services described in this Deliverable require interface with very similar functionalities. Consequently, in the following, the general functionalities of these interfaces are described, highlighting when needed the possible differences in the implementation between SE and PC service. It is worth noting that, since the main functionalities of the Power Quality Evaluation services directly run on-board of the APMUs, this service is not taken into account in this Section. The power quality results provided by the APMU are directly treated as any other measurement data coming from the field (via the ViSA gateway) and they are directly stored or visualized in the user interface through the software components described in the database or graphical user interface section.

Figure 14 shows a schematic view of the software components required as input and output interfaces for the SE and PC services. Both services first need to access the data of the grid when they are initialized (first run after the switch on of the service or after a reset). For this purpose, a **grid data API** needs to be available for interacting with the ViSA database and to get the required grid data. Once those data are acquired, a **grid data processor** processes this information and takes care of the conversion of the grid data from their original data format into the data format required internally by the service algorithm. After the initialization, both the services can run in real-time with a predefined execution rate. The main input during the real-time operation are the measurements. For the SE service, these measurements are coming from the measurement devices on the field, while for the PC service, this input actually corresponds to the result of the SE service. In both the cases, however, these data are obtained via the **service subscriber**, which is connected to the message broker in the ViSA gateway. Incoming measurements or estimates are then processed by a **measurement translator** interface, whose role is to convert the data format of the inputs from their original structure to the one used within the service. In parallel to the real-time measurements (or estimates for the PC service), both SE and PC also needs to get the notification for possible switch events in the grid that are going to modify the network topology. It is worth noting that the differentiation between measurement data, estimation data and switch event notifications can be achieved in the used publish/subscribe communication mechanism thanks to the use of different topics. When switch events occur, these are therefore received through the service subscriber (which needs to be subscribed to the associated topic) and they are then transmitted to the **topology processor**. The topology processor is a software interface that takes care of translating the received switch signal into a corresponding modification of the network topology used within the service algorithm.

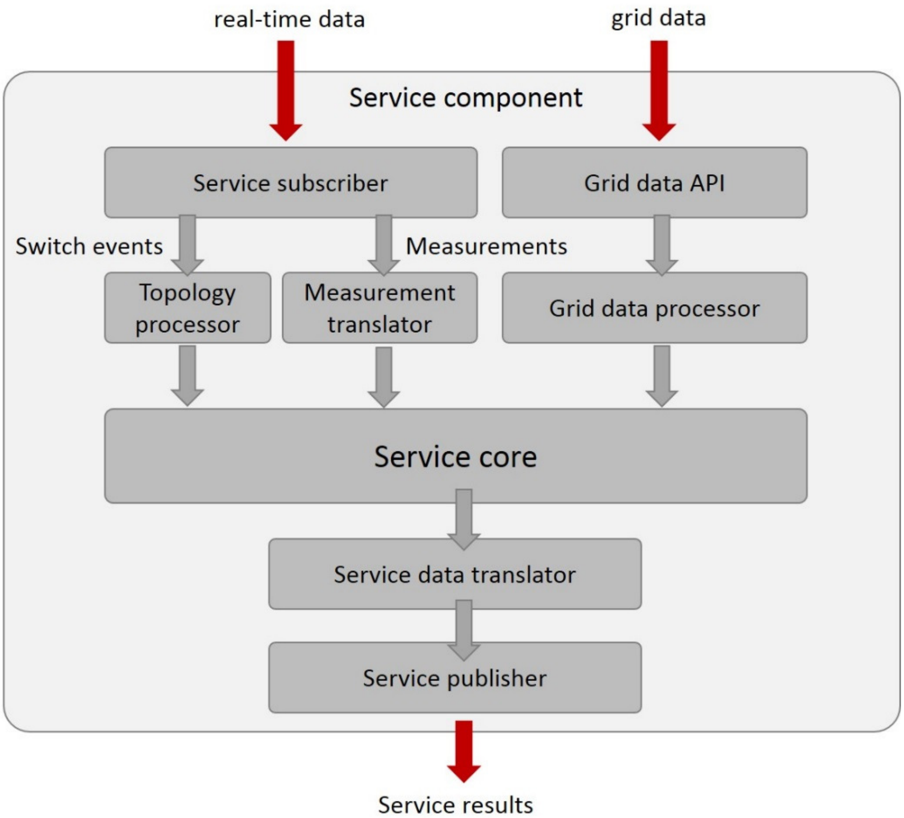


Figure 14: Schematic view of the interfaces for SE and PC services

In output, both the SE and PC services will use the same logic to send results, always following the publish/subscribe communication paradigm. First, a software interface (**service data translator**) will take care of the conversion of the service results into the data format used for the communication within the ViSA (for example relying on JSON data structure), and then the **service publisher** will accomplish the task of sending the result by assigning a specific topic to the data, wrapping them into the transport protocol used within the ViSA and finally establishing the communication and the sending to the message broker.

3.5 Graphical user interface component

The Graphical User Interface (GUI) is an essential component of the SOGNO platform, since it is the place where all service results will be displayed to provide system awareness to the operators. Depending on the services, on the requirements of the DSOs, and on the functionalities provided by the ViSA platform (set of implemented services, additional data analytics tools available, etc.), the list of data to be processed and visualized in the user interface can largely change. In general, in the SOGNO solution, the results of the services running in real-time will be forwarded to the GUI following the publish/subscribe mechanism, while other possible functionalities that need to access the data stored in the databases can be accessed via specifically developed APIs. Following this philosophy, the interfaces needed by the GUI are:

- **GUI subscriber:** it is responsible for the subscription to the desired topics and it is the component where the results of the real-time services will be received via a publish/subscribe mechanism.
- **GUI data translator:** This interface is responsible for translating service results into the desired visualization objects and sending them to a client application where they can be displayed.
- **GUI API:** this indicates those software components responsible for accessing specific data sets from the ViSA database and for making them available to the GUI. The implementation and the specific functionalities can largely vary depending on the accessed data and on the information that has to be visualized in the GUI.

Figure 15 gives a schematic view of the interfaces needed for the visualization of the desired data into the GUI provided to the DSOs. Concerning the services described in this Deliverable, the output of the SE service (in terms of bus voltages, line currents and powers, and power consumption or injection at the grid nodes) and the power quality parameters as provided by the PQE service will be visualized in real-time in the GUI.

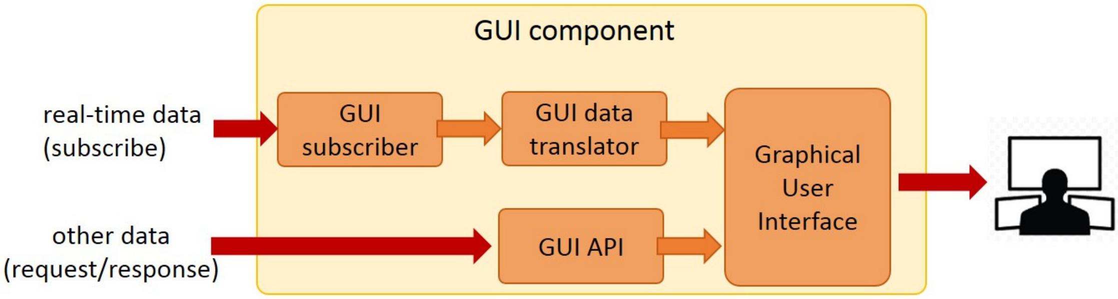


Figure 15: schematic view of the interfaces for the GUI component

3.6 ViSA services interaction architecture

Figure 16 shows the overall view of the ViSA services interaction from a logic perspective, highlighting the links among the different services. Each line symbolizes a publish/subscribe message. These messages are defined in channels and each service can subscribe to one or multiple channels and receive the published information. Concerning the system awareness services described in this Deliverable, it is worth noting the strong interconnection between the SE and PC services (PC uses as input the results from SE). This allows highlighting one of the main benefits of the conceived architecture and of the ViSA concept, namely the possibility to flexibly interconnect different services in order to provide the automation functionalities required by DSOs.

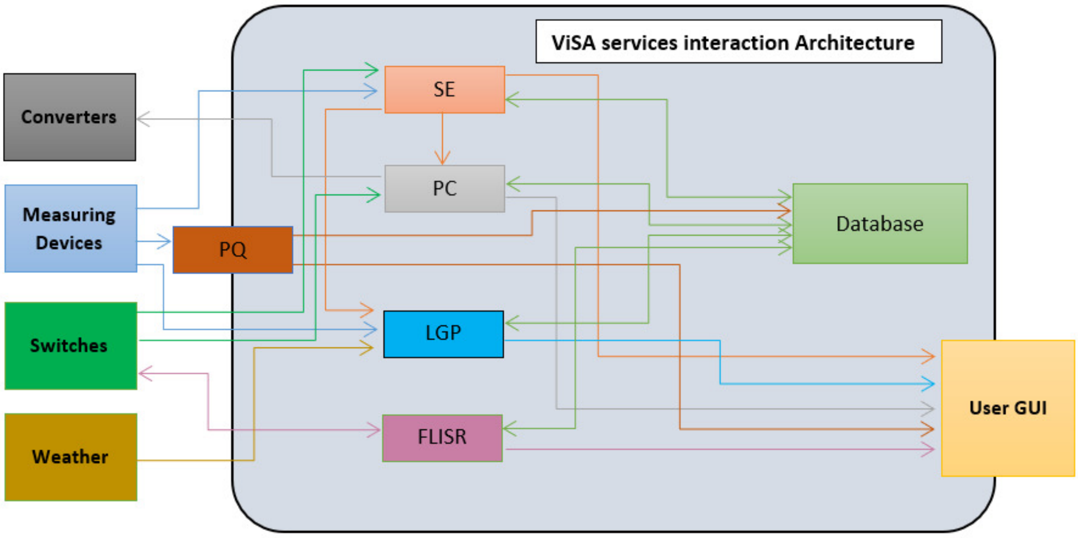


Figure 16: ViSA services interaction architecture

4. Conclusions

This deliverable shows the main concepts for the system awareness services developed in the SOGNO project to support DSOs in managing distribution grids. Three services are developed in SOGNO to this purpose: state estimation, power control, and power quality evaluation. The services developed in SOGNO allow a significant step forward for electricity grid operators to understand the behaviour of their network, to identify possible issues or critical aspects, to evaluate the need of specific countermeasures for improving efficiency or operational performance, and to have more reliable decision-making process. SOGNO system awareness services are obtained through the use of low cost measurement devices, but still paying due attention to the accuracies in the measurement chain, thus making the up-front investment for DSOs more affordable while guaranteeing minimum accuracy performance for the monitoring tools. In addition, SOGNO proposes the concept of ViSA, namely a virtualized substation environment for the deployment of all the substation intelligence. This is a revolutionary aspect of SOGNO, since it allows minimizing the installation of hardware in the field, distributing the computational and communication requirements, obtaining scalability, as well as opening the possibility to provide the entire monitoring platform as a turnkey service for DSOs.

5. List of Tables

6. List of Figures

7. Bibliography

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8. List of Abbreviations

ANN	Artificial Neural Network
API	Application Programming Interface
APMU	Advanced Power Measurement Unit
CIM	Common Information Model
DER	Distributed Energy Resources
DSO	Distribution System Operator
GUI	Graphical User Interface
JSON	JavaScript Object Notation
LPCT	Low Power Current Transformer
LPVT	Low Power Voltage Transformer
LV	Low Voltage
MQTT	Message Queuing Telemetry Transport
MV	Medium Voltage
OPF	Optimal Power Flow
PC	Power Control
PQE	Power Quality Evaluation
SE	State Estimation
SGAM	Smart Grid Architecture Model
SOGNO	Service Oriented Grid for the Network of the Future
ViSA	Virtualized Substation Automation
WLS	Weighted Least Squares
WP	Work Package

ANNEX

A1 – State estimation service inputs and outputs

A1.1 – SE Static inputs

Table A-1: SE input requirements from grid data topology

	NODES	LINES	CABLE DATA
GRID DATA TOPOLOGY	Node ID	Line ID	Cable type ID
	Phases	Phases	Series resistance Ω/km
	Neutral grounding type	Neutral	Series reactance Ω/km
	Nominal Voltage [kV]	Start node ID	Shunt admittance µS/km
	Node type	End node ID	Shunt capacitance µF/km
	Node category	Phase cable type ID	Homopolar series resistance Ω/km
	Nominal Power [kVA]	Neutral cable type ID	Homopolar series reactance Ω/km
	Typical power factor	Length [km]	Homopolar shunt admittance µS/km
			Homopolar shunt capacitance µS/km

Table A-2: SE input requirements from grid data components

	SWITCHES	TRANSFORMER DATA	MEASUREMENT INFRASTRUCTURE
GRID DATA COMPONENTS	Switch ID	Trafo ID	Meter ID
	Switch type	Start Node ID	Location Line/Node ID
	Start Node ID	End Node ID	Monitored quantities
	End Node ID	Primary connection	Measurement accuracy
	Normal Status	Secondary connection	Reporting rate [meas/sec]
		Phase shift [degrees]	
		Primary voltage [kV]	
		Secondary voltage [kV]	
		Nominal power [kVA]	

	Short circuit voltage [%]
	Short circuit losses [kW]
	Open circuit current [%]
	Open circuit losses [kW]
	OLTC
	Tap range [%]
	Number tap steps
	OLTC regulation

A1.2 – SE Real-time inputs

Table A-3: SE input requirements from measurement devices

	NAME	LOCOPMU	APMU	SWITCH
	Device ID	X	X	X
	Timestamp	X	X	X
FOR EACH CONNECTED COMPONENT	Voltage Magnitude	X	X	
	Voltage phase angle	X		
	Current magnitude	X	X	
	Current phase angle	X		
	Active power		X	
	Reactive power		X	
	Active power flow direction		X	
	Opening action			X
	Closing action			X
	Measurements (when available)			X

A1.3 – SE outputs

Table A-4: SE output results

	NODE	LINE
	Node ID	Line ID
FOR EACH CONNECTED PHASE	Voltage magnitude [kV]	Active power at the starting node [kV]
	Voltage phase angle [degrees]	Reactive power at the starting node [degrees]
	Active power consumption/ injection [kW]	Active power at the end node [kV]
	Reactive power consumption/ injection [kVar]	Reactive power at the end node [degrees]
	Current magnitude of the consumption/injection [A]	Branch current magnitude [A]
	Current phase angle of the consumption/injection [degrees]	Branch current phase angle [degrees]

A2 – Power control service inputs and outputs

A2.1 – PC Static inputs

Table A-5: PC input requirements from grid data topology

	NODES	LINES	CABLE DATA
GRID DATA TOPOLOGY	Node ID	Line ID	Cable type ID
	Phases	Phases	Series resistance Ω/km
	Neutral grounding type	Neutral	Series reactance Ω/km
	Nominal Voltage [kV]	Start node ID	Shunt admittance µS/km
	Node type	End node ID	Shunt capacitance µF/km
	Node category	Phase cable type ID	Homopolar series resistance Ω/km
	Nominal Power [kVA]	Neutral cable type ID	Homopolar series reactance Ω/km
		Length [km]	Homopolar shunt admittance µS/km
			Homopolar shunt capacitance µS/km

Table A-6: PC input requirements from grid data components

	SWITCHES	TRANSFORMER DATA
GRID DATA COMPONENTS	Switch ID	Trafo ID
	Switch type	Start Node ID
	Start Node ID	End Node ID
	End Node ID	Primary connection
	Normal Status	Secondary connection
		Phase shift [degrees]
		Primary voltage [kV]
		Secondary voltage [kV]
		Nominal power [kVA]
		Short circuit voltage [%]
		Short circuit losses [kW]
		Open circuit current [%]
		Open circuit losses [kW]
		OLTC
		Tap range [%]
		Number tap steps
		OLTC regulation

A2.2 – PC Real-time inputs

Table A-7: PC Input requirements from measurement devices

	NODE	LINE	SWITCHES
	Node ID	Line ID	Device ID
FOR EACH CONNECTED PHASE	Voltage magnitude [kV]	Active power at the starting node [kV]	Timestamp
	Voltage phase angle [degrees]	Reactive power at the starting node [degrees]	Opening action
	Active power consumption/ injection [kW]	Active power at the end node [kV]	Closing action
	Reactive power consumption/ injection [kVar]	Reactive power at the end node [degrees]	Measurements (when available)
	Current magnitude of the consumption/injection [A]	Branch current magnitude [A]	

	Current phase angle of the consumption/injection [degrees]	Branch current phase angle [degrees]

A2.3 – PC outputs

Table A-8: PC output fields

	NAME
FOR EACH DER NODE	DER Node ID
	Active power set point [kW]
	Reactive power set point [kVar]

A3 – Power quality evaluation service outputs

A3.1 – PQE outputs

Table A-9: PQE output fields

	NAME
FOR EACH CONNECTED APMU	Device ID
	Timestamp
	Voltage magnitude
	Current magnitude
	Active power
	Reactive power
	Active energy
	Reactive energy
	Power factor
	Active power flow direction
	Frequency
	Voltage harmonic distortion
	Current harmonic distortion
	Voltage unbalance
	Current unbalance