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Deliverable D5.3

Energy resilience and self-healing

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Abstract

This deliverable describes all implementation mechanisms and associated features, comprising the related specification and the subsequent description of software algorithms and hardware implementations, suitable for grid resilience and self-healing.

Moreover and as consequence of the complementarity with D5.2 – Energy Balancing – additional mechanisms were added towards energy resilience by means of energy balancing.

Throughout the deliverable, several mechanisms that are suitable for several e-balance architecture components are presented. Specific mechanisms that are suitable only for specific e-balance architecture components are also presented.

Disclaimer

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Executive Summary

This document presents a detailed description of the e-balance energy resilience and self-healing mechanisms within the Energy Management Platform. It comprises a full description on the resilience mechanisms, namely those related to grid resilience, by performing smart monitoring and control of LV and of MV grids, towards improving grid resilience, and related to energy resilience by means of using energy balancing features towards avoiding contingencies affecting grid resilience.

The detailed system implementation includes the detailed data interface among Management Units (MU) and other devices, as well as implementation details of the TLGMU, the MVGMU, the LVGMU, the LV Sensors, the Smart Meter and the CMU. For each of the mentioned devices, general aspects as well as specific aspects are described, referring to software and hardware implementation details. A summary of their expected use for each demonstrator is also presented. Moreover, validation results are also presented, derived from simulations.

The document also includes the presentation of the test cards, comprising their definition and major results.

Finally, a delivery summary and conclusions are presented.

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Abbreviations

AE	AutoEncoder
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CMU	Customer Management Unit
DER	Distributed Energy Resources
DERMU	DER Management Units
DG	Distributed Generation
DLMS	Device Language Message Specification
DMS	Distribution Management System
DMU	Device Management Unit
DSO	Distribution System Operator
DTC	Distribution Transformer Controller
EMP	Energy Management Platform
EPSO	Evolutionary Particle Swarm Optimization
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FAN	Field Area Network
FDIR	Fault Detection, Isolation and Restoration
GUI	Graphical User Interface
HAN	Home Area Network
HMI	Human-Machine Interface
HV	High Voltage
ICT	Information and Communication Technology
LAN	Local Area Network
LV	Low Voltage
LV-FAN	Low Voltage Field Area Network
LVGMU	LV Grid Management Unit
MDM	Metering and energy Data Management
MV	Medium Voltage
MV-FAN	Medium Voltage Field Area Network
MVGMU	MV Grid Management
PL	Public Street Lighting
PS	Primary Substation
PS-LAN	Primary Substation Local Area Network
RTDB	Real Time Database
SCADA	Supervisory Control And Data Acquisition
SGAM	Smart Grid Architecture Model
SS	Secondary Substation
SS-LAN	Secondary Substation Local Area Network
SSC	Smart Substation Controller
TLGMU	Top Level Grid Management Unit
TSO	Transmission Service Operator
WAN	Wide Area Network

1 Introduction

The main objective of the e-balance project is to design a smart and robust energy management system for the future electricity grid. This document provides the description of the technical features targeted for the implementation serving the project demonstrators, but also for the implementation of future deployments of the system.

This approach is based on the high level specification defined in deliverable D3.1 [3] and on the technical specification defined in deliverable D3.2 [4] and extends the description by providing the technical details of the involved functional modules as well as the information on the data to be exchanged. Both these factors influence the requirements on the applied hardware components, i.e., the estimated complexity of the software modules together with the definition of the required data to be exchanged, define the hardware requirements that are also addressed in this document. The system is modular and extendible in both aspects, i.e., if necessary additional modules can be defined and also additional data sets can be defined to provide additional functionality.

Section 2 presents a short review of the high level architecture of the e-balance system. There, it is described the management unit architecture and the distribution of the management units within the grid. Moreover, in that section a description is also given on how the architecture is to be implemented for both demonstrators, namely in Batalha – Portugal – and in Bronsbergen – The Netherlands.

Section 3 introduces all individual Grid Resilience components regarding the Energy Management Platform (EMP). Their role and functionality is briefly described. Furthermore, in this section the Energy Balancing components also participating towards energy resilience – also regarding the EMP – are introduced and briefly described.

In Section 4, details are given about the following implementations developed under task T5.3:

- The software modules describing the EMP’s Grid Resilience components
- The software modules describing the EMP’s Energy Balancing components towards energy resilience
- TLGMU
- MVGMU
- LVGMU
- DERMU
- Smart Meters
- CMU

The LV/PL Sensors – although being an important component of the e-balance architecture – are not described in this document, as their detailed presentation will be performed in deliverable D6.2.

Section 5 introduces the Grid Balancing features contributing towards grid resilience.

The overall D5.3 document is summarised in Section 6, where the main conclusions are highlighted.

1.1 Deliverable Position in the Project

Figure 1 shows the position of this deliverable within the e-balance project. This deliverable is part of work package 5 – Energy resilience and self-healing (WP5).

This document depicts the outcome of selecting, implementing and evaluating the resilience and self-healing mechanisms for the energy control and management features of the e-balance system. It follows the high-level functional specification we have defined based on the results obtained in work package 2, specifically the selected use cases (WP2). Moreover, it copes with the specifications obtained in work package 3, namely in the Functional Specification and in the Technical Specification (WP3). The document is a guideline on how to implement the energy resilience and self-healing features of the e-balance system.

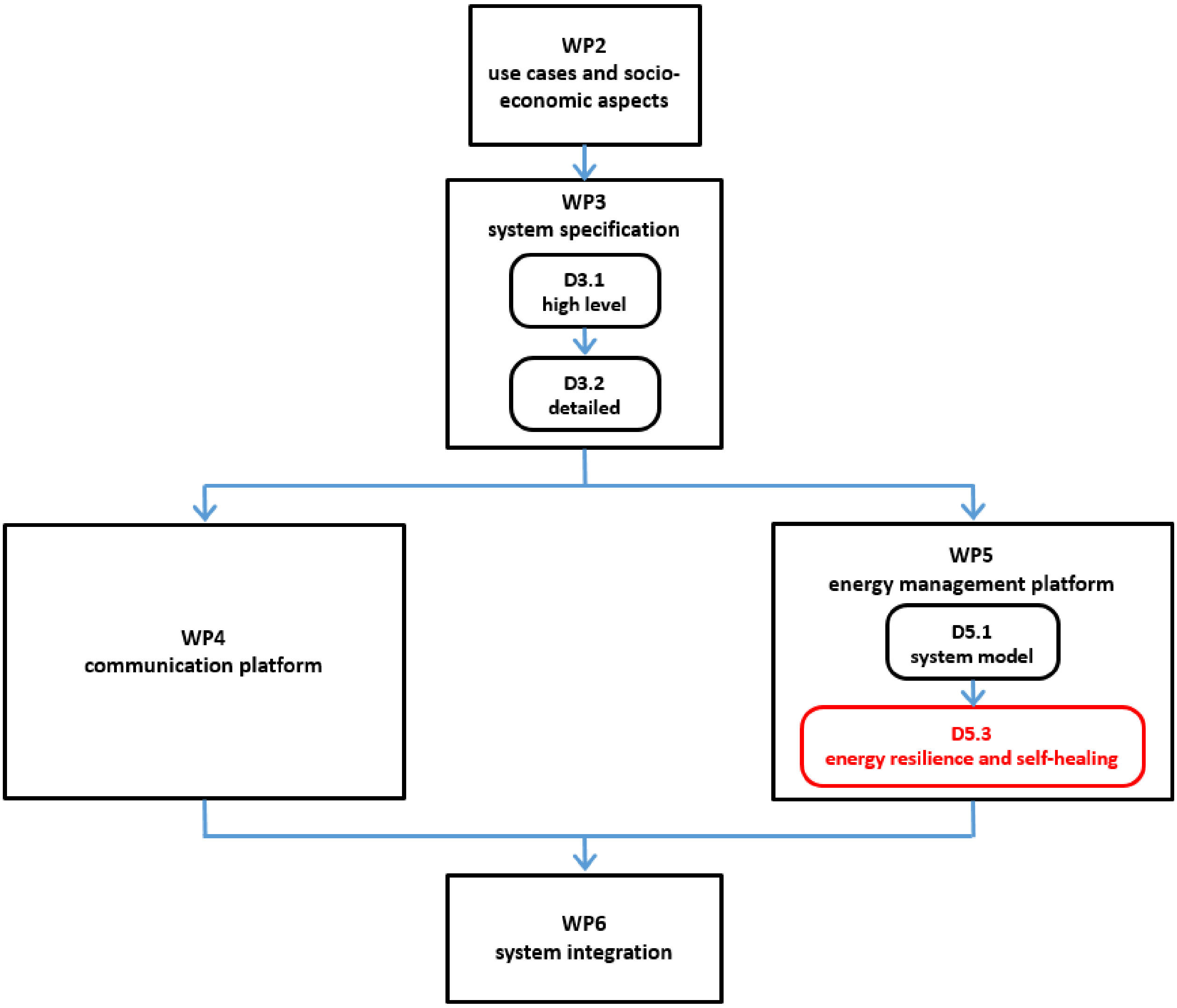


Figure 1: The position of the deliverable D5.3 within the e-balance project work package structure

2 The e-balance detailed system architecture

This section provides a review of the e-balance detailed system architecture. It provides a short summary of the deliverable D5.3 with the focus on the architecture of the generic management units and devices and on their placement within the smart grid.

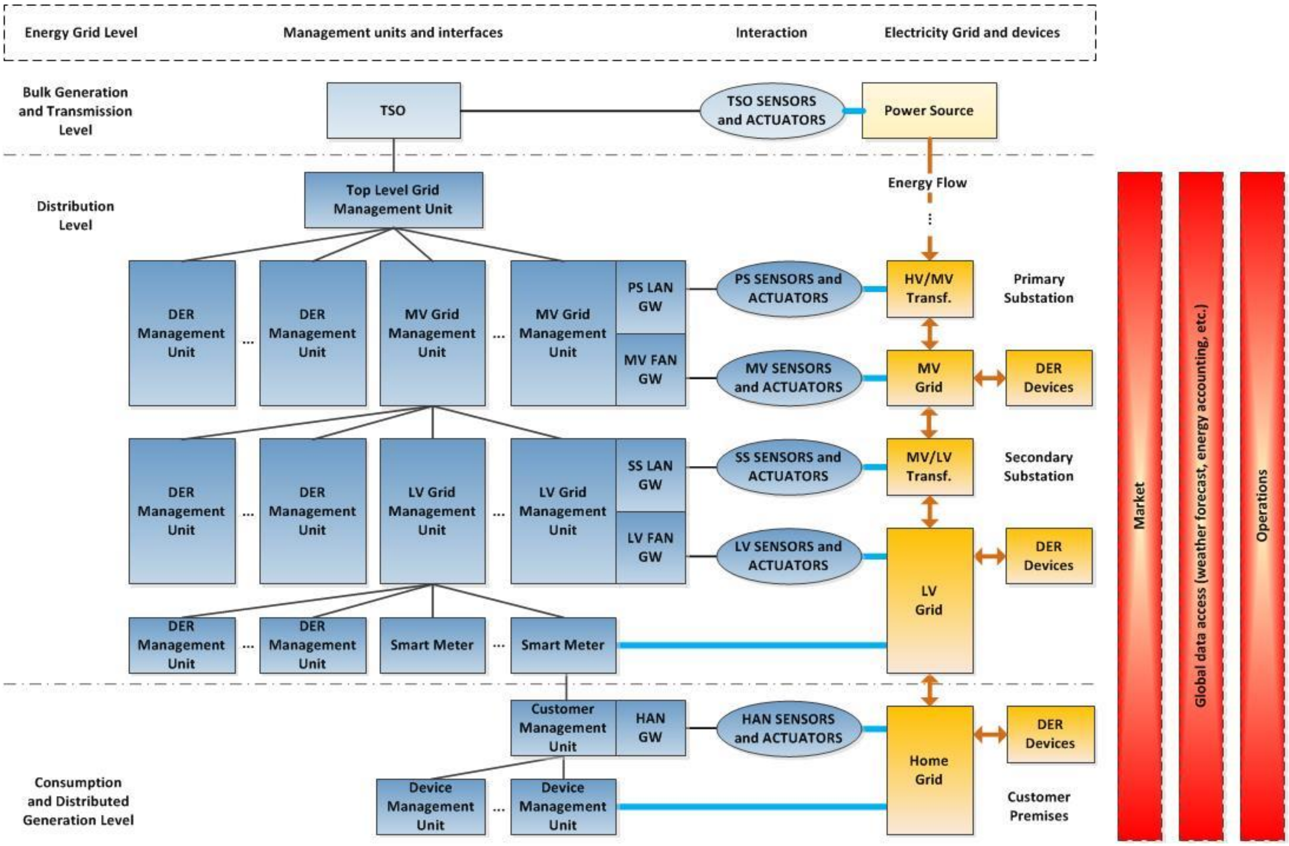


Figure 2: The e-balance detailed system architecture

Figure 2 shows the placement of the e-balance system components within the energy grid. This approach is compatible with the SGAM [15] architecture, but it has been adapted to the objectives of e-balance by detailing the domains and components that are the focus of the project and omitting the others that are out of the scope of the project. For simplification of the representation, the three dimensional SGAM model was transformed into a two dimensional hierarchical model, easier to handle. The Energy Grid level corresponds to the SGAM domains. The Market, Global Data Access and Operations layers correspond to the SGAM zones. The SGAM interoperability layers are distributed among the e-balance system components and their interaction with the energy grid components. The bulk generation and transmission levels are collapsed as they are out of the scope of the project. In e-balance we also subdivide the Distribution level into two segments: Medium Voltage (MV) and Low Voltage (LV).

Again, for clarification, in the further text of this document we use the term grid to refer to the energy grid. In contrast, the term network is used to represent the communication network within the e-balance system.

In Figure 2, the e-balance system components are represented by dark blue coloured shapes. The light blue boxes represent the Bulk Generation and Transmission Level that is out of the project’s scope. The e-balance system involves several management units and the figure depicts the hierarchical tree of these management units with a single management unit level for each voltage level in the grid. In very dense (communication) networks intermediate management unit levels may be applied to reduce the data load in the network and to distribute the local decisions further.

The yellow coloured shapes represent the grid and the devices within the grid. Finally, the red coloured boxes represent virtual layers like the Market, the Global Data Access and the Operations. The different lines in the figure represent different kinds of interaction between the components they connect. Black thin lines represent the communication network, i.e., the data exchange that involves the management units, as well as the sensors and actuators. Blue thick lines represent the interaction between the e-balance system and the grid, i.e., the retrieval of data from sensors located in the grid and control signals to trigger actions by actuators in the grid. Finally, the orange lines represent the flow of energy within the grid.

The e-balance management units have a common architecture, which is described in detail in Section 2.1. However, depending on the level, the management units may have different roles and duties. The processes executed on them may operate on behalf of different stakeholders and process data from different stakeholders. However, as at every level the concept of data collection and processing is similar and the e-balance system architecture is fractal-like, the management algorithms applied on different management levels share the same conceptual base at the maximum extent possible, which improves the scalability of the approach.

The device level is the lowest level represented in the architecture, referring to domestic devices. Such devices may be of any kind, including a home appliance that only consumes energy, but it may also be the inverter of a PV micro-generation or of a domestic storage unit. The device management unit (DMU) is a central unit of the device that is aware of the current state of all components that the device consists of, while controlling them. The DMU is also equipped with a communication module or gateway that allows upward communication with the higher level management unit, i.e., the customer management unit (CMU) that controls all the customer devices at the customer premises.

Due to the vast amount of possible devices it was decided to focus on standard solutions and not to develop a DMU on team's own. This allows the e-balance solution to have a better coverage as well as better scalability and applicability. The same applies to the communication technologies to be used within the home area network (HAN) that connects the DMUs and their corresponding CMU. For that reason, the customer management unit may be equipped with several communication modules or gateways. It communicates downwards with its underlying device management units, but it also communicates with HAN sensors and actuators that interact with the home grid providing grid monitoring, control and support the home automation functionality. The customer may give some of the control over the domestic devices at his premises to external stakeholders, like the DSO or an aggregator providing services. This control is given to the LVGMU through the CMU – at the customer premises border – and the Smart Meter – at the grid border. As an example, a PV inverter may be indirectly controlled by the LVGMU through the Smart Meter and the CMU.

The CMU is aware of the state of each device as well as of the individual and cumulative energy consumption and production figures. Thus, it can also provide local accounting features. However, in order to do this correctly the device has to be approved by a notified body. The smart meter is introduced as an additional layer in the architecture, as it provides the needed energy accounting in the border of the grid and the consumer or prosumer – the end users. This provides the consumers flexibility of choice for the brand of the CMU, in case it is certified for energy accounting. This allows also separating the customer and the distribution grid domains regarding the data and device ownership, as well as to identify and highlight the interface between these two domains.

The level above the CMUs consists of Smart Meters. In the present setting, the Smart Meters are located at the border of the customer premises, actually being a grid component. The Smart Meter dialogues with the CMU via its own Home Area Network (HAN) interface, when applicable. Depending on the implementation, the Smart Meter may also dialogue with the LVGMU via several possible ways, namely by DLMS/COSEM over Power Line Carrier (PLC) Prime or by DLMS/COSEM over RF Mesh/IEEE 802.15.4, among others.

The level above the Smart Meter consists of low voltage (LV) grid management units (LVGMU). In the presented setting, these management units are located at the secondary substations and each of them controls the sensors, actuators and CMUs – directly or via Smart Meters – located in the area of the grid, supplied with energy by this secondary substation. A LVGMU is equipped with communication gateways for the upward and downward communication within the e-balance management hierarchy. It is also equipped with communication gateways for communication with sensors and actuators located at the MV/LV transformer (Secondary Substation Local Area Network – SS-LAN) and also in the LV grid feeders related to the secondary substation (Low Voltage Field Area Network – LV-FAN). All these communication gateways may be different, depending on the technologies used in each part of the network. The LVGMU also controls the DERMUs related to LV grid connected DER in this area.

A distributed energy resource (DER) management unit (DERMU) corresponds to the device management unit for some specific DER devices that may be connected to different voltage levels of the grid, for example at the LV grid or at the MV grid. At each grid level, the DERMU can directly communicate with a higher level management unit in the distribution domain. When the DER is a LV grid asset, the corresponding DERMU is controlled by a LVGMU. If the DER is a MV grid asset, depending on its role and on its grid strategic placement, it can be controlled by a medium voltage (MV) grid management unit (MVGMU) – placed at a primary substation – or by a top level grid management unit (TLGMU) – placed at a dispatch control centre.

A MVGMU has a similar role when compared to its counterpart for the low voltage. A MV grid management unit resides at a primary substation. It is equipped with upward and downward communication gateways and controls all the sensors, actuators in the MV grid and LVGMUs located at secondary substations related to this primary substation. It also controls the DERMUs related to MV grid connected DER in this area. In order to interact with the sensors and actuators at the HV/MV transformer, the MVGMU is equipped with Primary Substation Local Area Network (PS-LAN) gateway. Similar, for communicating with the sensors and actuators in the MV grid related to the primary substation the Medium Voltage Field Area Network (MV-FAN) gateway is available at the MV grid management unit. Again, the communication gateways may use different communication technologies.

The top level grid management unit (TLGMU) controls all MVGMUs as well as all the DERMUs for DER connected directly to the MV grid, i.e., it collects all the status data and sends control signals to all the lower level management units. The top level grid management unit may be considered as a control centre that provides also interfaces for management tools, like supervisory control and data acquisition (SCADA), market management, outage management, Distribution Management System (DMS), and Metering and energy Data Management (MDM). The top level grid management system communicates also with the Transmission Service Operator (TSO).

At the bulk generation and transmission level, the TSO may also use sensors and actuators to interact with the transmission grid and the generation that are defined as the Power Source in the figure.

The e-balance fractal-like approach can reach even further, creating higher levels in the hierarchy with management units that provide bulk balancing for a country wide or even for the European grid. This is the power of this approach, as it provides scalability for the energy balancing.

The detailed management unit level architecture is presented in the following section.

2.1 Management Unit Architecture

An e-balance management unit controls all its directly subordinate system elements, i.e., lower level management units, sensors and actuators. It takes control decisions based on the user configuration and interaction as well as on the context consisting of data received from its parent management unit and the data obtained from these subordinate system elements.

The core functionality of the management unit and devices that interact with the respective part of the energy infrastructure is split into two main blocks, i.e., the communication platform (CP) and the energy management platform (EMP). The former is responsible for data gathering and exchange within the network, while the latter represents the logic that takes the local decisions based on the data. This logic is realized as a set of services, each providing a different functionality. The e-balance architecture is presented in Figure 3. This figure provides the general view on the major functional blocks as defined in deliverable D3.1.

As already mentioned in the previous section, the management unit communicates with sensors and actuators – the devices – that interact directly with the part of the grid the management unit is responsible for. It also communicates with its subordinate management units. Finally, each management unit, except the TLGMU, also communicates with its parent management unit. The TLGMU communicates with the TSO systems, out of scope of e-balance. All these mentioned different communications may use different communication technologies and thus, they may require different networking protocol stacks. Thus, the management unit architecture shown in Figure 3, allows several networking protocol stacks, each for a different purpose.

The data storage and exchange middleware is placed on top of the networking stacks. Its aim is to provide the abstract and common data addressing, data access and data exchange between different management units. The middleware is supported by the security and privacy mechanisms to protect the exchanged data. It provides the data interface that connects the communication platform and the energy management platform and allows the latter to access the data, and more services may be added.

The energy management platform is placed on top of the communication platform. It includes the logic modules or services that perform different kind of operations based on the data provided by the communication platform and also provide their results and control signals back through the communication platform as well. These services are supported by security and privacy mechanisms that operate at a higher level than their counterparts of the communication platform. Currently we have defined only two such services (energy balancing and grid resilience), but the general e-balance approach is not limited to these two.

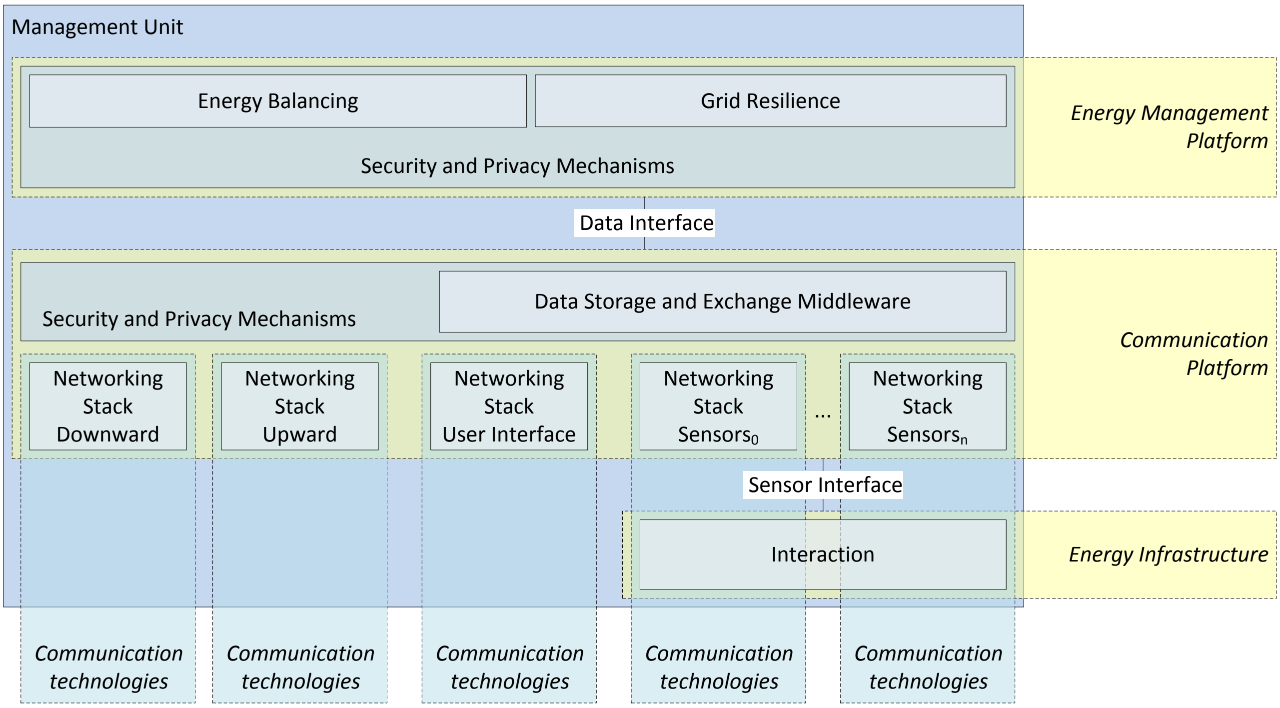


Figure 3: The general architecture of an e-balance management unit

The energy balancing service provides the estimates for energy to be produced and consumed in the (near) future. This estimation is based on the historic consumption data, but also on additional parameters, like the weather and weather forecast data. This service compares the predicted values with the actual situation and triggers actions on the devices and units under its control to keep its part of the grid in a stable state with respect to energy production and consumption. On the other hand, the grid resilience service analyses the state of its part of the grid and generates control signals to control the grid devices able to impact positively the quality of service, safety and overall operational performance.

These two above mentioned services are responsible for different aspects but they cooperate closely. They provide the status and summary to their counterparts on the parent management unit and generate control signals for the subordinate management units and actuators in the part of the grid their local management unit is responsible for. These control signals steer the actions necessary for energy balancing and management.

The communication platform can be regarded as a distributed and secure data exchange platform whereas the energy management platform stands for centralized and distributed logic within the grid.

2.2 The detailed system architecture for grid resilience and self-healing

This section explains how the system components are mapped onto the grid, while providing grid resilience and self-healing services.

All details presented in this section aim at establishing a bridge between the former specifications and requirements described in [3] and [4], towards the implementations – under description – expected to be deployed, while coping with the specific scope of each demonstrator. There are two main demonstrators – to be further described during the progression of WP6 – comprising multiple sites, which can be described as follows:

- The Batalha demonstrator, in Portugal, comprising the primary substation of São Jorge and two secondary substations – these demonstrators are hosted by EDP
- The Bronsbergen demonstrator, in the Netherlands, comprising two secondary substations – these demonstrators are hosted by Alliander

Despite each specific set of features, both demonstrators share a common approach regarding the architecture, as stated in Figure 2.

The Batalha demonstrator combines the TLGMU placed at the higher hierarchical systems, e.g. the dispatching control centre, the MVGMU placed at primary substations, the LVGMU placed at secondary substations, the LV FAN gateway and the LV sensors placed at secondary substations and at distribution cabinets, Smart Meters, the CMU – being specific to PV micro-generation control – and the PV inverter which comprises a built-in embedded DMU. All these components provide a set of features coping with the role of grid resilience.

The Bronsbergen demonstrator combines the MVGMU placed at primary substations, the LVGMU placed at secondary substations, the secondary substation LAN gateway and the corresponding sensors, Smart Meters, the CMU and several domestic devices that comprise built-in embedded DMUs. Some of these components provide a set of features coping with the role of grid resilience.

2.2.1 The detailed system architecture for the Batalha demonstrator

The Batalha demonstrator covers a full range of resilience and self-healing features, at both MV and LV grid level.

The system architecture serving the Batalha demonstrator is fully compatible with the e-balance system architecture shown in Figure 2.

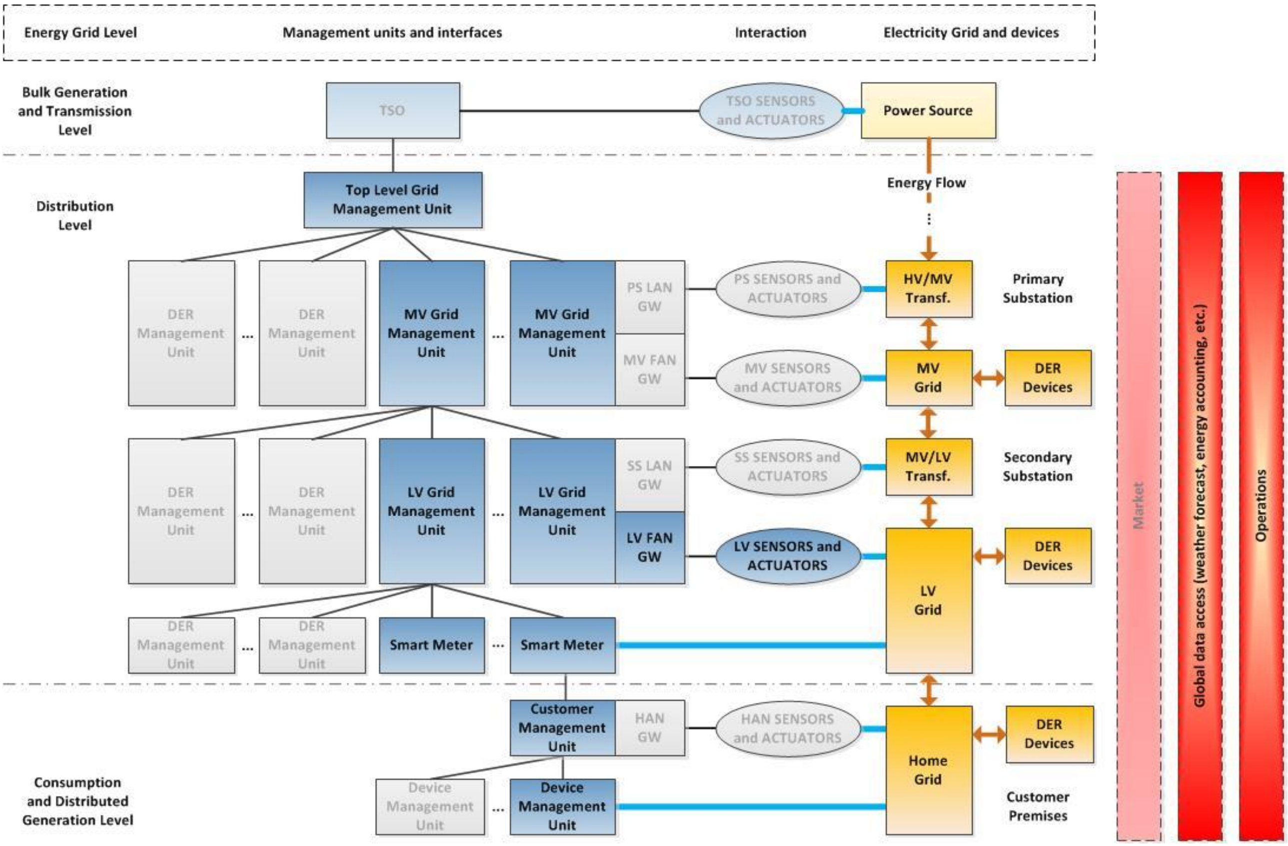


Figure 4: Detailed system architecture for grid resilience serving the Batalha demonstrator

In Figure 4, the e-balance system components, which are designed, implemented and tested, aiming for deployment at the Batalha demonstrator, are represented by dark blue coloured shapes. The remaining grey shapes correspond to those system components not addressed in the current demonstration scope, although fully compatible with the current development, in line with the e-balance system architecture.

Again, the light blue boxes represent the Bulk Generation and Transmission Level that is out of the project's scope. The yellow coloured shapes represent the electric grid and the grid or home assets.

The red and pink coloured boxes represent virtual layers, e.g. the Market, the Global Data Access and the Operations. Excluding the Market virtual layer, all apply for the current development, to be deployed in Batalha, as no further market scope is to be demonstrated, besides the data being managed and used by the system devices, namely for grid operation, although also comprising metering data.

The device level is the lowest level represented in the architecture. In the case of Batalha, PV inverters will participate in the e-balance system architecture, where each inverter will act as a device management unit (DMU).

A PV inverter controller was designed and implemented, which corresponds to an outcome of task T5.3. Such controller matches the role of a customer management unit (CMU) being responsible for controlling a PV inverter, according to the grid conditions and to the overall set-points received from the upstream low voltage grid management unit (LVGMU). The implemented CMU is equipped with a communication module or gateway that allows upward communication – via a Smart Meter – with the higher level management unit, i.e., the LVGMU, while controlling the downstream device – the PV inverter – placed at the householder premises.

The developed CMU is equipped with two communication modules or gateways. It communicates downwards with its underlying DMU, the inverter. It also communicates with the HAN interface of the PV installation Smart Meter, providing grid monitoring and control features towards controlling the in-house PV micro-generation inverter.

The level above the CMUs consists of Smart Meters. In the present setting, the Smart Meters are located at the border of the customer premises, actually being a grid component. The Smart Meter dialogues with the CMU via its own Home Area Network (HAN) interface, when applicable. It also dialogues with the LVGMU via two possible ways, either by DLMS/COSEM over Power Line Carrier (PLC) Prime or by DLMS/COSEM over RF Mesh/IEEE 802.15.4.

Smart Meters also play a role on providing monitoring features, thus acting as sensors, for specific applications, namely for providing grid key LV distribution cabinets with metering and sensor capabilities.

The Smart Meters to be used in the Batalha demonstrator already exist. They belong to a smart metering support infrastructure.

The level above all Smart Meters consists of one or more LVGMUs. In the presented setting, these management units are located at secondary substations, each of them controls the LV sensors and CMUs – via a Smart Meter – located in the area of the served LV grid, supplied with energy by this secondary substation. A LVGMU is equipped with communication gateways for the upward and downward communication within the e-balance management hierarchy. It is also equipped with communication gateways for communication with LV sensors located at the LV grid feeders related to the secondary substation (Low Voltage Field Area Network – LV-FAN). The sensors for the MV/LV transformer (Secondary Substation Local Area Network – SS-LAN) do not participate in this demonstrator.

In the current implementation, the specific LVGMU features – defined under the e-balance project and described in Sections 3 and 4 – are another outcome of task T5.3 and they were developed on top of an existing industrial product – a Distribution Transformer Controller. Moreover, a LV-FAN communication gateway and LV sensors were developed which corresponds to an outcome of task T6.2. The developed communication technology is DLMS/COSEM over PLC Prime.

The level above all LVGMUs consists of one or more medium voltage grid management units (MVGMUs). A MVGMU is similar to its counterpart for the low voltage, but residing at a primary substation. It is equipped with upward and downward communication gateways and controls all the sensors and actuators inside the primary substation, as well as in the MV grid. It also controls all LVGMUs located at secondary substations related to this primary substation. It also controls the DER Management Units (DERMUs) related to LV grid connected DER in this area.

In the current implementation, the specific MVGMU features – defined under the e-balance project and described in Sections 3 and 4 – are another outcome of task T5.3 and they were developed by Efacec. The MVGMU runs over a database, which results from previously stored grid snapshots. Therefore, it is out of scope the inclusion of sensors and actuators at the HV/MV substation or at the MV grid level.

The top level grid management unit (TLGMU) controls all MVGMUs, i.e., it collects all the status and measurement data and sends control signals to all the lower level management units. The top level grid management unit acts as a control centre that provides also interfaces for corporate management systems, like supervisory control and data acquisition (SCADA), market management, outage management (OMS), Distribution Management System (DMS), as well as Metering and energy Data Management (MDM). The top level grid management system communicates also with the Transmission Service Operator (TSO).

In the current implementation, the specific TLGMU features – defined under the e-balance project and described in Sections 3 and 4 – are another outcome of task T5.3 and they were developed on top of an existing industrial solution, the SCATEX+, a SCADA/DMS solution, by Efacec.

2.2.2 The detailed system architecture for the Bronsbergen demonstrator

The Bronsbergen demonstrator covers a full range of resilience features, at both MV and LV grid level, also comprising the integration of energy balancing features (an outcome from task T5.2, also within WP5) for providing microgrid resilient grids.

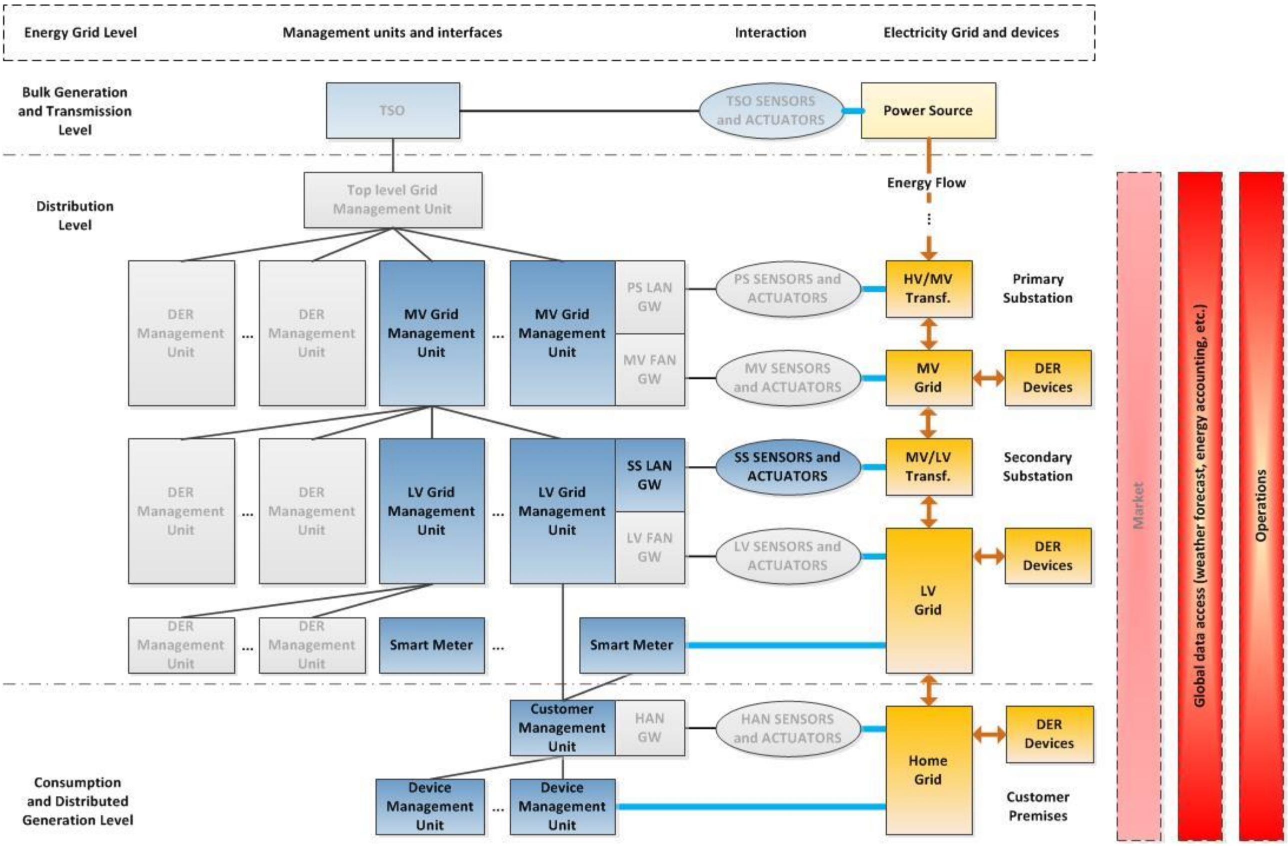


Figure 5: Detailed system architecture for grid resilience serving the Bronsbergen demonstrator

In Figure 5, the e-balance system components that were designed, implemented and tested, aiming for deployment at the Bronsbergen demonstrator, are represented by dark blue coloured shapes. The remaining grey shapes correspond to those system components not addressed in the current demonstration scope, although fully compatible with the current development, in line with the e-balance system architecture.

Again, the light blue boxes represent the Bulk Generation and Transmission Level that is out of the project's scope. The yellow coloured shapes represent the electric grid and the grid or home assets.

The red coloured boxes represent virtual layers, e.g. the Market, the Global Data Access and the Operations. Excluding the Market virtual layer, all layers apply for the current development, to be deployed in Bronsbergen.

The device level is the lowest level represented in the architecture. In the case of Bronsbergen, Smart Domestic IEDs will participate in the e-balance system architecture, where each smart device will act as a device management unit (DMU). Moreover, several domestic units will also participate, comprising PV inverters and one householder storage inverter. All these will participate as end user DMUs.

A customer management unit (CMU) was designed and implemented, which corresponds to an outcome of task T5.3. Such CMU is responsible for controlling all householder DMUs, comprising the Smart Domestic IEDs, the PV inverter and the storage inverter, according to the grid conditions and to the overall set-points received from the upstream low voltage grid management unit (LVGMU). The implemented CMU is equipped with a communication module or gateway that allows upward communication with the higher level management unit, i.e., the LVGMU, while controlling the downstream device – the DMUs – placed at the householder premises.

The developed CMU is equipped with two communication modules or gateways. It communicates downwards with its underlying DMUs. It also communicates with the HAN interface of the PV installation Smart Meter, providing grid monitoring and control features towards controlling the in-house PV micro-generation inverter. Moreover, it dialogues with and controls the storage inverter existing at the selected householder. Due to the characteristics of the existing Smart Metering system, the CMU also dialogues with the upper level system, the LVGMU, via a specific WAN interface.

The level above the CMUs consists of Smart Meters. In the present setting, the Smart Meters are located at the border of the customer premises, actually being a grid component. The Smart Meter dialogues with the CMU via its own serial port interface. They belong to a smart metering support infrastructure. These Smart Meters do not provide an interface to an upper level, e.g. to the LVGMU, as the present smart metering support infrastructure was not designed to cope with such interface. That is why the CMU dialogues with both the Smart Meter and the LVGMU, in the Bronsbergen demonstrator case, to overcome the interfacing limitations of the Smart Meter.

In this scope, Smart Meters play a role on providing monitoring features, thus acting as sensors for specific LV applications, namely for providing valuable data to the CMU, which, as said, is able to overcome the smart metering platform limitations by sharing LV grid valuable data with the LVGMU.

The level above all Smart Meters playing the role of householder meters, consists of a metering management infrastructure which is out of scope of the e-balance system.

Yet, there is an upper level regarding the CMUs, corresponding to one or more LVGMUs. In the presented setting, these management units are located at the secondary substations and each of them controls the CMUs located in the area of the served LV grid, supplied with energy by this secondary substation. A LVGMU is equipped with communication gateways for the upward and downward communication within the e-balance management hierarchy. It is also equipped with communication gateways for communication with Smart Meters providing LV grid monitoring) located at the MV/LV transformer (Secondary Substation Local Area Network – SS-LAN).

In the current implementation, there are no specific resilience features for the MVGMU, as its role is meant only for providing balancing features, as described in [6].

3 Grid resilience mechanisms

This section presents a full description of all grid resilience mechanisms.

Figure 6 presents the detailed general architecture of a management unit. In the following sections, a deeper look will be made regarding on how each specific e-balance component – e.g. a management unit or a device – performs towards grid resilience.

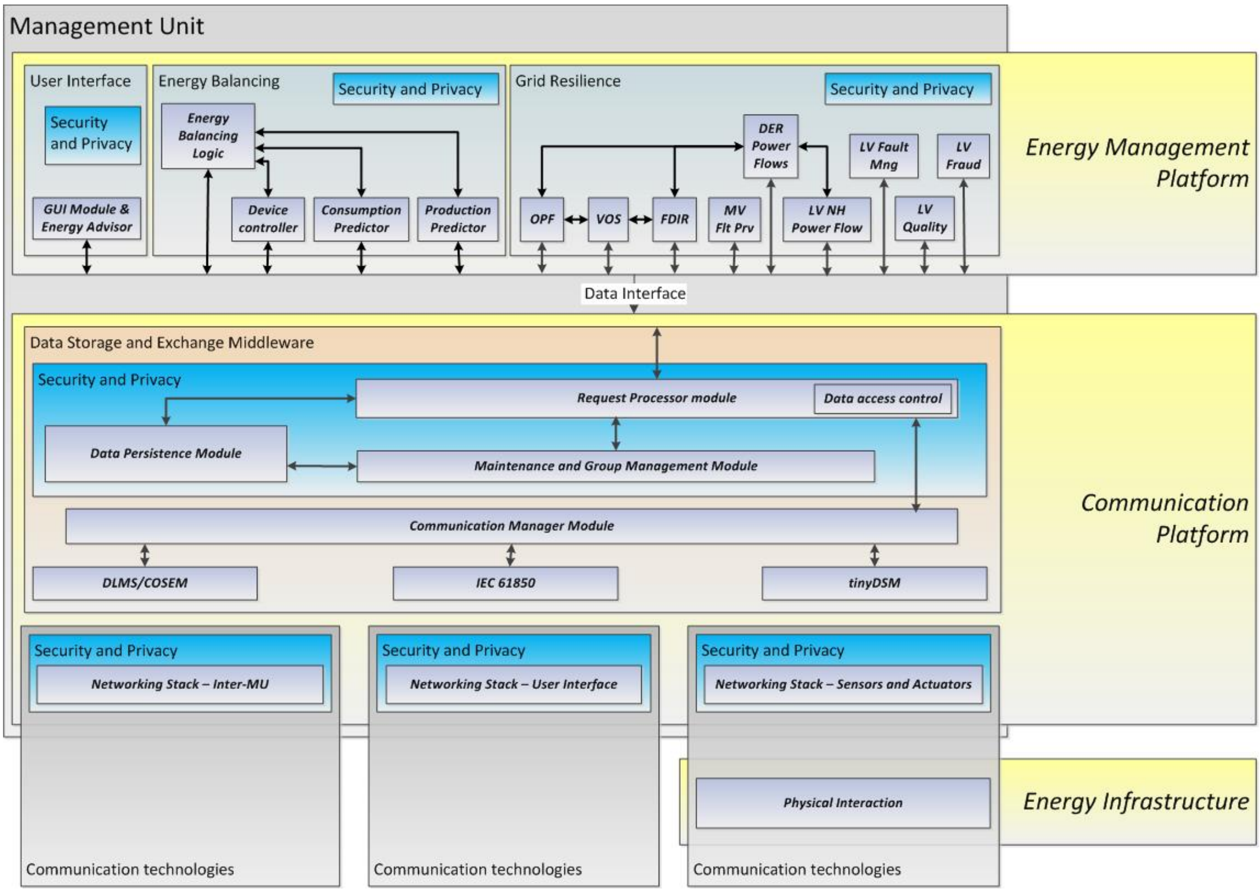


Figure 6: The general e-balance management unit architecture – the system architecture

3.1 Grid resilience briefing

3.1.1 The grid resilience components within each management unit

In this section, all EMP's – Energy Management Platform – software components related to Grid Resilience will be described, with the exception of the "MV Flt Prv" component – standing for MV Fault Prevention – as this component, although defined, was not selected for development and implementation. Figure 7 shows the EMP Grid Resilience components, which were actually developed.

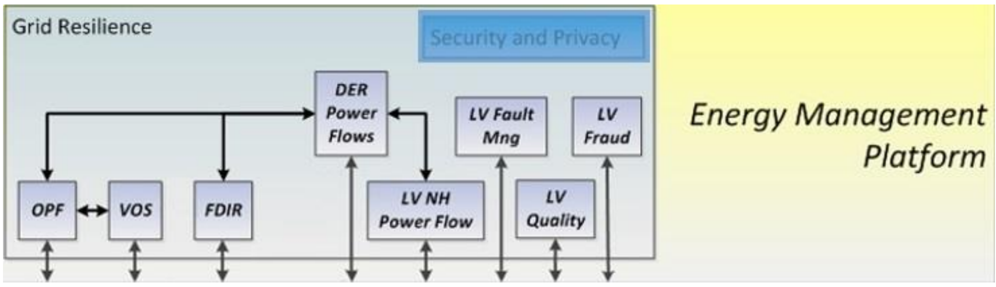


Figure 7: The Energy Management Platform (EMP) Grid Resilience components

The mentioned components were developed under task T5.3. Their names stand for:

- OPF – Optimized Power Flow
- VOS – Validation of Optimized Solutions
- FDIR – Fault Detection, Isolation and Restoration
- DER Power Flows – Distributed Energy Resources Power Flows
- LV NH Power Flow – Low Voltage Neighbourhood Power Flow
- LV Fault Mng – Low Voltage Fault Management
- LV Quality – Low Voltage Quality
- LV Fraud – Low Voltage Fraud

Those components are meant or are available to be deployed in several e-balance Management Units (MUs) and devices as described in Table 1.

Table 1: Relation between the e-balance architecture components and their grid resilience modules

Management units and other devices	**e-balance architecture components name**							
	OPF	**VOS**	**FDIR**	**DER Power Flows**	**LV NH Power Flow**	**LV Fault Mng**	**LV Quality**	**LV Fraud**
TLGMU	performs	performs						
MVGMU			performs	performs				
LVGMU				performs	performs	performs	performs	performs
DERMU								
LV Sensors				support	support	support	support	
Smart Meters				support	support	support	support	support
CMU						performs		
DMU						supports		

Note: For easing the above table understanding, one should interpret, e.g. “MVGMU **performs** the **DER Power Flows** component features, regarding grid resilience” and “Smart Meters **support** the **LV Quality** component features, regarding grid resilience”.

3.1.2 Grid resilience components brief description

The following sections briefly describe the role of each grid resilience component.

3.1.2.1 Optimized Power Flow

This section describes the Optimized Power Flow (OPF) component within the EMP, which is highlighted in Figure 8.

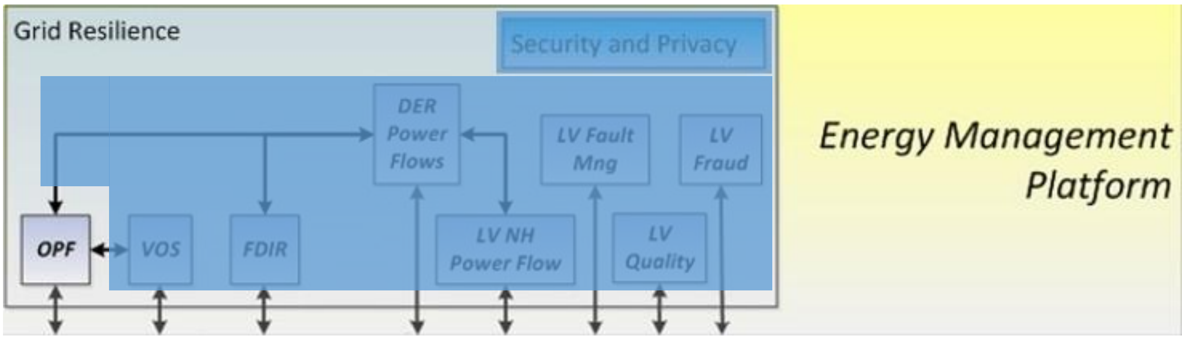


Figure 8: The EMP Grid Resilience “OPF” component

The OPF module’s main objective is to determine the optimal MV grid topology, which minimizes the grid active power losses and consequently its operating costs. The primary task is to find a set of system states, including switch state, within a region defined by the operating constraints such as voltage limits and branch flow limits. The secondary task is to optimize a cost function within this region. Typically, in OPF, the dispatch of active power is considered constant, which means that the power input from the transmission grid and the distributed power generation, are considered constant. The results obtained by this module must comply with operational constraints such as equipment operating limits, system security limits and radial operation of the grid.

Being suitable for defining optimal MV grid topologies under different cost function optimization criteria, the OPF component is also used by the FDIR component, as the latter relies on OPF’s ability to provide optimal grid topologies for downstream restoration, upon fault detection and faulty grid segment isolation (see Section 3.1.2.3).

The OPF component can be performed in real-time and in study environment based on the data provided by the SCADA/DMS (within the TLGMU) and by the lower control levels namely the Low Voltage Grid Management Unit (LVGMU), the Medium Voltage Grid Management Unit (MVGMU) and the Distributed Energy Resources Management Unit (DERMU), when applicable. Several types of data are required for an OPF package, namely the grid model and initial topology as well as real time measurements such as voltages, currents and power at different points of the grid.

The Validation of Optimized Solution (VOS) component will be responsible for implementing and validating the optimal reconfiguration solution for the MV grid determined by the OPF component. From a user or automatic process perspective, the OPF calls the VOS transparently; therefore, the OPF will find the topology, which minimizes the active power losses considering the actual state of the distribution grid under study. The solution found will have to comply with the operation constraints of the distribution grid, so that the final solution is always feasible.

The algorithm main control variables are the grid controllable switches required for reconfiguring the grid. The solution found will have to comply with all operational constrains considered in the framework of this optimization problem. Additionally, the module can also consider additional control variables such as, Volt/VAr regulation equipment such as transformer tap changers, capacitor bank or even grid supporting DER in order to help maintain voltage within limits and consequently reduce the power losses in the grid.

The OPF module can operate in two modes: a preventive or a corrective mode. In preventive mode, the OPF will run in order to improve the efficiency of MV operation by minimizing the active power losses of the system or in order to avoid possible congestion or voltage problems. However, when a violation – e.g. too low or high voltage, feeders’ congestion, excessive active power losses – or a fault are detected, the OPF can run in order to solve the operating restrictions. It considers the controllable equipment connected to the MV grid and primary and secondary substations – grid switches, taps in transformers, capacitor banks, and possibly DER units connected to the MV grid.

Therefore, four modes of operation can be defined for the OPF module, namely:

- Mode 1 ─ Reconfiguration mode that searches for the optimal grid configuration. In this mode, the OPF module will consider the available switches in order to determine the optimal grid topology.
- Mode 2 ─ Power flow optimization mode, which determines the optimal state variables without considering the reconfiguration of the distribution grid (i.e. switches are not considered controllable variables). In this case, the OPF will provide the optimal states for transformers and capacitor banks taps and the coordination with DER units in order to ensure that the MV grid voltages are within limits.
- Mode 3 ─ Runs both reconfiguration and power flow optimization. This mode combines the optimization objectives of Mode 1 and Mode 2.
- Mode 4 ─ Restoration mode, where the OPF will find alternative grid configurations which minimize the power not supplied after fault isolation.

The mode of operation can be selected manually by the distribution system operator or automatically if supported by other applications.

Considering the OPF mode of operation, the grid configuration will be optimized considering an objective function, which is a definition of how the solution state is to be evaluated and includes a mean of penalizing small changes of controls, in order to avoid unnecessary changes. Two different objective functions can be selected namely:

- Minimize the sum of active power losses (total or specifically for a given MV grid).
- Minimize the sum of active power not supplied. This objective function is selected in Mode 4.

The solution found by the algorithm will have to comply with the following constrains, namely:

- Maximum and minimum apparent, active and reactive power of DER units;
- Active power in groups of lines and transformers;
- Minimum and Maximum values for node voltages magnitudes;
- Transformer tap changer settings (initial, maximum and minimum tap position);
- Capacitor settings (e.g. reactive power capacity, maximum and minimum voltages);
- Maximum capacity of primary and secondary substation transformers and of the interconnection with the transmission system.

To maintain optimal set points under varying loads and grid topology, it is desirable to have remote control of transformer taps. Time skew from SCADA needs to be taken into account for the verifiability of the results. The concept of real time in OPF is in the order of 10 to 15 minutes (output and results analysis), and afterwards the time skew problems are different from the ones related with other real time functions.

The output of an OPF is a set of recommended controls, but not necessarily the secure and optimized sequence of steps to go from the initial state to the calculated final state. The results information includes all the operational parameters such as voltage, active and reactive power on each node, flows on the branches and angles, power factor and active and reactive losses. Also, the set of actions to change the network configuration to the optimized topology is given. Optimization is only possible if the grid is controllable, i.e. the control centre must have control of equipment such as grid controllable switches or tap changers. Optimization is restricted to those parts of the grid which are controllable.

3.1.2.2 Validation of Optimized Solutions

This section describes the “VOS” component within the EMP, which is highlighted in Figure 9.

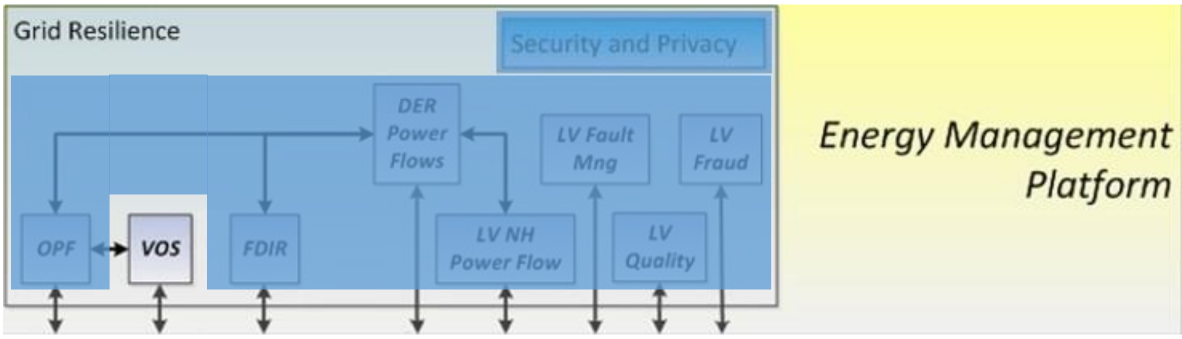


Figure 9: The EMP Grid Resilience “VOS” component

The main objective of the Validation of Optimized Solutions (VOS) application is to determine a reconfiguration procedure according to the optimal reconfiguration scheme determined by the OPF module. As mentioned before, the OPF only determines the switching actions that must be made to improve the actual configuration and not necessarily the correct order of doing it. Therefore, the VOS module will be responsible for determining an automated reconfiguration sequence, ensuring the security of the distribution grid during the sequence steps.

The reconfiguration procedures will depend on the grid topology and in the type of remotely controlled switches available (circuit breakers and/or sectionalizers). Typically, the procedure starts by closing the open loop and then opening the normally closed devices. However, additional switching actions and synchronization procedures may be required depending if the loop is connected to the same primary substation or interconnects two different substations.

Additionally, during the grid reconfiguration it is necessary to consider the presence of DER, particularly DG based on synchronous generators or other DER coupled to the grid through power electronic devices with grid-forming capabilities (i.e. capability of imposing a voltage and frequency reference to the system). Otherwise, the switching actions performed during the reconfiguration procedure could isolate a small portion of the grid integrating these units. Without adequate coordination and synchronization equipment this situation should be avoided. Therefore, when involved in the reconfiguration, the DG or DER should be disconnected until the normal operating conditions are met.

Similarly to the OPF module the VOS application assumes that the TLGMU is able to interact with central services, particularly with:

- SCADA system, in order to characterize the state of grid switching equipment and check for abnormal operating conditions or maintenance actions in the grid under analysis. Additionally, the VOS should be able to change the status of switching devices remotely and possibly lock or disable some of the automatisms implemented. In case of post-fault conditions the algorithm requires the identification of the faulted area or segment in order to ensure that the reconfiguration sequence maintains the affected area isolated from the rest of the grid.
- Power Flow application, in order to validate the initial state of the grid and verify if the intermediate and final solutions do not compromise the security of the system.

The VOS module determines an automated reconfiguration sequence, ensuring the security of the distribution grid during the sequence steps. This application will be responsible for implementing and validating the optimal reconfiguration solution for the MV grid determined by the OPF module.

Reconfiguring the MV grid may be required in the following situations:

- **Normal operating conditions**. Distribution grid reconfiguration is performed in order to reduce active power losses or to improve grid voltage profile.
- **Pre-fault conditions.** Distribution grid reconfiguration may be required in order to solve technical restrictions such as congestion or voltage problems.
- **Post-fault conditions**. After the correct location, identification and isolation of a faulted grid area, including automatic reclosing actions, grid reconfiguration may be required in order to minimize the power not supplied and active power losses.

The VOS component requires full knowledge of the actual operating state and of the initial and final values determined by the OPF module. Additionally, this component requires a detailed characterization of the grid reconfiguration equipment (i.e. circuit breakers, switches or reclosers) regarding its state, location, operability mode and remote control capabilities.

Before starting the reconfiguration sequence, the VOS module has to ensure that the solution found by the OPF module is valid considering current grid operation conditions. If the reconfiguration solution found continues to satisfy the objective function of the OPF module (e.g. total power losses) and the grid is operating under normal conditions (i.e. faults located and isolated), the module will determine the reconfiguration sequence.

After validating the optimal grid configuration and confirming that the distribution grid is prepared to be reconfigured, the module will then determine the automated reconfiguration sequence, which consists in a sequence of steps including the control of the grid switching equipment in order to achieve the final topology.

When considering the integration of DER, the sequence determined should avoid the formation of unwanted islands during the intermediate steps of the procedure and ensures the correct action of the distribution protection systems. After finalizing the reconfiguration sequence, the module will also validate the final operation state of the grid and compare it with the estimated conditions from the OPF module.

Before implementing the sequence determined, a power flow study is performed in order to ensure that the grid operation limits are respected and avoid the tripping of protection systems or the formation of unwanted islanded systems (e.g. when DG units are connected to the grid feeders).

The sequence will then be implemented after validation and can run in the following modes:

- **Manual** – in this case the module return a reconfiguration sequence which will then be validated and implemented manually by the distribution grid operator.
- **Automatic** – in this case the reconfiguration sequence will run automatically. Prior validation of the automated sequence may be required by the distribution grid operator.

When the procedure ends, a new power flow study is performed in order to verify whether the new configuration meets the OPF objectives and respects the grid operating constraints.

3.1.2.3 Fault Detection, Isolation and Restoration

This section describes the "FDIR" component within the EMP, which is highlighted in Figure 10.

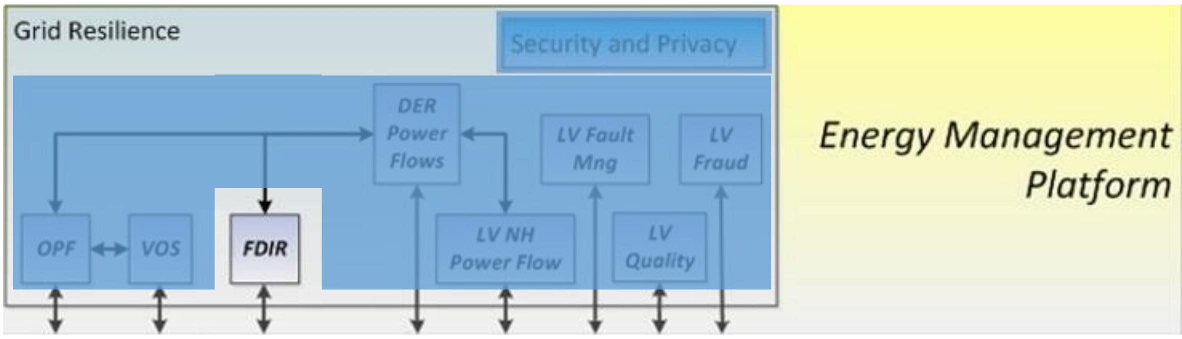


Figure 10: The EMP Grid Resilience "FDIR" component

The main objective of the MV Fault Detection, Isolation and Restoration (FDIR) component is to monitor the MV grid and actively identify and locate MV faults and help restore service to the unaffected segments of the grid. This component is incorporated at the MVGMU, monitoring the primary substation MV panels and the respective switching and sensors installed downstream in MV feeders. When a fault occurs, the module is activated in order to locate and identify the faulted equipment. The final state of the grid switching equipment will be combined with the information from the LVGMU – also monitoring the secondary substation's MV infeed, bus-bar and outfeed bays –, in order to provide the most probable location where the fault occurred. This data will then be transmitted upstream to the centralized services in order to support distribution grid operators in the coordination of the field teams.

The FDIR module implements a solution oriented towards distribution MV grids, providing a list of possible fault locations and a list of actions to isolate the faulted zone and to optimize power restoration to the healthy non-energized grid circuits. It is intended to be used in radial or meshed sub-grids connected downstream the primary substation. Regarding fault location, the module can incorporate the following data groups:

- **Logical information**, concerning the state (opened/closed) of the switching gear or detectors in the MV grid below the substation circuit breaker. This information allows the comparison of the pre-fault state of the grid with the actual state, required for a first identification of the faulted feeder segments. Special care is to be given to devices such as fault detectors and reclosers, since the information they provide performs a great role in narrowing the list of possible fault location candidates. For example, when a recloser (normally closed) changes its final state to closed, it indicates that the line segments connected upstream (between the substation and the recloser) should not be considered as likely candidates to be the fault location.
- **Electrical information**, namely short-circuit current, distance or impedance value provided by the circuit breakers, reclosers and other MV sensors installed in the grid. This information, if available, is used to make an estimate of the minimum and maximum fault distance, considering the fault to be a three phase symmetrical, zero fault resistance short circuit (so giving the longest distance).

Based on the data available, the MVGMU performs MV feeder state monitoring. If a fault is detected, the module will provide the most probable locations where the fault occurred. The reconfiguration rules for each feeder should be incorporated in the component in order to better identify the possible affected areas. The rules adopted will depend on the switching and protection equipment connected to the MV feeders.

Regarding the input data required, the module can run only with the logical data associated to the topological configuration of the MV feeders. This will allow the identification of the switching and sensor devices within the faulted area. However, the additional input information referred above will help reduce the number of possible fault locations, leading to an accurate and fast location of the fault. As outputs, the module will return a list of the MV line segments where the fault is more likely to occur. If the inputs include electrical information, fault distance will also be estimated. Besides identifying the line segments and equipment within the faulted area, the module should provide the geographical location for supporting field operators.

The implementation of this module takes into consideration the following assumptions:

- MV feeders are equipped with remote controlled switches and/or circuit breakers, in order to reconfigure the grid. If the fault detection and isolation depends exclusively on the substation circuit breaker and protection devices, fault location will be conducted based on the impedance calculation. A large estimation error may be obtained.
- Primary substations have local processing and monitoring capabilities, capable of monitoring MV feeders, sensors and actuators. A topology processor is required at the MVGMU.
- Impedance of MV feeders is known. This data is required when performing distance estimation. Otherwise, fault location will exclusively depend on the topology analysis and real-time data (remote logical signals, measurements and alarms).

In what concerns isolation of the fault, this module performs a topological analysis in the faulted feeder in order to determine the minimum area limited by operable switches that fully encloses the faulted area. After isolation, the FDIR module calculates the proper restoration sequences for both upstream and downstream schemes. The calculation of the sequence of actions to isolate and restore power is performed by the OPF module using a specific OPF objective function and definition of possible controls in the grid.

Upstream restoration:

- If the fault can be isolated beyond the tripped feeder breaker then that breaker can be reclosed since there is a decrease in the feeder load after faulty grid segment isolation.
- If there is no operable switch being able to separate the feeder breaker from the fault, then no upstream restoration can be performed in this case.

Downstream restoration

- Unlike upstream restoration, where reclosing the tripped breaker is always a safe operation, downstream restoration beyond the faulty grid segment is more complex because transferring the de-energized loads to adjacent feeders may compromise operational grid constraints, like thermal or voltage limits. In order to ensure that operation limits are not violated during and after reconfiguration, the system may have to explore multiple reconfiguration possibilities, and in the limit, it may end up with a solution that is not able to re-energize all grid segments that were isolated from the faulty grid segment.

This module may run in two main modes:

- **Manual** – in this case the module generates a switching order that implements the computed reconfiguration sequence. This switching order is normally exported to the TLGMU, where it can then be taken by an operator for execution. Alternatively and within the e-balance goals for the Batalha demonstrator, an operator can also take the switching order at the MVGMU. The operator is free to add some actions to the switching order, or to not execute some of the proposed actions.
- **Automatic** – in this case the reconfiguration sequence will run automatically at the MVGMU. The module is responsible for generating the switching control signals according to the identifiers of the grid switching equipment and sends it through the local MVGMU system. For each control signal the module will wait for a confirmation of the final state of the remote controlled grid equipment. If for some reason the switching action fails, the module aborts the sequence execution and returns an alert to the grid operator. After successful or unsuccessful execution, the module generates the corresponding switching order, stating the execution time for each instruction, and exports it to the TLGMU where it is archived. This switching order can then be consulted / analysed by operators.

The calculation of a safe and optimized sequence of topology reconfiguration actions is complex, namely the downstream restoration, taking in account the following main aspects of the problem:

- Transferring the de-energized loads to adjacent feeders may compromise operational grid constraints like thermal or voltage limits
- Analysis of multiple topology combination of circuits depending on the number of available operable normal open points.

The complex problem of downstream restoration is solved by an OPF function (see Section 3.1.2.1) whose target is to minimize the power not supplied after fault isolation, while still granting that the found solution complies with the following constrains:

- Minimum and Maximum values for node voltages magnitudes;
- Maximum capacity of lines;
- Maximum capacity of primary substation transformers

3.1.2.4 DER Power Flows

This section describes the “DER Power Flows” component within the EMP, which is highlighted in Figure 11.

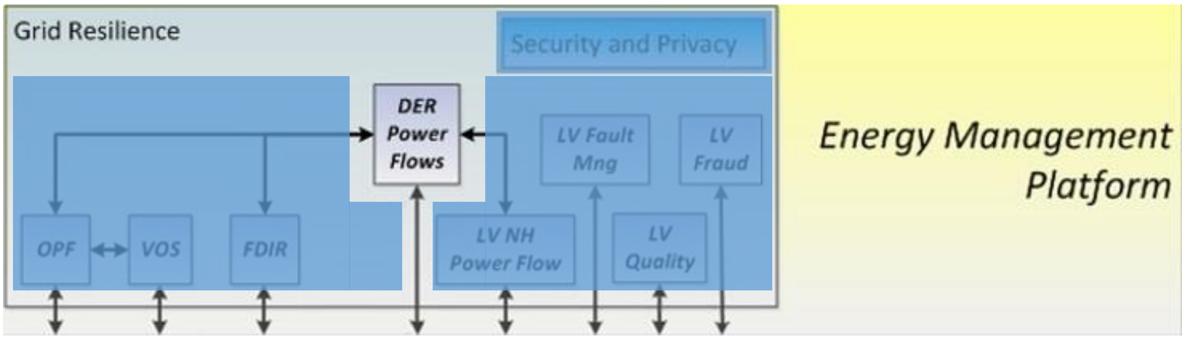


Figure 11: The EMP Grid Resilience “DER Power Flows” component

DER include storage, distributed generation units either based on RES (i.e. solar photovoltaic or wind), low carbon technologies (fuel cells, microturbines) usually associated to Combined Heat and Power (CHP) and flexible loads, which are connected to the distribution grid at the MV and LV levels.

Real-time awareness of DER power consumption or generation as well as building a relevant historical database are important for distribution grid control. This is needed to be able to correctly prevent, identify and correct potential problems related with the large scale integration of DER resources and at the same time enable innovative DER grid supporting strategies.

The main objective of the DER power flows application is to provide the necessary information for the interaction of DER units with the DSO. It assumes that there is measuring and communication capabilities at the DER devices level, providing the adequate means for collecting (quasi) real-time information from the DER devices (e.g. power consumption, maximum and minimum capacity). In case DER are connected at the home grid level, such capabilities are coordinated by the customer management unit and the smart metering equipment.

The DER Power Flows component was designed to match the implementation described within the Use Case 14, which can be found in [12]. There, only the LV grid was addressed. Nevertheless, it was an implementation goal to enable the same feature within the MV grid.

The DERPF component is responsible for aggregating the filtered measurements, while providing an aggregate view of the DER power injection/consumption. The information processed by this component will exchange information between the following grid resilience components:

- Optimized Power Flow (OPF) – DERPF is responsible for providing information of MV DER units to the OPF module, such as telemetered measurements from DER (active and reactive power injection) and availability for participating in the control (voltage or reactive power regulation capacity).
- Fault Detection, Isolation and Restoration (FDIR), where the DER power flow application provides pre-fault information of the power injected by the DER units connected to the MV feeders affected by the fault.
- LV Neighbourhood Power Flow (NPF), where information is exchanged by both applications. The telemetered measurements of DER are provided to the LV NPF application as well as the historical database collected. When there isn’t real time communication with the LV DER units and only historical data is available, the LV Neighbourhood Power Flow provides the estimated injected power from the DER units as well as the voltage in the connection node.

3.1.2.5 LV Neighbourhood Power Flow

This section describes the “LV NH Power Flow” component within the EMP, which is highlighted in Figure 12.

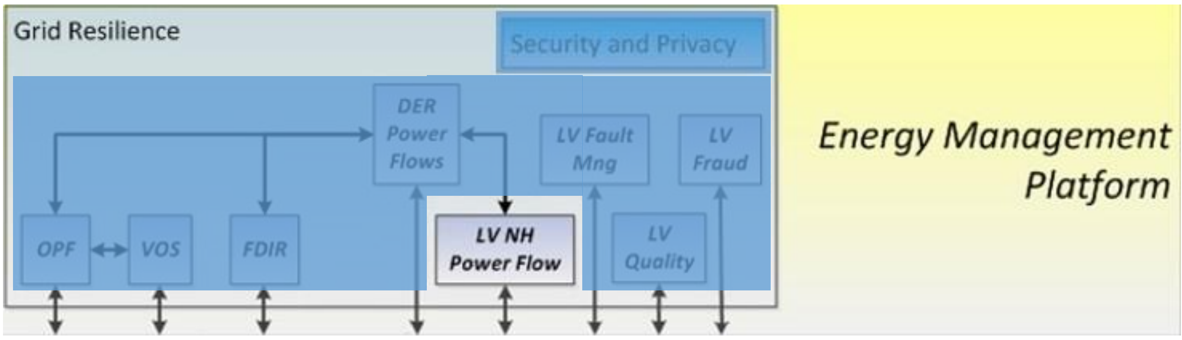


Figure 12: The EMP Grid Resilience “LV NH Power Flow” component

The main objective of the LV Neighborhood Power Flow (NPF) module is to provide a synchronous and accurate characterization of the LV grid operation state, in order to identify potential problems occurring in the LV grid (e.g. voltage limit violation, congestion) or to optimize grid operation.

The module was specifically designed to deal with LV grid distinct characteristics and challenges, incorporating a state estimation algorithm which is responsible for determining the grid state, based only on a limited number of real time measurements and on other relevant information from historic. This allows the reduction of the nodes required to provide data in real-time through the use of pseudo-measurements – a value not measured, instead, it is imposed by a duly user. At the same time, the algorithm was designed to deal with the unbalanced nature of the LV grid, due to the uneven distribution of loads and DER by the three-phases of the system.

The NPF will be responsible for determining the LV grid state (i.e. voltages, currents and power flows) considering the errors affecting real-time measurements and historical data. When real-time data is not sufficient to ensure the observability of the system under study, the state estimator will calculate load and DER values based on historical data.

3.1.2.6 LV Fault Management

This section describes the “LV Fault Mng” component within the EMP, which is highlighted in Figure 13.

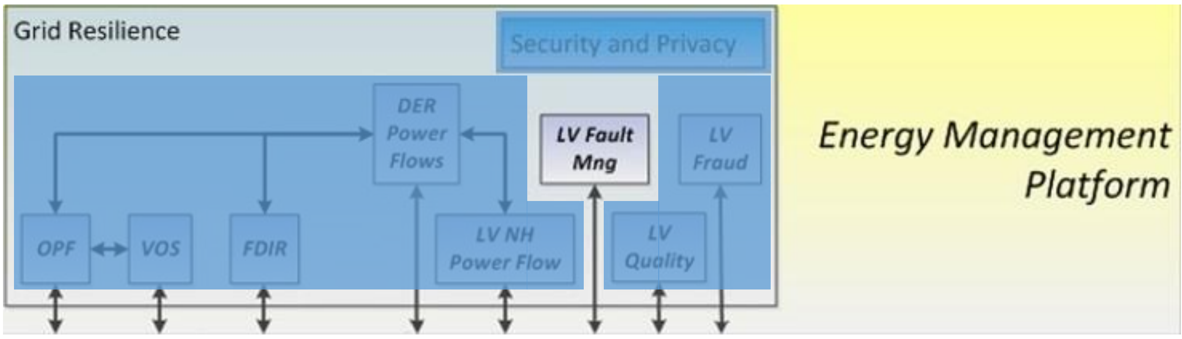


Figure 13: The EMP Grid Resilience “LV Fault Mng” component

This module processes LV grid data kept on a real time database.

Three main algorithms constitute LV Fault Management software component:

- LV Fault Detection and Location
- LV Fault Detection on Fused Luminaires
- LV Fault Prevention
    - Voltage Regulation
    - Fuse Preventive Maintenance (possible Loads redistribution or Grid upgrade)

The LV fault management features comprise the actuation over distributed power generation to keep voltage inside the legal limits, the prevention of fuse faults by warning for fuse over current and overloading and any kind of current fault detection and location, occurring on a LV feeder segment or on a public street lighting circuit. Moreover, fault management also comprises the detection and location of blown-up public street lighting bulbs.

While current faults are tagged as such by remote sensors, the role of this module is to process the incoming alarm data in order to assess it, taking into consideration the existing topology information. Being aware of that topology, the module processes the data kept in the database, which was sent by remote sensors, determining the location of the fault, which is set to alarm in the database. Besides remote sensors, any smart meters deployed along the LV feeders can also play a monitoring role, as they also provide useful data for enabling fault detection and location.

Upon fault location, the algorithm can then poll smart meters communicating via power line carrier or via GPRS, in order to tune de fault location into a deeper level. For those smart meters communicating otherwise, e.g. by RF Mesh technology, another feature is available, which is “last gasp”. When power goes down, a Smart Meter with the last gasp feature enabled is able to communicate its upcoming energising dying status, also known as shutting down.

With the topology feature enabled, the LVGMU is able to better tune the fault location by using last gasp alarm data, as – when available and set at the real time database – it allows the LVGMU algorithm to improve the tuning of the fault location, leveraging the outcome into a deeper level.

The identification process of public street lighting bulb faults occurs at this module, with the sensors playing a passive role, as they only report new current values which are communicated upstream according to a variation triggered threshold. Once this component monitors a sudden current change, the blown-up light bulb detector is triggered, hence detecting the occurrence of a possible blown-up situation. The algorithm compares the current difference between adjacent sensors at each consecutive algorithm sampling, so that a clear location of the candidate blown-up occurrence is achieved. The number of sensors determines the accuracy of detection: the more sensors, the finer location the algorithm can reach.

This module functionality for voltage fault prevention is done by requesting smart meters, in the LV Grid, for phase voltages and when an over pre-configured voltage is detected, a power set point is calculated and sent to the necessary DGs, to keep the grid voltage inside limits.

The LV Grid Fuses preventive replacement is done by electrical current reading, excess of electrical current may cause a fuse melting and near these conditions, an alarm is set. On fuse alarm, the DSO can preventively programme fuse maintenance or if necessary a load redistribution or even a grid upgrade, so the detected currents can be supported without a LV fault.

3.1.2.7 LV Quality

This section describes the "LV Quality" component within the EMP, which is highlighted in Figure 14.

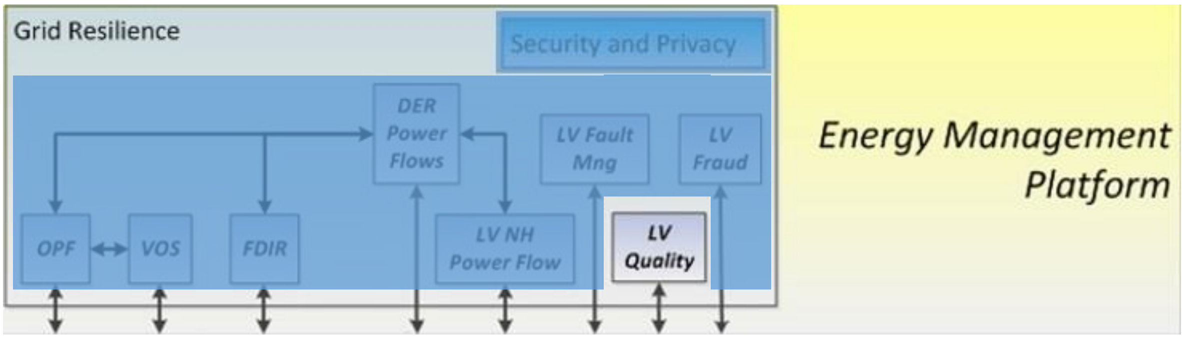


Figure 14: The EMP Grid Resilience "LV Quality" component

Despite of the DSO responsibility to ensure reliability and quality of the power supply, in fact distribution grids suffer from technical quality issues. The LV Quality component main goal is to provide intelligent processing and analysis from LV grid data, referring to power quality and to service interruptions.

Smart meters are able to detect and store information related to service interruptions and voltage disturbances. Depending on the severity of disturbances, Smart Meters may automatically generate an alarm which notifies the LVGMU, but only in the case for voltage disturbances. Regarding the service interruption data, the Smart Meters keep an event log which is remotely accessed by the LVGMU. With this data, the LVGMU is able to keep an internal database describing the overall LV distribution grid availability status.

The LV Quality application manages the alarm data and triggers specific actions or tools considering voltage alarms or grid interruption data. If the voltage limit is violated, the application calls a specific function that controls microgeneration units in order to keep the feeder voltage within the expected limits. At the same time if interruptions are detected within a specific grid area, this information is sent to the LV Fault management application for processing. Power quality data is kept on a real time database and is sent periodically to the higher control levels, providing additional information do distribution grid operators in order to enable the identification of problematic areas of the grid, where additional monitoring or intervention is required. The information required to characterize grid technical quality has different sources:

- Smart Meters, which are able to detect and store information related to service interruptions and voltage disturbances. Depending on the severity of the disturbance the Smart Meter may automatically generate an alarm which notifies the LVGMU.
- Grid Sensors, providing redundant information, which may help to identify disturbances.

Continuity of service is associated with the occurrence of interruptions to the supply and is quantified according to the frequency (i.e. number of interruptions) and duration of the interruptions. Power quality is quantified through voltage quality defined by the following characteristics:

- Addressed in the current energy resilience implementation
  - Magnitude of supply voltage
  - Voltage sags, swell, and momentary interruptions
- Out of scope of the current energy resilience implementation
  - System frequency
  - Harmonic and inter-harmonics
  - Voltage unbalance
  - Flicker emission
  - Transients

3.1.2.8 LV Fraud Detection

This section describes the “LV Fraud” component within the EMP, which is highlighted in Figure 15.

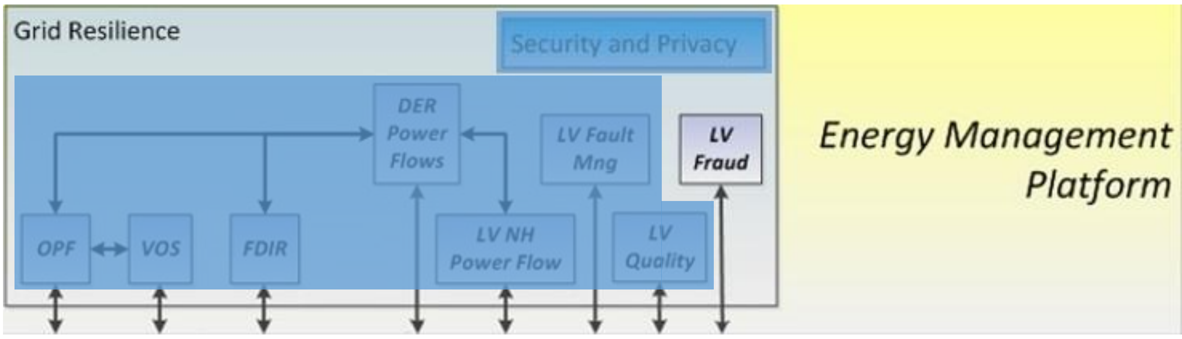


Figure 15: The EMP Grid Resilience “LV Fraud” component

The main goal of the LV Fraud Detection module is to identify possible fraud activities as well as the most probable location for its occurrence, based on the information provided by the smart meters and LV sensors connected downstream. The module combines advanced functionalities of Smart Meter with distributed intelligence integrated at the LVGMU.

This component will have a predefined configuration with the technical losses for each feeder to be used in the fraud detection algorithm. The module will run in a time base period and will launch the fraud detection and location algorithm, which will try to identify or at least narrow down the most probable locations for the occurrence of fraudulent activities. Different search levels can be implemented if enough data are available, namely search at the feeder segments or at customer level. Feeder segment search requires metering equipment installed on the feeders. By analyzing the energy measurements, currents or load diagrams (according to the sensor metering capabilities) it might be possible to identify the line segments with larger probability of fraud occurrence. In order to do that adequate mapping of Smart Meter will be required, as discussed previously. At the customer level, the module will have to analyze customers’ energy and power consumption historic and meter fraud detection alarms. However, such data should be checked and validated with additional information from the grid and/or substation sensors.

As outputs the Fraud Detection module will generate critical and non-critical alarms when the probability of fraud occurrence is high, providing a list of possible locations or grid areas where fraud activities are likely to occur. The module will also store the information collected in order to provide to higher control levels, namely central services, with a detailed historical database.

3.1.3 Use case and demonstration matrix

In Deliverable D2.1 [2], a set of use cases has been defined related to grid resilience. Some of those use cases are to be demonstrated in Batalha, which are given in Table 2. This table relates the use cases to be demonstrated with the Management Units and Devices planned for development within the e-balance project.

Table 2: Use cases related to grid resilience [2], planned for the Batalha demo, in Portugal

use case #	Title	Related e-balance MUs and devices
13	Neighbourhood power flows	LVGMU, LV Sensors, Smart Meters
14	DER power flows	MVGMU, LVGMU, LV Sensors, Smart Meters
15	Optimized power flow	TLGMU
17	Validation of optimized solutions	TLGMU
18	Quality of supply measurement	LVGMU
20	Fraud detection	LVGMU, Smart Meters
21	Losses calculation	LVGMU, LV Sensors, Smart Meters
22	LV fault detection and location	LVGMU, LV Sensors, Smart Meters
23	Public street lighting (PL) faults and fused luminaires detection and location	LVGMU, PL Sensors
24	Fault prevention (LV)	LVGMU, LV Sensors, Smart Meters, CMU, DMU – via each PV inverter
29	MV fault detection and location	MVGMU
30	Automatic grid service restoration - self-healing (MV)	MVGMU

3.1.4 A broader perspective of the e-balance components for the Batalha demonstrator

Figure 16 depicts the main e-balance physical components of the Batalha demonstrator, comprising Management Units (MU) and devices, as well as the main standards used for communication between them. A glimpse on the hardware and application/software components is also given. Moreover, Figure 16 also highlights which Use Cases (UC) were covered, in line with what was described in Table 2.

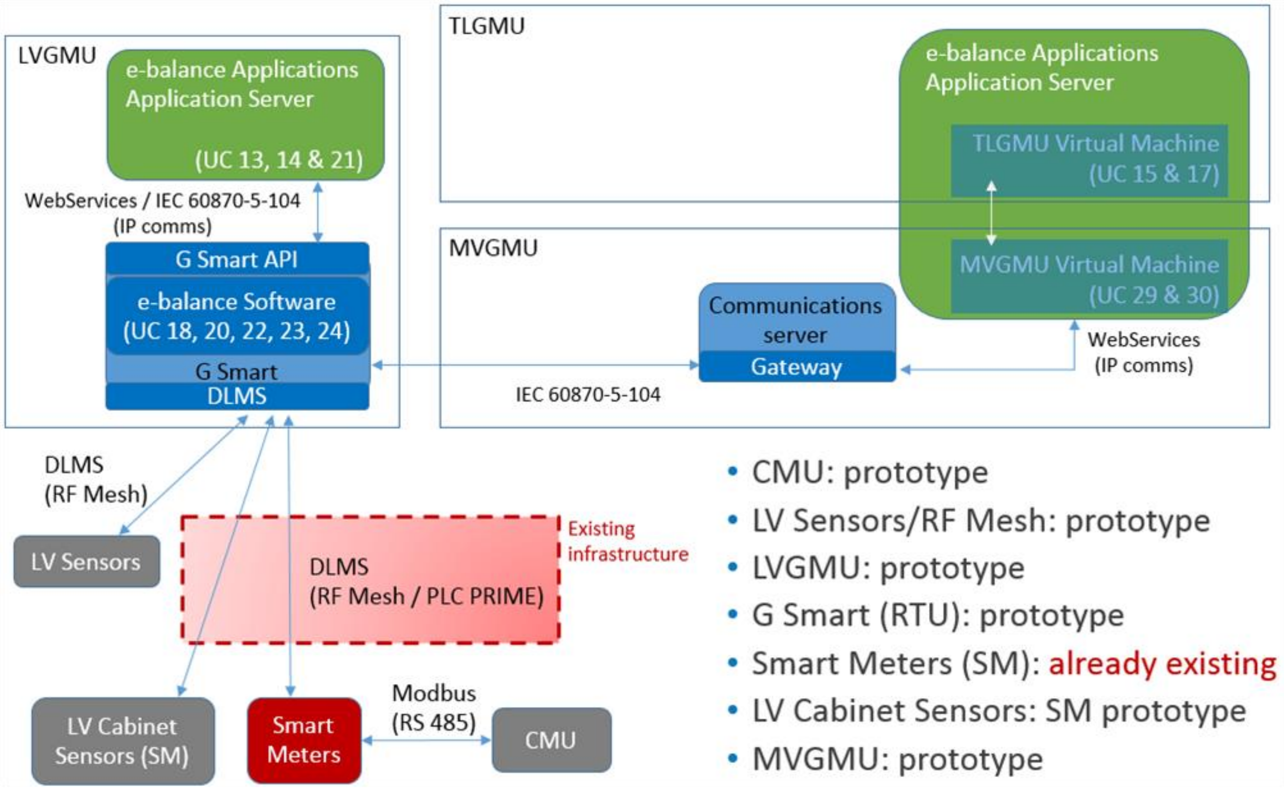


Figure 16: The physical components of e-balance and their role on supporting the Batalha selected use cases

According to the e-balance reference architecture targeted for the Batalha demonstrator, at the lower level, the CMU – by INOV – plays the role of a home server, being responsible for controlling the PV inverter according to set-points sent by the LVGMU. The interface between the LVGMU and the CMU is performed by the Smart Meter associated to the micro-production asset. In one hand, the Smart Meter dialogues with the LVGMU via DLMS/COSEM, over a PLC Prime communication media. Other media such as RF Mesh – IEEE 802.15.4 compliant – is also an alternative.

It is worth mentioning that the existing Smart Metering infrastructure already exists, comprising Smart Meters from different manufacturers, thus being used to support the e-balance demonstration needs. Such infrastructure also plays a major role on grid resilience, as it privides valuable timeseries data regarding power consumption, power generation and voltages. This data, together with the LV sensors realtime data, are used by the LVGMU.

Regarding the LV grid and the public street lighting circuits, the measurements monitoring is performed by LV sensors – by INOV – and by 3-phase off-the-shelf smart meters – by Efacec. They are installed in overhead cabinets and in street distribution cabinets, respectively in aerial and in underground grid segments. Their role is to provide data to the LVGMU.

The LVGMU is based on the G Smart industrial product – by Efacec –, matching the same role of the DTC – Distribution Transformer Controller –,EDP's definition for the secondary substation controller within the INOVGRID project. The G Smart hardware comprises an iMX6 800 MHz CPU – by Freescale – with 512 MB RAM and 2 GB NAND Flash.

It is up to the LVGMU to assess data and to carry on with the implemented algorithms, aiming at successfully accomplishing the selected Use Cases towards grid resilience, which are identified in Figure 17 and described in Table 3. Specifically regarding the implementations for Use Cases 13, 14 and 21, an off-the-shelf embedded computer is also used, which grants the needed computational capabilities to support the G Smart. Such embedded computer comprises one quadcore CPU, as well as 16 GB memory and 500 GB hard disk.

Separately from the above scope, there is the MVGMU and the TLGMU, which play different roles regarding MV grid resilience, each focused on specific Use Cases, also identified in Figure 18 and described in Table 4.

The MVGMU features developed within e-balance – by Efacec – are compliant with the SSC – Smart Substation Controller – the EDP's definition for the primary substation served MV grid area, which plays a decentralised management role over MV distribution grid areas, within the INOVGRID project. As depicted in Figure 19, the MVGMU supports the features related to the Use Cases 29 and 30.

The TLGMU is based on the SCATE X+ solution, which is a SCADA/DMS system – by Efacec. The features developed within e-balance also serve the goals of the INOVGRID project, while enhancing the current Efacec portfolio in the SCADA/DMS domain. As depicted in Figure 17, the TLGMU supports the features related to the Use Cases 15 and 17, shortly described in Table 3.

The hardware characteristics suitable to support the MVGMU and TLGMU scope, comprise a computer server with two 3 GHz 6 core CPU, as well as with 48 GB RAM and two 500 GB hard disks. This scope also includes a workstation – for HMI purposes – comprising one 2.5 GHz 2 core CPU, as well as 4 GB RAM and 300 GB hard disk.

4 The detailed system implementation of grid and energy resilience, and self-healing

4.1 Implementation Details of the Grid Resilience Components

The following sections describe the implementation details for each grid resilience component.

4.1.1 Optimized Power Flow

As described in Section 3.1.2.1, the OPF component provides a new grid operating topology state, as a result of grid input data, coping with specific cost function criteria.

The native feature of OPF aims at finding the best grid topology by performing switching remote control, which minimizes the active power losses – the criterion – considering the actual topology state of the distribution grid under operational improvement. The solution found will have to comply with the operation constraints of the distribution grid, so that the final solution is always feasible. In this case, OPF performs in Mode 1.

The criterion can be different, namely observing only other controllable grid assets such as capacitor bank and transformer taps. In this case, the aiming is to ensure that MV grid node voltages are within the operational limits – the criterion – which means that OPF performs in Mode 2.

The OPF performs in Mode 3 when the criteria for Mode 1 and for Mode 2 are combined.

The OPF results for Mode 1, Mode 2 and Mode 3 embed the outcome of VOS, as VOS – see Section 4.1.2 – aims at validating and helping the user to choose the best grid topology, among the alternatives initially proposed by OPF.

Finally, the OPF can also perform in Mode 4, aiming at finding the best grid topology configurations that minimize the power not supplied after fault isolation. Fault isolation and grid service restoration is performed by FDIR – see Section 4.1.3 –, upon fault detection and location. Therefore, FDIR also embeds the outcome of OPF – in Mode 4.

4.1.1.1 Functional Model

The general architecture of the OPF component is presented in Figure 17, being composed of a core module, which is constituted by the OPF functions and by its inputs and outputs, organized in different data structures.

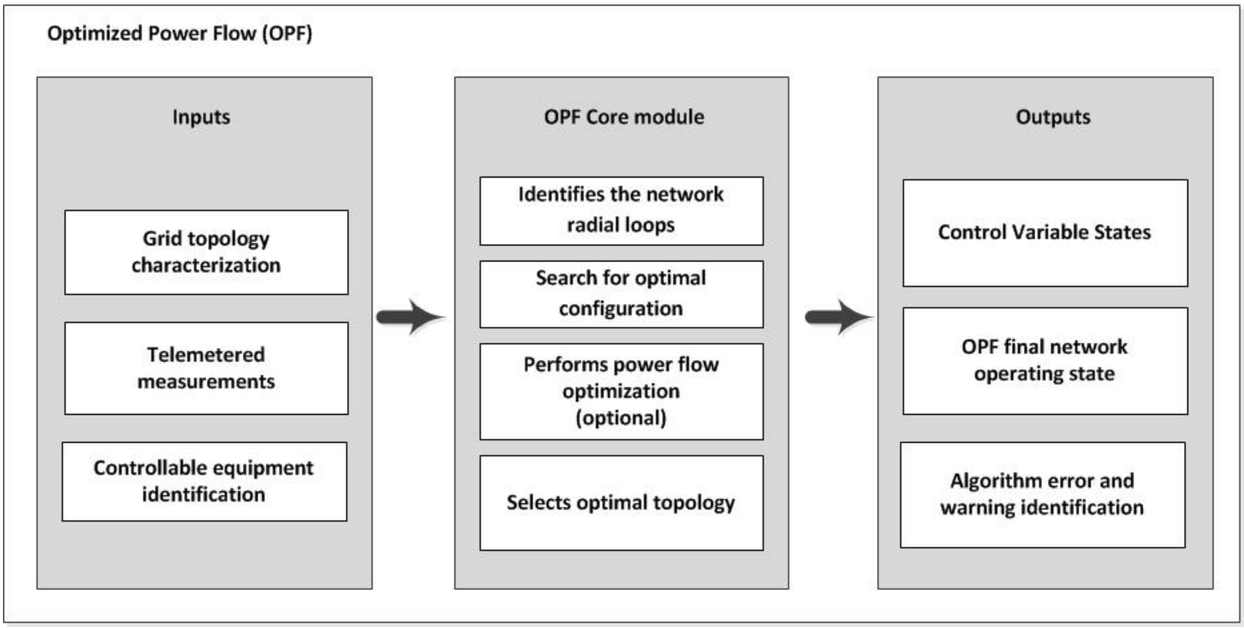


Figure 17: General architecture of the OPF component

This module returns a final reconfiguration scheme (list of switching operations that correspond to the best switch state control variables) and the optimal value for the other control variables of the OPF problem. The distribution grid optimal state complies with operational constrains considered in the framework of this optimization problem, which is the minimization of the sum of active power losses (total or specifically for a given MV grid) – the criterion. This criterion corresponds to a specific objective function.

Actually, the objective function is defined as a result of a component setting, thus enabling the selection of the algorithm mode. The algorithm will perform defining the optimal reconfiguration solution, which minimizes the active power losses of the distribution grid, considering the controllable switches available. When configured otherwise and while performing in Mode 4, the algorithm will define the optimal reconfiguration solution minimizing the sum of active power not supplied, thus defining the optimal grid topology – subsequently to fault isolation, OPF provides grid service restoration – after the occurrence of a grid fault.

The given reconfiguration schemes represent only the switching actions that must be made to improve the actual configuration and not necessarily the correct order of doing it. It is not this module responsibility to determine the correct order of switching operations to reconfigure the distribution grid. That role is meant to be performed by the VOS component, therefore with VOS being embedded in the overall OPF functionality.

The structures to be used with the OPF module, for maintaining input data, output data and internal results will be shared by the whole set of functions.

The run modes (real-time or study mode) are specified and controlled by the caller – the DSO will call the module through the Energy Management Platform (EMP). The OPF function is the same for both run modes. All the parameters are provided by the caller and will not be requested by the OPF module. The caller is also responsible for the proper activation of the module and for the requirement of some results. It is only possible to run one OPF at the same time using the same dataset composed of the module inputs.

Matching the e-balance goals definition, two different objective functions can be selected, namely:

- Mode 1: Minimization of the sum of active power losses (total or specifically for a given MV grid).
- Mode 4: Minimization of the sum of active power not supplied.

4.1.1.2 OPF inputs

The inputs of the OPF module are identified in Table 3 and Table 4, and can be divided in three main groups:

- **Grid topology characterization**, in order to build the initial grid topology and identify its feeders and transformers electric characteristics. The correct characterization of the grid topology requires real-time information on the grid switches status, provided by the TLGMU.
- **Telemetered measurements**, in order to characterize the grid operating state (e.g. power consumption and generation) and initialize the grid model (e.g. voltage magnitudes). As explained earlier, the OPF algorithm will only be effective when considering a synchronous set of data. Therefore, the measurements should be pre-processed by a distribution state estimator application – an available feature, developed out of the e-balance project scope.
- **Control variable identification.** Based on the operating mode selected, the module may control different groups of equipment: MV grid switches, transformer and capacitor bank taps and DER units providing grid support. For each group it is required to identify the equipment state, availability to be controlled and technical limits (e.g. tap maximum and minimum position, maximum capacity of DER, among others).

Regarding the MV grid topology, the OPF module can run for the entire grid or for a selected area of the MV grid, which is useful particularly in Mode 4, where the algorithm's main objective is to find a solution for the MV grid affected by a fault. However, it requires the identification of the respective grid areas under study. These inputs are provided by the TLGMU system, namely providing input data for switch states and for identifying grid areas and islands, as well as for grid impedance characteristics.

As inputs, the system also requires information from power consumption, generation and power exchange with the transmission and LV grids. Voltage in MV grid nodes may also be included in order to better characterize the grid operating state. The information will be provided by the TLGMU which will receive information from the lower control levels and from the DERMU of the DER connected to MV grids, when applicable.

Table 3: OPF module inputs

Input	**Description**	**Source**
Grid Topology	Includes the initial grid topology, and circuit-breakers and switching device status. It also includes the identification of the MV grid islands under study	TLGMU
Electric characteristics of the grid elements	Includes feeders, transformer impedances	TLGMU
Telemetered measurements from distribution grid	Voltages, currents and power consumption	TLGMU (Primary Substation, MV sensors and Secondary Substation. Should be pre-processed by a state estimator module)
Telemetered measurements from DER	Power injected/consumed by the DER units connected to MV grid.	TLGMU and DERMU (if considered) of DER connected at the MV level
LTC and capacitor bank tap settings	Indicates the initial tap position of capacitor banks and transformer taps	TLGMU (From Primary Substation sensors)

List of equipment that cannot be controlled	Transformers, capacitor banks, DER and grid connections	DSO
Type of control variables to be used	Transformers and capacitor banks taps, voltage in DER, or voltage in grid connections	DSO and DERMU (if considered)
List of faulted elements	When applicable	TLGMU

Table 4: OPF module inputs provided by the DSO

Input	**Description**	**Source**
Objective function to use during optimization	1. minimize the sum of active power losses for all the system; 2. minimize the sum of active power not supplied and the active power losses for all system;	DSO
Constrains	1. apparent, active and reactive power in generators; 2. apparent power in transformers and transmission lines; 3. active power in groups of lines and transformers; 4. minimum and maximum values for node voltages magnitudes; 5. LTC and capacitor settings.	DSO and DERMU of DER connected at the MV level

4.1.1.3 OPF outputs

After finding the optimal topology for the distribution grid the OPF provides the final state of the control variables, as well as the final state of the grid, regarding node and bus voltages and line power flows. The outputs of the algorithm are identified in tables Table 5 to **Fehler! Verweisquelle konnte nicht gefunden werden.**. Considering the final state of the control variables, the OPF provides information related to the grid operations state, namely regarding voltages, currents and active and reactive power flows, as identified in Table 5. Additionally, the module also provides information related to the algorithm as indicated in Table 6.
As mentioned before, the grid under analysis may include more than one MV grid (i.e. more than one island). Therefore, the outputs will be organized according to the following structure:

- **Global results**, including global active and reactive power losses, power consumption and generation and maximum and minimum voltages and line currents.
- **Island results**, characterizing for each island the grid operating state (voltage, current, power consumption and generation). Identifies the grid elements of each island.
- **Grid elements**, namely, nodes, buses, lines, DER, grid interconnection, transformers and capacitor banks. As mentioned before, equipment has distinct references in order to facilitate their identification.
- **Controllable equipment**, according to the list defined in the inputs. The equipment identification, initial and final states are identified.

Table 5: OPF Outputs – Control variables

Control Variable	**Description**
Switching devices final state	Identifies the final state for the grid circuit-breakers and switches, including the switches to be operated in order to obtain the optimal solution. Only applicable if reconfiguration is considered.
Transformer tap changers state	Identifies the final state namely the respective tap position for the transformers of the MV grid under analysis.
Capacitor bank state	Identifies the final tap position for capacitor banks of the MV grid under analysis.
DER	Identifies the reference voltage or reactive power for the DER units connected to MV grid and participating in voltage regulation.

Table 6: OPF Outputs – Optimal power flow results

Optimal power flow results	**Description**
Grid voltage	Determines the initial and final voltage magnitudes and angles at all buses, and magnitude voltage deviation from nominal or from specified value for voltage controlled nodes in each bus.
Power Flows	Determines the active and reactive power flows and currents at all lines and transformers.
Power losses	Determines the active and reactive power losses at all lines and transformers for the initial and final operating points.
Consumption and Generation Power	Determines the real and reactive power generations and consumptions for the final point.
Maximum and minimum voltages	Identifies the maximum and minimum voltage magnitude deviations obtained for the distribution grid under study for the initial and final points.
Maximum Line Currents	Identifies the maximum line current deviation obtained for the initial and final points.

Table 7: OPF Outputs – Algorithm control

Algorithm information	**Description**
Error Flag	Identifies specific errors which might occur when running the OPF module (invalid inputs or algorithm parameters, error running the algorithm).
OPF information	Returns the number of iterations and the maximum error obtained for the real and reactive power mismatch.

4.1.1.4 OPF Component Algorithm

Based on the inputs described previously, the OPF algorithm will determine the optimal MV grid state considering the list of control variables to be used, namely: switching equipment available for reconfiguring the grid, transformer and capacitor bank taps' position and the active and reactive power generated by the DER units connected to the MV grid. The control variables to be used will depend on the OPF mode of operation selected.

The algorithm of the OPF module is represented in Figure 18 and is composed of eight main functions:

1. **Pre-Processing** – Based on the grid topology and controllable switches this function identifies the radial operation loops for reconfiguration purposes. MV grids operated in a meshed configuration are not considered. The initial state of the grid is stored for initializing the grid model and for comparison purposes.
2. **Search for optimal configuration** – Based on the radial loops identified previously, this function will change the state variable of the switches for each radial loop in order to achieve the optimal configuration. In case the OPF is performing in Mode 2, the list of faulty components will be used in order to isolate the faulted MV segment and/or the faulty grid equipment.
3. **Feasibility Evaluation** – The feasibility of each radial loop identified is evaluated through a power flow algorithm in order to verify if the power imported by the transmission system and provided by local generation is sufficient to supply the loads. This operation is done maintaining the radial topology of the grid.
4. **Fitness Calculus** – For each solution defined by the algorithm it will be attributed a score based on a fitness function defined according to the objective function.
5. **Performs power flow optimization (optional).** The module will perform the power flow optimization for each radial loop configuration found, considering the other state variables, such as: magnitude of node voltages, capacitors bank and transformers optimal tap positions. This optimization process searches for the optimal values considering the operation constraints of the distribution grid, so that the solution found is always feasible.
6. **Selects the optimal topology**, by selecting the grid configuration which minimizes the objective function selected according to a stop criterion. If more than one island is selected, the system will define the best solution which minimizes the total area of the grid considered.
7. **Stop Criterion Evaluation** – According to the stop criterion chose, evaluation of the value of the objective function;
8. **Results -** For the selected circuit, the component builds the *Result Structures Processes*. This is the final functional block and is responsible for the data exportation to the result structures and to rounding off the integer variables.

Every time the algorithm runs, it returns an integer stating the overall result (0 = success, >0 = errors have occurred).

The functions composing the component are specified in more detailed in the next sub-sections.

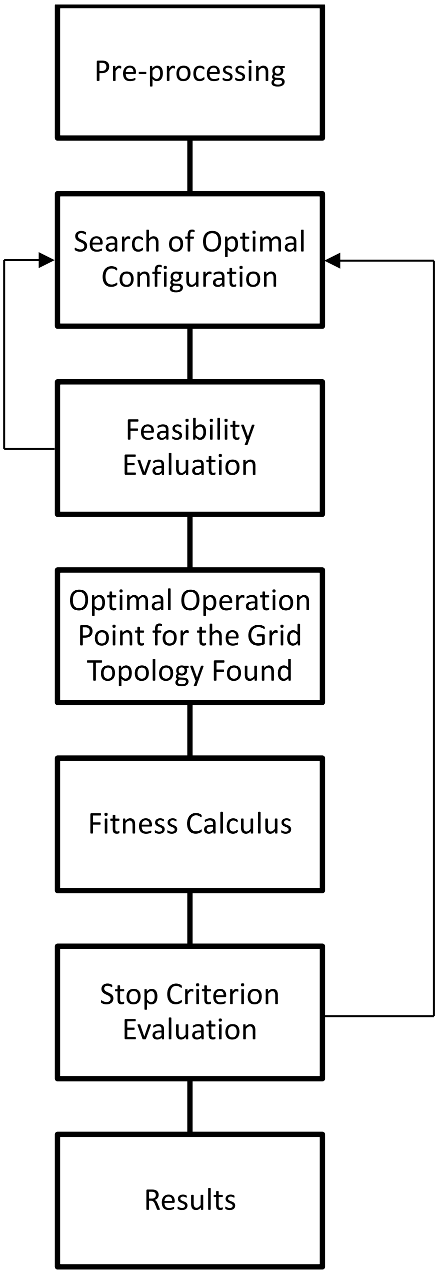


Figure 18: Process Diagram for OPF Application

4.1.1.4.1 Pre-Processing Processes

The OPF is prepared to run different studies over each grid model data structure. Every time the algorithm runs, the OPF application creates a dedicated result structure only for the grid area that was selected. The system may maintain different result structures and the related grid model data instance used as input for the OPF.

Based on the initial state of the grid topology of the grid, this process will also finds the grid loops in the grid in order to mark the switches forming the loop as frozen (not operable switches for reconfiguration purposes). If no open loops detected, return an error code corresponding to “no reconfiguration possible due to meshed grid”.

4.1.1.4.2 Search for Optimal Configuration

The search for Optimal Configuration changes the state variable of the switches of the distribution grid in order to achieve the optimal configuration, according to the fitness function considered. This operation is done maintaining the radial topology of the grid, where it was already radial, and is done by a metaheuristic process. The best solution is determined by a stochastic tournament based on the fitness value determined for each solution.

4.1.1.4.3 Feasibility Evaluation

The feasibility evaluation runs a power flow algorithm for the grid topology found in the previous step. The goal is to find out if all loads of the system are fed so that determining the feasibility of the grid configuration. If the optimal topology is unfeasible the process returns an error and the algorithm returns to the previous step.

4.1.1.4.4 Optimal Operation Point for the Grid Topology Found

The Optimal Operation Point for the Grid Topology Found has the objective of determining the optimal values for the rest of the state variables of the problem, like magnitude of node voltages capacitors bank and transformers optimal taps and others. This optimization process searches for the optimal values considering the operation constraints of the distribution grid, so that the solution found is always feasible.

4.1.1.4.5 Fitness Calculus

The fitness calculus is determined for each optimal configuration found considering the objective function selected. Two different objective functions can be selected:

1. minimize the sum of active power losses;

$$P_{losses} = \sum_j p_j \, , j = 1,2, \dots , n_{lines}$$

2. minimize the sum of active power not supplied and the active power losses for all system.

$$\sum_L PNS_k \text{ and } \quad P_{losses} = \sum_j p_j \, , j = 1,2, \dots , n_{lines}$$

4.1.1.4.6 Stop Criterion Evaluation

The stop criterion is based on the evolution of the fitness function value, by comparing the fitness value calculated in the previous step of the method in different iterations of the process. The number of iterations between the two iterations evaluated can be customized by the user.

4.1.1.4.7 Results

The outcome of the distribution optimal power flow process is exported to the application’s result structures. This process performs according to the description made in subsection 4.1.1.3, which is detailed in Table 5, Table 6 and Table 7.

4.1.2 Validation of Optimized Solutions

4.1.2.1 Functional Model

The VOS module determines and can implement automatically a valid reconfiguration sequence, based on the results provided by the OPF module. The general architecture of the VOS component is represented in Figure 19.

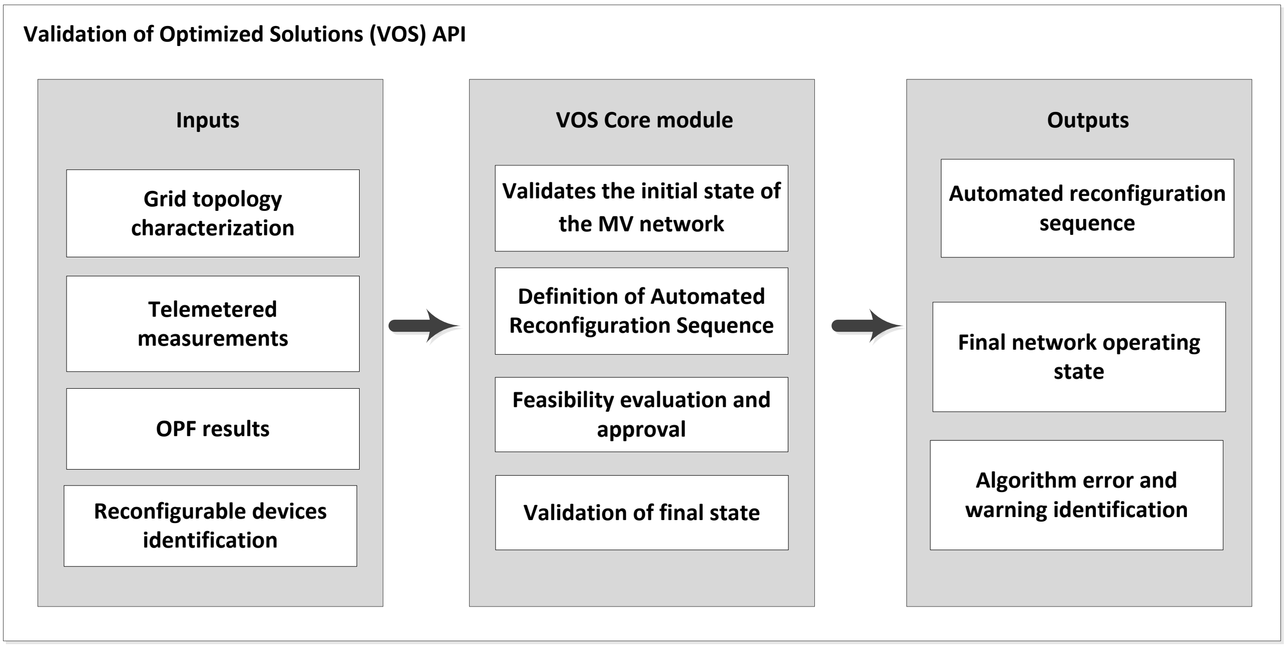


Figure 19: General architecture of the VOS component

The VOS is a complementary module the OPF component, sharing common functions such to the OPF algorithm. Therefore, it should be accessible to the user through the same graphical user interface (GUI) as the OPF, in order to enable the user to run the VOS module after obtaining a solution from the OPF module.

The VOS functions to be performed are:

- Preprocessing of topology information, telemetered measurements and event/alarms.
- Validation of OPF solution considering the current state of the grid.
- Identification of the grid island involved in the reconfiguration sequence.
- Identification of possible switching actions considering the equipment available.
- Identification of possible reconfiguration sequences.
- Selecting the valid switching action considering grid current and voltage limits.
- Providing a detailed description of the grid final state by quantities discriminated per phase;
- Enabling the implementation of the reconfiguration sequence.

The function related to the implementation of the reconfiguration sequence can be enabled/ disabled by the user.

All the parameters are provided by the caller and will not be requested by the VOS module. The caller is also responsible for the proper activation of the module and for the requirement of some results.

4.1.2.2 VOS inputs

The inputs of the VOS module are identified in Table 7 and can be divided in five main groups:

- **Grid topology characterization**, in order to build the initial grid topology and identify the feeders and transformers electric characteristics. The characterization of the grid topology and grid characteristics will be required in order to validate the initial state of the MV grid and to perform the power flow studies required to validate the automated reconfiguration sequence. The parameters of overcurrent protections of the substation MV feeders should also be known.
- **Telemetered measurements**, in order to characterize the grid operating state (e.g. power consumption and generation) and initialize the grid model (e.g. voltage magnitudes). Similarly to the OPF module, a synchronous set of data is required. Therefore, the measurements should be pre-processed by a distribution state estimator application. The values provided by the state estimator will also be used in order to compare the actual state of the grid with the initial and final grid state determined by the OPF module.
- **Alarms and events**, indicating possible faults, maintenance actions and other situations which invalidate the reconfiguration procedure or the participation of some equipment.
- **OPF results**, namely the initial and final state of the grid switches and circuit breakers and the optimal power flow results. Regarding the state of the grid switches it will be necessary to compare the actual state of the switches (provided by the telemetered measurements) with the initial conditions considered in the OPF results. Also, the global results such as total and island active power losses and power not supplied are required in order to validate the effectiveness of the implementation of the reconfiguration procedure. A data structure similar to the OPF output data structure will be adopted in order to facilitate the transfer of data between the modules (i.e. data is organized according to global, island, grid elements and controllable equipment results and data).
- **Identification of DER units**, regarding its point of connection to the MV grid considered. For each DER unit it should be identified the island, adjacent feeders and nodes to which it is connected. This will be important when reconfiguring feeders with DER units, in order to avoid the formation of unwanted islands during the restoration sequence.
- **Reconfigurable devices identification.** The switches and circuit breakers involved in the optimal grid configuration require a detailed characterization of its state, type, remote control capabilities and location. Table 8 summarizes the options of the input data structure of these devices.
- **Automation pre-defined sequences.** Identification of automation rules involved in the operation of one or more switching or sectionalizer equipment. This information should be updated when new equipment is added or with changes in the topology. The reconfiguration procedures will depend on the grid topology and in the type of remotely controlled switches available (circuit breakers and/or sectionalizers). Typically, the procedure starts by closing the open loop and then opening the normally closed device. However, additional switching actions and synchronization procedures may be required depending if the loop is connected to the same primary substation or interconnects two different substations.

Table 7: VOS module inputs

Input	**Description**	**Source**
Grid Topology	Includes the initial grid topology, and circuit-breakers and switching device status. It also includes the identification of the MV grid islands under study.	TLGMU
Electric characteristics of the grid elements	Includes feeders and transformer impedances	TLGMU

Telemetered measurements from distribution grid	Voltages, currents and power consumption	TLGMU (Primary Substation, MV and Secondary Substation sensors. Should be pre-processed by a state estimator module)
OPF results	Grid voltages, power flows, active power losses, maximum and minimum voltage and maximum line currents, total active power not supplied.	OPF module
Telemetered measurements from DER	Power injected/consumed by the DER units connected to MV grid.	TLGMU and DERMU (if considered) of DER connected at the MV level
Identification of DER units	Identification of the island, node and feeders to which each DER are connected.	TLGMU
Reconfigurable devices identification (switches and circuit breakers)	Characterization of its state, type, remote control capabilities and location	TLGMU

Table 8: VOS inputs – Reconfigurable devices identification

Device characteristic	Description
Device	Identification of the type of equipment: circuit breaker or switch
Actual state	Indicates if the device is open, closed or in other states (i.e. locked, state undefined)
OPF initial state	Indicates the initial state considered by the OPF module.
OPF final state	Indicates the final state determined by the OPF module.
Location	Identifies if the device is associated to a primary substation, secondary substation or connected to a feeder.
Control	Indicates if the device can be controlled locally or manually, on load manoeuvrable or not.

4.1.2.3 VOS outputs

The main output of the VOS application is the correct and optimized reconfiguration sequence, composed by a set of switching control signals organized sequentially in order to achieve the desired topology and meet the new operation objectives. The reconfiguration procedure may also require additional control actions such as: change of transformer and capacitor taps and/or intermediate set-points for DER (voltage, reactive and active power). In addition, the module will also provide additional information related to the grid operating state during and after the reconfiguration as well as the identification of possible errors which might occur when running the module. This information can be used by the distribution grid operator or by the other modules integrated at the TLGMU.

Table 9 indicates the VOS outputs which constitute the automated generated reconfiguration sequence. For each step of the procedure, the module identifies the grid area under study (i.e. island and substation(s) identification) and the switching devices state.

The results of the final power flow are also provided by the module as described in Table 10. The reconfiguration sequence will only be implemented if the grid security is maintained, namely voltage and line current limits. If not, a new solution should be found for the grid reconfiguration.

As described in Table 11, the algorithm will not run when the initial state error flag is active, meaning that the initial state of the grid does not correspond to the initial conditions of the OPF module or if any alarms related to the grid areas under study indicate that the grid conditions are not adequate to perform the reconfiguration. This error flag should also trigger a notification to the distribution grid operator.

Table 9: VOS Outputs – Automated Reconfiguration Sequence

Control Variable	**Description**
Total number of sequence steps	Indicates the number of steps involved in the reconfiguration procedure.
Island identification	Identifies the grid area involved in the reconfiguration *ith* step.
Substation identification	Identifies the substation(s) involved in the reconfiguration *ith* step.
Switching devices states	Control signal indicating the final state for the grid circuit-breakers or switches for the reconfiguration *ith* step. As discussed earlier, the devices require the identification of their location and options.
Transformer tap changers state	Identifies the final state namely the respective tap position for the transformers of the MV grid under analysis.
Capacitor bank state	Identifies the final tap position for capacitor banks of the MV grid under analysis.
DER	Identifies the reference voltage, active and reactive power for the DER units connected to MV grid and participating in voltage regulation.
Auxiliary control	Used only if necessary to lock the switching device state or enable/disable any other automation option for the reconfiguration *ith* step.

Table 10: VOS Outputs – Final grid operating state

Optimal power flow results	**Description**
Grid voltage	Determines the initial and final voltage magnitudes and angles at all buses, and magnitude voltage deviation from nominal or from specified value for voltage controlled nodes in each bus
Power Flows	Determines the active and reactive power flows and currents at all lines and transformers.
Power losses	Determines the active and reactive power losses at all lines and transformers for the initial and final operating points.
Maximum and minimum voltages	Identifies the maximum and minimum voltage magnitude deviations obtained for the distribution grid under study for the initial and final points.
Maximum Line Currents	Identifies the maximum line current deviation obtained for the initial and final points.

Total active power losses	Determines the total active power losses in the distribution grid area under study.
Total active power not supplied	Determines the total active power losses not supplied by comparing the initial power consumption to the final power consumption.
Deviation to optimal active power losses	Determines the deviation of the active power losses to the value defined by the OPF module
Deviation to optimal power not supplied	Determines the deviation of the power not supplied to the value defined by the OPF module.

Table 11: VOS Outputs – Errors and warnings

Algorithm information	**Description**
Initial state error	Returns an error when the current grid state does not correspond to the initial conditions considered by the OPF module (e.g. initial state of grid switches). It also returns an error if the module detects any alarms related to the availability of the grid (e.g. specific grid areas under fault state or maintenance actions).
Sequence error	Returns an error when the algorithm fails to define a valid reconfiguration sequence, which should ensure a secure state of the grid (i.e. voltage and current within limits).
OPF deviation warning	Returns a warning when the final power flow used to validate the reconfiguration sequence does not meet the objective active power losses or power not supplied.

4.1.2.4 VOS Component Algorithm

Five main functions constitute the core module of the VOS component, namely:

- **Preprocessing Processes**, building the input and results structure required for the VOS internal functions.
- **Validation of the distribution grid initial state**, which checks if the grid can be reconfigured. For example, the VOS algorithm will only proceed with the grid configuration if current power losses are within a pre-defined dead-band, defined according to the OPF module. The objective values of the goal active power losses and/or active power not supplied are saved for validating the reconfiguration procedure. If DER units are considered the algorithm should also save the connection node and adjacent feeders where the units are connected.
- **Definition of the automated reconfiguration sequence,** which defines the switching actions required to reconfigure the system to match the optimal grid topology. This analysis requires the knowledge of DSO automation procedures considering the switching equipment installed and the feeder topology of the grid under study. Reconfiguring the MV grid may include switching actions at the substation, feeder and even at the HV grid.
- **Validation of the automated reconfiguration sequence and approval**. Intermediate analysis of the grid operation conditions may be required in order to avoid possible congestion problems during the reconfiguration steps. A power flow function will be called in order to validate the intermediate and final steps of the reconfiguration procedure.

- **Running the automated reconfiguration sequence**. It is responsible for generating the switching control signals according to the identifiers of the grid switching equipment and sends it through the TLGMU, here seen as a SCADA system.
- **Validation of the final state of the grid.** After finishing the reconfiguration sequence, this function will confirm the final state of all switching devices involved in the reconfiguration process. Moreover, it will run a power flow in order to confirm that the OPF objectives – i.e. active power losses and/or power not supplied – were met and that all the operational constraints are maintained within limits, namely voltage and current limits, interconnection capacity.

The VOS algorithm is represented in Figure 20. The functions composing the VOS component are specified in more detailed in the next sub-sections.

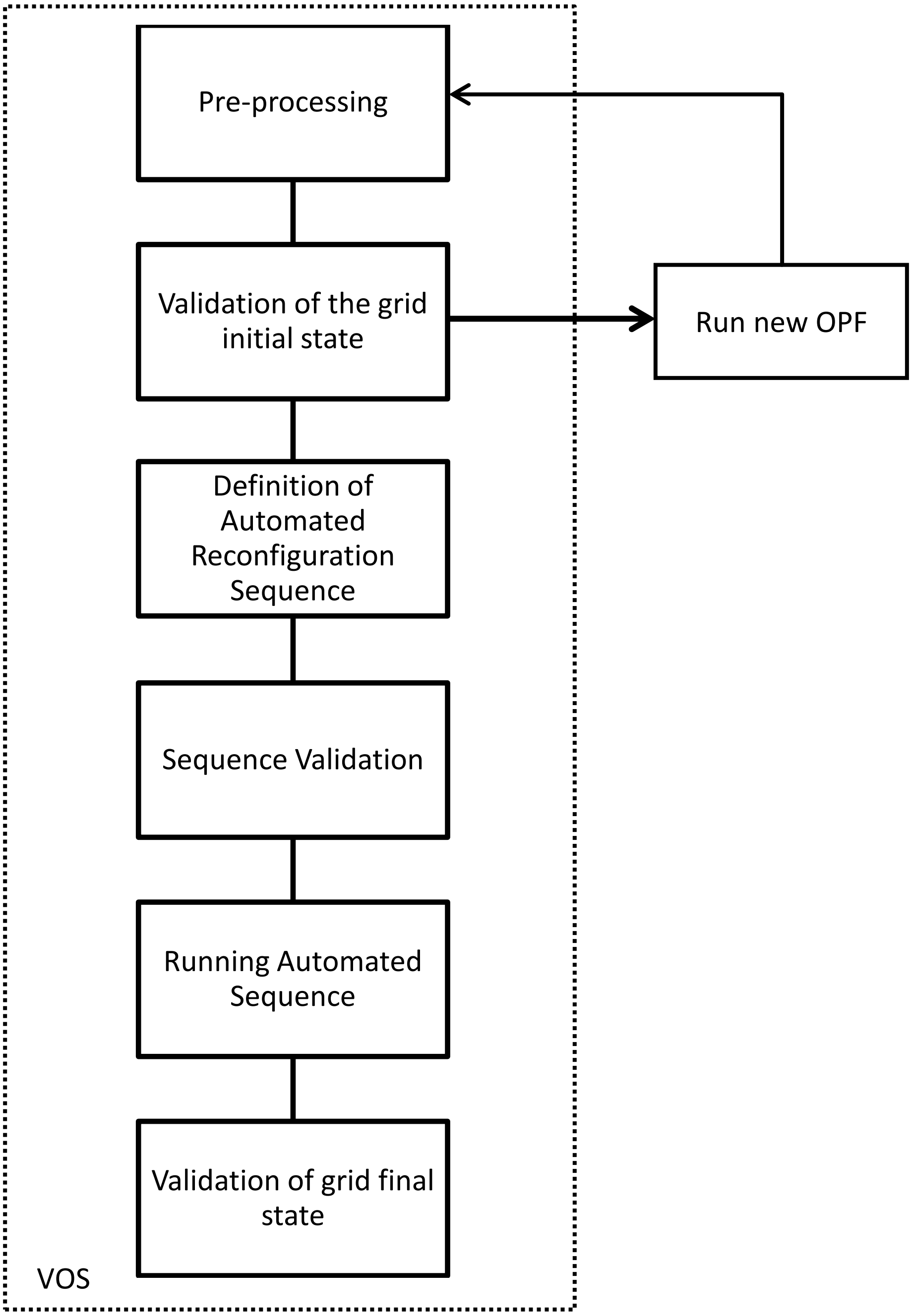


Figure 20: Process Diagram for VOS Application

4.1.2.4.1 Pre-processing Processes

The VOS module requires information from the TLGMU – e.g. a SCADA/DMS system – and from OPF in order to:

- Characterize actual the grid state, topology and other situations which are related to grid reconfiguration.
- Characterize the final state of the grid after reconfiguration.
- Identify the area of the grid which will be involved and affected by the reconfiguration procedure.
- Identify situations (such as faults and maintenance actions) which may invalidate the reconfiguration procedure or the operation of one or more switching devices.

This process contains three main functions:

- Building grid data structure function for creating the data structures for each instance containing the grid topological information, telemetered measurements, event/alarms and switching equipment state and automation rules required for the internal functions. It will also build a dedicated result structure for the grid area identified.
- Create result structure in order to accommodate de equipment under analysis.
- Function for defining the grid islands involved in the reconfiguration procedure. This will include the identification of the all the switching equipment which can possible be involved in the grid reconfiguration procedure.

4.1.2.4.2 Validation grid state

This process will be responsible for checking if it is possible to implement the new configuration, namely if no incoherencies are found regarding the grid state for which the optimal reconfiguration was defined by the OPF module or if there is any alarm

In a first stage the function checks with the TLGMU’s SCADA system if there are any active alarms which compromise the successful reconfiguration of the system (e.g. fault alarms at feeders and substations, maintenance actions locking switches’ operation).

Then, it will check the operating conditions of the grid in order to verify if the OPF reconfiguration scheme is still valid. In order to do that, a power flow study should be performed in order to validate OPF results. The values of the OPF objective function namely active power losses and/or active power not supplied are saved for validating the reconfiguration procedure. If DER units are considered the algorithm should also save the connection node and adjacent feeders where the units are connected.

4.1.2.4.3 Definition of Automated Reconfiguration Sequence

The definition of the reconfiguration sequence searches for the switching sequence which enables the implementation of the optimal topology of the grid and is done by a metaheuristic process.

First, the process will define a set of switching actions required to reconfigure the system to match the optimal grid topology. This analysis requires the knowledge of DSO automation procedures considering the switching equipment installed and the feeder topology of the grid under study. Reconfiguring the MV grid may include switching actions at the substation, feeder and even at the HV grid.

4.1.2.4.4 Validation of the automated reconfiguration sequence and approval

In order to ensure that the grid operation is safe during the reconfiguration procedure, an intermediate analysis of the grid operation conditions will be performed by running a power flow in order to evaluate grid voltage and currents. This function will return the estimated grid conditions and a return an error/warning if one of the following conditions is verified:

- Grid voltages outside admissible limits
- Feeder congestions
- Feeder current will lead to inadequacy of protection systems.

The interaction with the distribution grid operator may be required in order to validate the final procedure.

4.1.2.4.5 Running the automated reconfiguration sequence

It is responsible for generating the switching control signals according to the identifiers of the grid switching equipment and sends it through the TLGMU's SCADA system. For each control signal the algorithm will wait for a confirmation of the final state of the device. If for some reason the switching action fails, the algorithm returns an error and tries to return to the initial grid configuration.

4.1.2.4.6 Validation of final state

After finishing the reconfiguration sequence, this function will confirm the final state of all switching devices involved in the reconfiguration process. It will run a power flow in order to confirm that the OPF objectives (i.e. active power losses and/or power not supplied) were met and that all the operational constraints namely: voltage and current limits, interconnection capacity are maintained within limits.

4.1.3 Fault Detection, Isolation and Restoration (FDIR)

As described in Section 3.1.2.1, the OPF component provides a new grid operating topology state, as a result of grid input data, coping with specific cost function criteria.

When performing in Mode 4, the OPF component aims at finding the best grid topology configuration that minimizes the power not supplied after fault isolation. Therefore, FDIR embeds the outcome of OPF – in Mode 4. Thus, fault isolation and grid service restoration is performed by FDIR, upon fault detection and location.

4.1.3.1 Functional Model

The FDIR module monitors the MV grid in order to identify and locate MV faults and help restore service to the unaffected segments of the grid.

This section details the fault location function of the FDIR module. As described previously, the fault isolation and grid service restoration is calculated by the OPF. Details of the restoration algorithm, inputs and outputs are described in section 4.1.1.

The structures to be used by the FDIR module, for maintaining input data, output data and internal results will be shared by the whole set of function. All the parameters are provided by the caller by its own initiative and not requested by the FDIR module. The caller (DSO) is also responsible for the proper activation of the module.The user is also responsible to indicate the circuit breaker tripped due to the fault. In case more than one circuit breaker trips, the user is responsible for giving as an input to the module only the reference to the most hierarchically important breaker. The circuit breaker at a substation is, for example, hierarchically more important than the circuit breaker on a capacitor bank located in the sub-grid below it.

Regarding MV grid automation, Table 12 summarizes the type of equipment which can be considered in this module. If the sub-grid under study is equipped with reclosers, it is necessary to consider that although a fault exists, the final state of the breaker may be “closed”, due to the action of the recloser. The information on the circuit breaker to be used as input for the module should then be gathered in the following way: a) either the information on the fact that the circuit breaker experienced a reclosure cycle is available, and therefore its identification, or b) the information on the fact that one of the sub-grid reclosers has changed state must be used by the user to determine the circuit breaker in question.

Table 12: MV grid protection, control and automation characterization

Location	Device	Protection	Automatism	Remote control	Remote measurements/ fault current indicator
Primary substation	Circuit breaker	IED installed in feeder Functions: Overcurrent, High impedance fault detection, Voltage detection, Broken conductor detection	Automatic reclosing (typically composed by 1 fast cycle+ 2 slow cycles)	Yes	Can provide the devices status and fault current measurement
MV feeders	Recloser (Sectionalizer/ switch mode)	Typically designed to break load current and no fault current	Automatic reclosing based on VT automatism	Yes	Can provide the devices status

	Recloser (Sectionalizer/ switch mode)	Designed to break fault current	Automatic reclosing based on fault detection and VT automatism	Yes	Can provide the devices status and possibly fault current indication, measurement and direction. Possible chronological event history.
	Recloser (circuit breaker mode)	Designed to break fault current	Automatic reclosing similar to primary substation	Yes	Can provide the devices status and possibly fault current indication, measurement and direction. Possible chronological event history.
	MV fault current indicator	No	No	No	Triggered when fault current is detected

4.1.3.2 FDIR inputs

The key inputs of the FDIR module are related to the MV grid topology and state of the sensors and actuators installed in the primary substation and connected downstream to the 1MV feeders. However, additional information can also be provided by the different hierarchical levels of the e-balance system architecture. The inputs of the module are detailed in Table 13 and will be organized considering the topology of the MV grid, meaning that to each MV feeder it should be associated the respective line segments, sensors and actuators data, as shown in Figure 21.

Table 13: FDIR module inputs

Input	Description	Source
Grid Topology	Includes the grid topology, and circuit-breakers and switching device status, after fault and reclosing automatisms have finished. The data is organized according to the substation MV feeders.	TLGMU, MVGMU (at the Batalha demonstrator)
Electric characteristics of the grid elements	Includes MV feeders impedances	TLGMU
Reconfigurable devices identification (switches and circuit breakers)	Characterization of its state, type, remote control capabilities, automation functions and location	TLGMU, MVGMU (at the Batalha demonstrator)
Telemetered measurements from MV distribution grid	Voltages and fault currents	(Primary Substation, MV feeders and Secondary Substation sensors)
Identification of DER units	Identification of the island, node and feeders to which each DER are connected.	TLGMU, MVGMU (at the Batalha demonstrator)

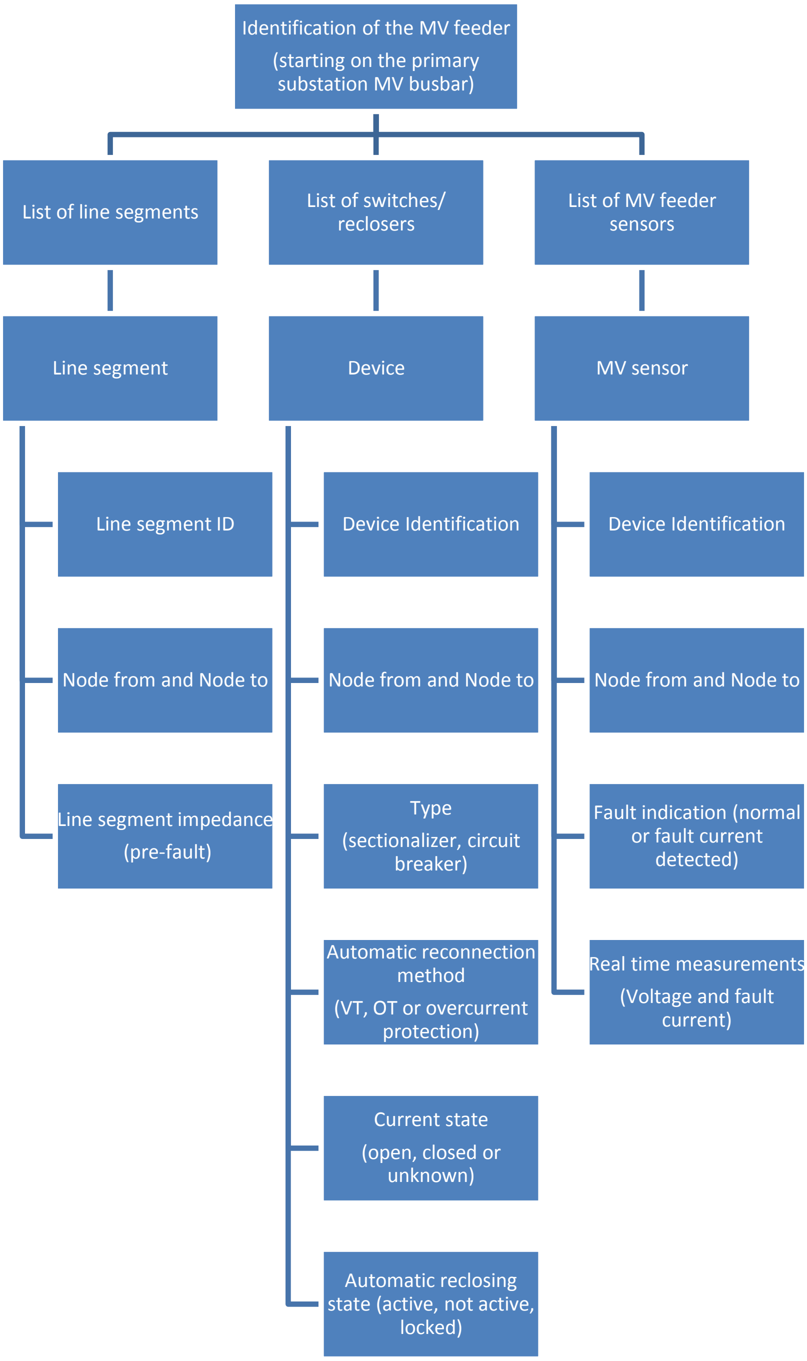


Figure 21: Structure of FDIR input data

4.1.3.3 FDIR outputs

As outputs the FDIR module will return a list of the MV line segments where the fault is more likely to have occurred. If the inputs include electrical information an estimated distance will also be provided. Geographical information of the most probable locations can also be provided in order to support fault identification and confirmation in the field. Moreover and as described in Section 3.1.2.1, the FDIR component embeds the OPF component thus, returning the list of the MV switching orders suitable to isolate the fault or faults, while suggesting the best topology minimizing the energy not supplied downstream the faulty area. Upstream the faulty area, the service reposition is performed directly, yet, assuring that no overload of transformers or of equipment occur. Moreover, the algorithm also assures that no overcurrent occurs over the MV grid branches, nor overvoltage occurs over the MV grid nodes.

Additionally, the module also includes control flags indicating the success or errors of the algorithm.

4.1.3.4 FDIR Component Algorithm

The algorithm of the FDIR application serving the goal of fault detection is represented in Figure 22. The next subsections describe each step in more detail. The role of OPF performing in Mode 4 – embedded in FDIR component – was described in Section 4.1.1.

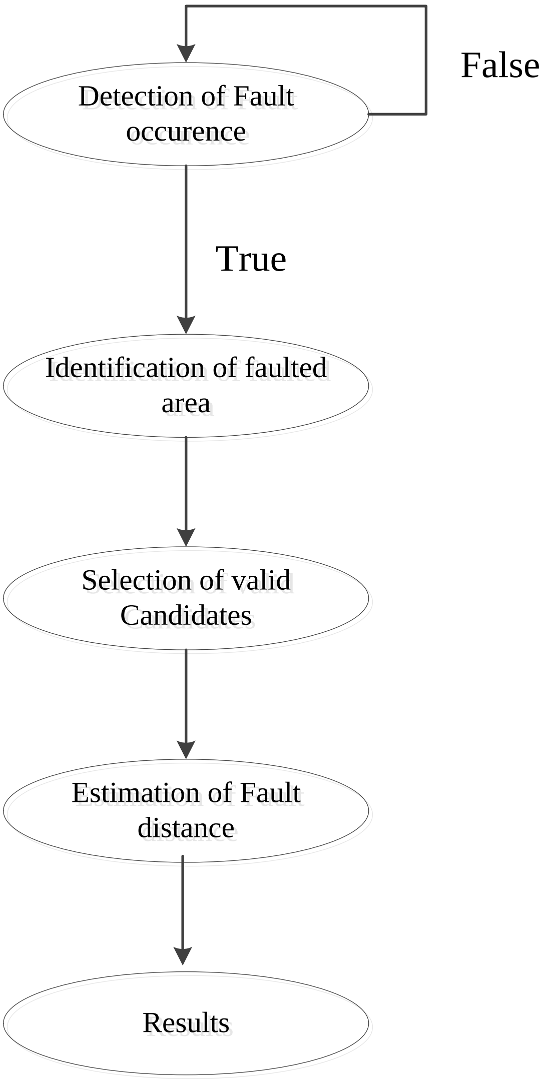


Figure 22: Process Diagram for the FDIR’s fault location

4.1.3.4.1 Detection of fault occurrences

This process is responsible for triggering the fault location process. This function should run periodically, searching for changes in devices status or be triggered by the MVGMU when an alarm is generated involving the MV substation and feeders’ actuators. The module should also differentiate changes in the devices status due to faults occurring downstream from MV grid reconfiguration procedures conducted under normal operating conditions. In order to do that, the MVGMU should receive from the distribution grid operator information related to optimal reconfiguration procedures, such as the ones resulting from the OPF and VOS modules. However, the algorithm should compare this information to possible fault alarms, since faults can also occur as a consequence of reconfiguration procedures. The information from MV fault current indicators will provide key information in order to correctly identify the occurrence of a fault.

4.1.3.4.2 Identification of faulted area

The identification of faulted area function identifies the possible faulted line segments. First, an algorithm compares the grid pre-fault state to the post-disturbance state and identifies the line segments that were isolated starting by the farthest node from the substation. This function builds an array of the line segments that are likely candidates to be the fault location, generating an initial solution to the problem. For the line segment identified, the algorithm finds which terminal of a switching device is farthest from a bus-bar. The “farthest” criterion is obtained by the number of equipment present between the switching device terminal until the bus-bar. As results an integer is returned stating the overall result (0 = success, >0 = errors have occurred).

4.1.3.4.3 Isolation and restoration

Please consult Section 4.1.1, specifically where OPF performing in Mode 4 is described.

4.1.3.4.4 Selection of Valid Fault Candidates

This process will verify the initial identification of affected line segments with the following information:

- Switching equipment automatisms and MV voltage fault indicators. When reclosers are installed in MV feeders, they usually incorporate a reclosing automatism which is coordinated with substation reclosers and other devices connected in the feeder. If such rules are known it is possible to eliminate some of the healthy feeders which were also isolated. If the algorithm starts by the end of the feeder, the fault will be located in the first line segment(s) where a fault indicator was triggered.
- Fault current measured at the circuit breakers or advanced reclosers to estimate fault distance.
- Fault current indicators

4.1.3.4.5 Estimation of fault distance (optional depending on the availability of information)

The module uses the fault current measured at the circuit breakers or reclosers to make an estimate of the interval between a minimum and a maximum fault distance. The fault current data might be considered to be unreliable. If so, a given percentage is attributed in order to increase the minimum and maximum fault distance considered, consequently increasing the number of possible line segments within the faulted area. A top-down approach is then followed (starting at the open circuit breaker) until a non-candidate line segment is found.

Fault impedance estimation algorithm should take into consideration the errors caused by the connection of distributed generation or loads connected along the feeder. Depending on the error obtained from the distance estimation, this may help refining the fault zone identification, reducing the list of possible line segments affected by the fault. If this type of data is available it can also help to produce an accurate estimate of the fault location. The line segment candidates list identified in prior functions will be considered and the final possibility that the fault is located in each one of them is calculated.

4.1.3.4.6 Building Results

This process will build the results structure with the outputs of the FDIR algorithm, namely:

- list of line segments with fault possibility
- list of equipment between circuit breaker and the line segments with fault possibility
- list of equipment in the fault zone
- List of switching orders to isolate fault

- List of switching orders to restore service upon fault occurrence

4.1.4 DER Power Flows

4.1.4.1 Functional Model

The main objective of the DERPF component is to improve the monitoring capability of distribution grids, by providing a real-time characterization of the DER connected to the distribution system, regarding their power generation or consumption, maximum available capacity and availability to participate in grid supporting strategies. Additionally, that characterization also stores the information in order to build a local historical database. This information is useful for the NPF application, running at the LVGMU.

The module is meant to incorporate four types of information:

- **Identification and characterization of DER devices connected downstream**. Includes the bus where the units are connected, the type of DER device (i.e. storage, DG, CHP or EV) and their technical limits.
- **Telemetered values**, such as active and reactive power flow. Additionally voltage and current magnitude may also be provided. If available logical information related to the status of DER can also be included.
- **Load/Generation day, week and monthly power and energy curves** in order to build the historical database. Advanced metering systems are usually capable of determining local power generation/consumption curves. If such functionality is available the DERPF module will then have to determine the aggregated power and energy curves.

As outputs this application provides the following information:

- (Quasi) real-time active and reactive power flow (i.e. consumption and generation) in each bus of the grid, aggregated by sub-grid, feeder and/or by DER technology or type.
- Active and reactive power deviation regarding historical information.
- Deviation to maximum admissible power in the grid interconnection to the upstream system, in a bus and/or feeder.
- Aggregated power and energy curves to be included in the historical database and to send to the upper control levels.

The telemetered values of active and reactive power, as well as the power and energy curves aggregated at the secondary substation level of DER units connected at the MV and LV grid, will be inputs of other grid applications namely: the OPF, FDIR and LV NPF.

In the case of the LV DER units, where only historical data is available, the LV NPF application can be used in order to estimate the actual active and reactive power injected by the DER unit.

4.1.4.2 DERPF inputs

The inputs of the DERPF component are based on telemetered values from DER units. If such data is missing the LV NPF results will be considered instead. DER telemetered data can be provided by two sources:

- Directly from DER devices connected at the LV and MV levels. It is assumed that the DER devices connected to LV and MV grids are also equipped with advanced metering equipment, ensuring the measurement of power, voltage and currents.
- Through CMU interfacing – and managing – the home DER devices with the distribution grid. Telemetered data can be provided by the respective smart meter.
- From the LV DERMU, providing to the MV DERMU aggregated data of the LV DER devices.

Table 14 summarizes the inputs of the DERPF application. The characterization of DER devices are also required due to their distinct operation principles and technical restrictions. Table 15 summarizes the characteristics, which can be provided considering DER technology. In some cases, the installations may incorporate more than one technology (e.g. distributed generation and storage). In this case, if individual information is not available, they are classified as combined DER units. The total power injected/consumed by the combined unit is considered.

Table 14: DERPF inputs

Input	**Description**	**Source**
DER node identification	List of the nodes where DER is connected.	Topology processor
DER output	Power consumption or absorption from distributed energy resources per bus.	Telemetered values /State Estimator module (LVGMU/NPF)
Grid voltage	Voltage magnitudes in the DER nodes.	Telemetered values / State Estimator module (LVGMU/NPF)

Table 15: DERPF inputs – characterization of devices and operational data

Input	**Description**
DER node identification	Nodes where DER is connected
DER status	Connected or disconnected
DER technology	Three types of DER can be considered [1]: - Distributed Generation: renewable based (wind and solar), low carbon technologies (micro-turbines and fuel cells), synchronous generators, asynchronous generator. - Stationary Storage: battery, flywheel, supercapacitor, among other - Electric Vehicles charging infrastructure When more than one unit are connected to the same installation without individual metering, the unit will be classified as Combined DER.
Power limits	Maximum and minimum power capacity. In storage case it should be provided discharging and charging power limits.
Remote control availability	Some units may only provide remote metering. Others may allow remote control (connect/disconnecting signals or power control signals)
Grid supporting services	DER can participate in one or more services (e.g. voltage support, congestion management, demand side management, among others)

4.1.4.3 DERPF outputs

As outputs the module will provide two main types of information:

- Synchronous DER power flow information and analysis, providing (quasi) real-time information and analysing it considering historical data and grid technical limits.
- DER historical database and analysis
- Warning and failure database, providing alarms capable to trigger local intelligence applications or notify higher control levels.

The general data structure of the module DER power flow information and analysis is detailed in Table 16.

As referred in previous section the DERPF module will also provide a detailed historic of DER power flows and events. The module will provide pre-configured power curves and energy considering the DER technologies connected to the distribution grid under analysis, aggregated by feeder or by substation. This data will then be sent to the upstream control levels.

The DERPF module integrated at the MV level will consider the secondary substation as an aggregated DER unit, which has the ability to change its power flow with the grid based on the availability to participate in grid services. Aggregated data by DER technology can also be used to correctly characterize DER at the MV distribution level.

Table 16: DERPF outputs – DER power flow information

Outputs	**Description**
DER power flow	Total active and reactive power injection/consumption per bus, feeder and sub-grid interconnection point. The results can be divided according to the DER types, namely: distributed generation, storage and EV or combined DER.
DER energy flow	Total energy produced/consumed by DER aggregated by unit, bus, feeder and sub-grid interconnection point. The results should be divided according to the DER types, namely: distributed generation, storage and EV or combined DER.
Power deviation	Active and reactive power deviation yield compared to historical database. Determined for each node, feeder and point of interconnection, considering the different DER technology type connected.
Voltage deviation	Determines for each node the voltage deviation to the nominal value.
Maximum and minimum power generation	Identifies the device/node/feeder with maximum power generation from DG and storage in discharging mode.
Maximum and minimum voltage	Identifies the node/feeder with maximum and minimum voltage measured.
Availability of DER to participate in grid services	Determines the power flexibility of the different types of DER devices in order to participate in grid supporting services. It can be divided in availability to increase or decrease power generation/consumption.
Number of DER devices participating in grid supporting services	Identifies the number of DER devices per type which are currently participating in grid supporting services. Should be divided by each type of service being provided.

Number of DER devices disconnected	Identifies the number of DER devices which are disconnected (according to DER technology type).
Number of DER devices under failure	Identifies the number of DER devices which state is not known, or that have disconnected due to the action of protection systems or communication failures (according to DER technology type).

4.1.4.4 DERPF functions

The DERPF component incorporates the following groups of functions:

- (**Quasi) real-time analysis of DER data**, which are responsible for processing (quasi) real-time data of DER devices and determining the aggregated values for the grid under study and for each feeder.
- **Build historical database**, based on the real-time data provided. It may also include some additional functions to build the aggregated power curves for different periods of time (day, week, month and year).
- **Event management**. This group of functions can generate specific notifications to the GMU and upstream control levels based on events (i.e. alarms) and based on comparison of (quasi) real-time data against the historical database.
- **Interface with grid supporting services application,** determining the availability of DER to participate change their behaviour and identifying the units which are available or currently participating in such services.

Regarding the first group of functions, the results will be organized hierarchically considering each DER device, feeder where they are connected and ultimately the aggregated analysis at the substation level.

The functions related to the DER historical database main objective are to build a database of the DER telemetered values and related events. From the DSO point of view, it is not relevant to store the data of a particular DER device. Instead aggregated data at the feeder and substation level differentiated by technology type can be more relevant. Two distinct basic databases can be derived:

- DER active and reactive power, energy and voltage analysis, which stores the information determined at the feeder and substation level.
- Event and alarm database, which stores the alarms generated by the event management.

A second level function will be responsible for building the aggregated power curves. Pre-configuration of such curves should be available considering the following parameters:

- Period under analysis (day, week, month and year)
- DER technology
- Location: feeder or point of interconnection

A function will also determine the total DER energy (generated and consumed) according to the same parameters referred above.

4.1.5 LV Neighbourhood Power Flow

4.1.5.1 Functional Model

The LV Neighbourhood Power Flow – NPF – component is responsible for determining the LV grid state – i.e. voltages, currents and power flows – considering the errors affecting real-time measurements and historical data. The NPF module consists of a three-phase unbalanced state estimator designed to provide a complete voltage solution in terms of magnitudes. In addition, it can estimate values for the injected active power in a given bus. It runs on the LVGMU.

The proposed algorithm is based on the use of artificial intelligence, namely in the concept of AutoEncoders (AE), which uses both historical and real-time data to ensure the observability of the system under study. The main advantage of this approach is that the application doesn't require the information about some grid parameters – namely, branch technical characteristics – as well as synchronous measurements of active and reactive power in all grid nodes – as in the case of a conventional power flow application. The minimum necessary requirements for running it and provide the correspondent solution are, at least, historical data samples for a period of one week regarding the variables to be estimated and one real time measurement. However, its accuracy may be compromised when considered a reduced number of telemetry equipment – higher redundancy on the set of real time measurements and a larger set of historical data available will for sure decrease the state estimation error. The NPF can be applied to a sub-grid of a bigger system, as long as there is enough information. To call a NPF for a specific LV grid, the caller must provide a list of equipment that is included in the subset. The main functions related to the LV NPF are summarized below:

- Pre-process of the input data to build the AE architecture in terms of quantity of historical data and of real-time measurements to be used, as well as of variables to be estimated – running initially and for each change in measurements set;
- Identification of observable and unobservable parts of the grid based on minimum needed measurements; if the grid is unobservable, the module returns to the user this information;
- Training of the AutoEncoders (AE) – running weekly or more frequently when topology changes or the AE architecture is re-defined;
- Estimation of bus voltage magnitudes, active power bus injections and MV/LV transformer tap settings (if applicable) based on available data for the grid (telemetered data); this only includes the initially classified observable areas;
- If the number of available measurements is very high, there is the possibility of identifying anomalous measurements in the grid under analysis, whenever they exist.

4.1.5.2 NPF inputs

Input data of the NPF module are detailed in Table 17 and can be divided in six groups:

- **Telemetered measurements**, from measuring devices spread all over the grid;
- **Virtual measurements**, regarding buses where power injections – and consumptions – are null;
- **Pseudo measurements**, consisting of historical data for the training of the algorithm.
- **Grid topology data,** in order to model the grid under study.
- **Manually entered information used to update the grid model,** namely the status of circuit breakers and disconnect switches, position of transformer taps and of capacitor banks taps.
- **Manually specified information or results from other modules**, such as:
  - Active and reactive branch power flows
  - Branch current flows
  - Active and reactive loads and generations
  - Active and reactive generation or consumption by DER
  - Bus voltage magnitudes

Table 17: NPF module inputs

Input	Description	Source
Grid Topology	Includes the identification of the loads and generation connection to each bus (including phase of connection) as well as the buses relative position.	LVGMU may be set locally or fed from TLGMU
Telemetered measurements from distribution grid	Voltage magnitudes, active and reactive branch power flows, branch current flows, active and reactive loads and DER power generation.	Smart meters, DERMU, LVGMU LV sensors and actuators and secondary substation
Transformer taps	Tap position	LVGMU
Historical database	Includes measurements from all the buses of the grid, considering load and DER units.	Smart meters, DERMU, LVGMU LV sensors and actuators and secondary substation

4.1.5.3 NPF outputs

Table 18 summarizes the possible outputs of the NPF module. It includes the grid voltage, currents and power flows as well as relevant information for evaluating the data provided by the real-time measurements and pseudo-measurements, as well as the accuracy of the state estimation results. The outputs of the module can be used in the next cycle of the module as pseudo-measurements. The outputs of the NPF module will largely depend on the input information available.

The presence of inconsistencies is indicated and descriptive information about the inconsistency is provided. When possible, this information includes the data value that most likely is erroneous.

Table 18: NPF Outputs – Final grid operating state

NPF results	Description
Grid voltage	Voltage magnitudes and phase angles of the grid model buses at each phase, including at the open end of open-ended branches.
Active power injection	Bus active and reactive power injections per phase.
Power Flows	Determines the active and reactive power flows per phase in all lines and transformers.
Power Losses	Determines active and reactive power losses.
Currents	Magnitude and phase of line and transformer currents at each phase.
DER output	Power consumption or absorption from distributed energy resources.
Inputs	Set of input data (telemetered or pseudo-measurements) used.
Residuals	Residuals (estimated-available input value) of all used input data.
Inconsistencies identified	The presence of inconsistencies is indicated and descriptive information about the inconsistency is provided. When possible, this information includes the data value that most likely is erroneous.

4.1.5.4 NPF Component Algorithm

The NPF algorithm is represented in Figure 23 and is composed of six functional blocks:

- Topological Analysis – The application starts by analysing the topology of the grid, crossing this information with measurements. This analysis can be performed using a set of simple heuristic rules. At the end, the function should provide the topology of the grid to be analysed by selecting, from this macro point of view, a set of coherent data.
- Observability Analysis – In this step, the application selects a set of data so that the grid under analysis is observable. The data to be used can be telemetered measurements and, if necessary, pseudo-measurements.
- Training Process – At this stage, the data necessary data is obtained from the historical database. Also useful information about the real-time measurements and about the state variables that will be later used when running the algorithm is saved. Based on the set of historical data selected, the training process is then run through a Resilient Back Propagation algorithm - using Minimum square error criterion. The output of this process is an AE object properly trained for a given topology;
- State Estimation process – Using the already trained AE and telemetered data available for the grid, a constrained search approach is applied for finding the missing grid values. In the context of this state estimation problem, the missing values are necessarily the state variables to be estimated – magnitude voltage values and active power injections as well as MV/LV transformer tap settings – if applicable. Afterwards, an optimization process reconstructs the state variables through the minimization of the error between all the inputs and outputs of the AE. An Evolutionary Particle Swarm Optimization – EPSO – was the optimization algorithm chosen for reconstructing the missing state variables.
- Output Data Analysis – Once the running process finishes, the application computes the residuals – output-input difference – of all measurements and convergence errors – output-input difference – of each estimated variable. These values are then compared with pre-defined threshold and measurements having relative larger residuals are marked.
- Building Results – In this module all grid variables, even if not estimated, are computed using the estimated state vector.

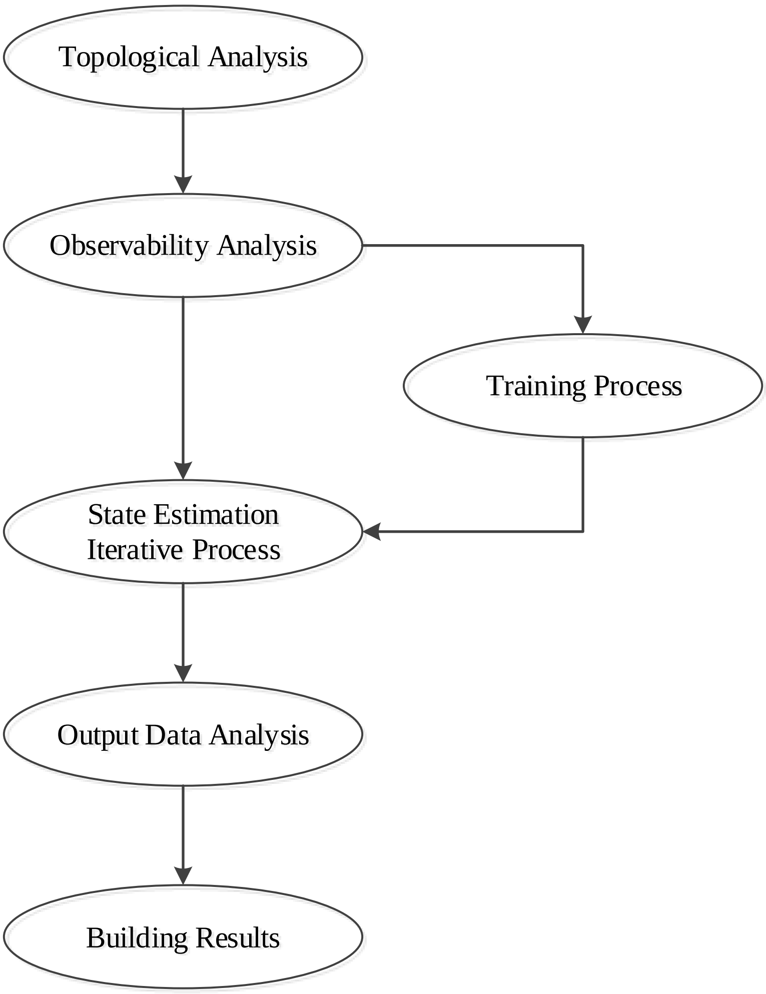


Figure 23: Process Diagram for the NPF Application

4.1.5.4.1 Topological Analysis

The application starts by analysing the topology of the grid, while crossing this information with measurements. At the end, the aiming is to fixing the topology of the grid, not in the sense of knowing all the branch connections between buses – something that could be unfeasible in the large majority of the grids due to the lack of information –, but in the sense of knowing which buses belong to each feeder or at least to the correspondent MV/LV substation – in a worst case. This task is very important since changes in topology usually imply either running a new training process – for the new topology – or selecting an appropriated AE specific for the new topology, in such case, whenever there is already in the process memory an AE trained for historical data related to that topology;

4.1.5.4.2 Observability Analysis

In this step, the application selects a set of data so that the grid under analysis is observable. For ensuring observability, it is mandatory the existence of at least historical data samples for one week regarding the variables to be estimated and one measurement available in real time. The set of measurements are selected in order to ensure that the grid to be analysed is observable. The data can be of different types:

- telemetered data;
- information provided by the historical database;
- manually introduced measurements.

4.1.5.4.3 Training Process

An effective state estimation using AE requires inevitably a large historical database, which needs to contain data about the variables that are passed to the AE – missing signals and measurements recorded. This is crucial for a successful and effective training process, since it is what enables the AE to learn the necessary patterns/correlations between the electrical variables of a given grid.

The flowchart presented in Figure 24 presents the main steps required to properly train an AE.

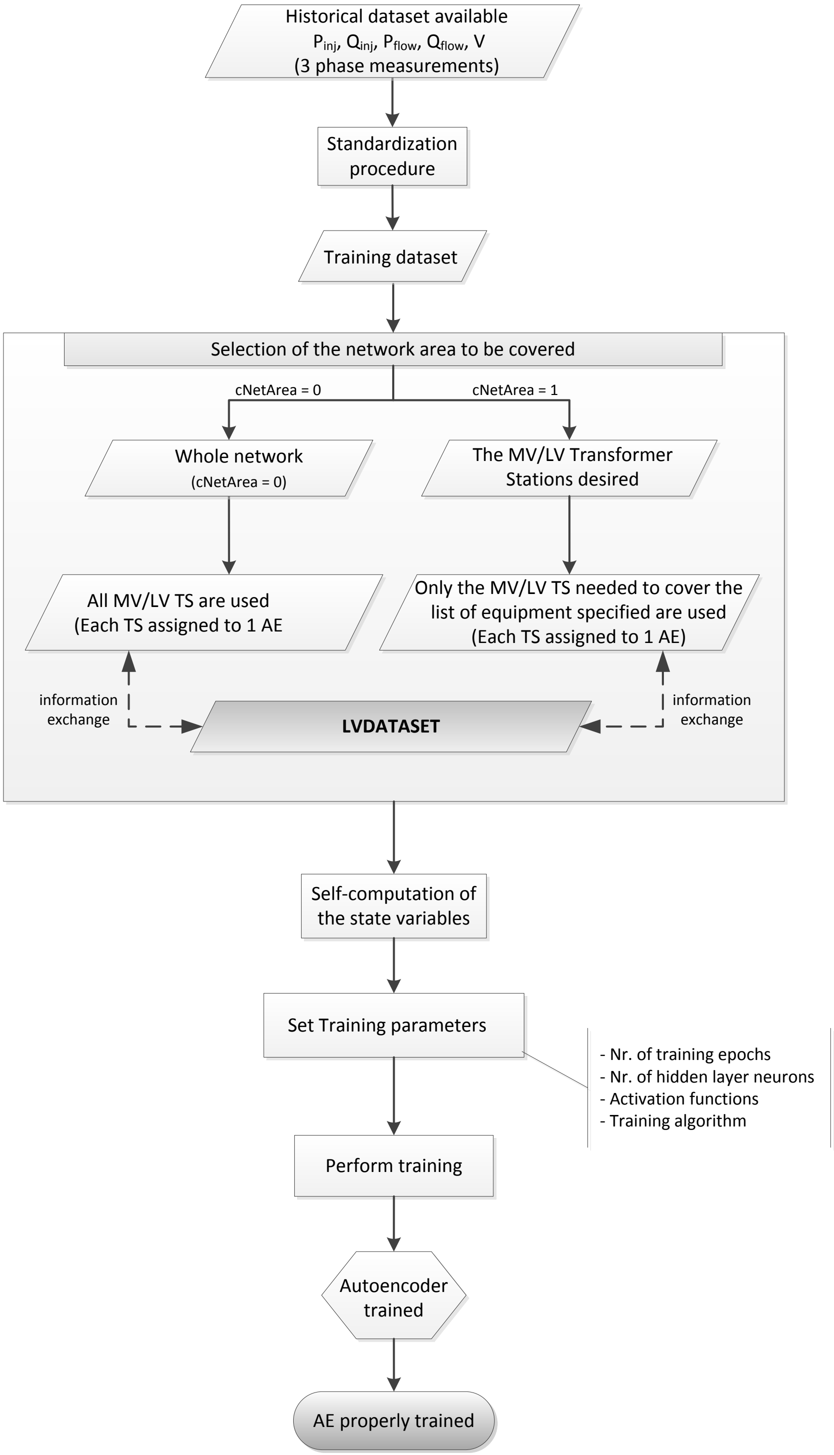


Figure 24: Flowchart of the overall process used to train the AE

4.1.5.4.4 State Estimation Iterative Process

After having the AE properly trained, the meta-heuristic process EPSO is then incorporated to reconstruct the missing variables, which corresponds to the execution of the state estimation process.

Finally, it is important to state that during the execution of the state estimation algorithm, the following occurrences deserve special attention:

- Topology changes: Whenever topology changes are verified, it necessary the selection of an appropriated AE specific for the new topology – whenever there is in the process memory an AE trained for the historical data related to the new topology. Otherwise, a new training process should be executed for the new grid topology.
- Additional historical data: if new historical data is added to the historical database, it should be considered the possibility of training a new AE for creating a new data set. Other possibility is to perform a retraining of the existing AE. In this case, the AE existing in the process memory – already trained – is loaded and an additional training process is performed over the already trained AE, but now only using the new historical information.

4.1.5.4.5 Building Results

This module determines the contribution of power injection equipment for the nodal balance and builds the structures with the results of the NPF component.

The NPF provides relevant results for monitoring and controlling a specific LV grid or an area including more than one network. The outputs provided are the following:

- Voltage magnitude of each phase
- Voltage angle of each phase
- Active power injected in the node
- Reactive power injected in the node
- Total active power generation in the island at each phase
- Total reactive power generation in the island at each phase
- Total active power consumption in the island at each phase
- Total reactive power consumption in the island at each phase
- Total active power losses in the island at each phase
- Total reactive power losses in the island at each phase
- Maximum voltage magnitude related to nominal value in the island at each phase
- Minimum voltage magnitude related to nominal value in the island at each phase

4.1.6 LV Fault Management - Fault Detection, Location and Fused Luminaires

4.1.6.1 Functional Model

The LV Fault Management component runs on the LVGMU. For the purpose of LV Fault Management, all features were developed to perform on the G Smart device, by Efacec.

The LV Fault Management – Fault Detection, Location and Fused Luminaires integrates two algorithms for managing faults in the LV grid:

- LV Fault Detection and Location
- Fused Luminaires Detection and Location on Public Street Lighting

The inputs and outputs of the LV Fault Management component are presented in Figure 25.

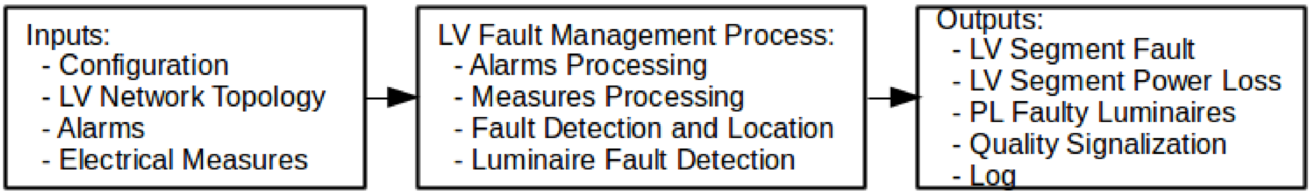


Figure 25: Inputs and outputs of the LV Fault Management process

In order to perform, this component uses as inputs static configurations that should be provided at component start up, and real time data (polled or on event):

- Configuration: Set of data necessary for the component to run;
- LV Grid Topology: from LV sensor devices and segments identification;
- Alarms: On event alarms, spontaneously sent by LV grid Sensors;
  - Among these, Last Gasp messages are also processed by the LV Fault Management component – upon an outage, the sensor is still able to state it is going to shut down;
- Measures: Periodically polled electrical measures;

After the input conditions are met, the component will run, starting the LV Fault Management process.

The output of the process indicates the state of each LV Segments in the LV grid, providing information and alarms about the electrical measures exceeding their configured limits, while a log is generated.

The output data can then be shared to the upward systems, e.g. the TLGMU – through the protocol IEC 60870-5-104 – by the up-link communication protocols and/or be shown by the local GUI/HMI.

4.1.6.2 LV Fault Management Inputs

The LV Management inputs can be organized in Configurations and Live Data, as indicated in Table 19.

Table 19: Configurations and Live Data for the LV Fault Management component

Input	Description	Source
Configuration	Cyclic execution period;	TLGMU (SCADA level) LVGMU (local level)
Grid Topology	Includes the initial grid topology (LV Sensors and Segments)	TLGMU (SCADA level)
Telemetered measurements from distribution grid	Real time voltages, currents and power	LV Sensors (comprising smart meters)
Alarms	Spontaneous events (Voltage and current over limit, Last Gasp, LV Fault)	LV Sensors

4.1.6.3 LV Fault Management Outputs

The LV Fault Management component outputs are indicated in Table 20.

Table 20: Outputs of the LV Fault Management component

Control Variable	Description
LV Segments Fault	Identifies the LV grid segments with faults.
LV Segments Power Loss	Identifies LV Segments in power loss status.
Quality Signalization	Identifies the segments where the voltage or current limits were exceeded.
PL Segments Luminaire Fault	Identifies the PL segments with luminaire faults
PL Lamps Fault	Identifies, for each PL segment, the number of lamps failed
Log	Writes into the internal Log all relevant information.

The outputs are stored in the local real time database and consequently they are available to other software modules, e.g. for local HMI or for enabling up-link protocol communications.

4.1.6.4 Algorithm

The LV Fault Management process is shown in Figure 26.

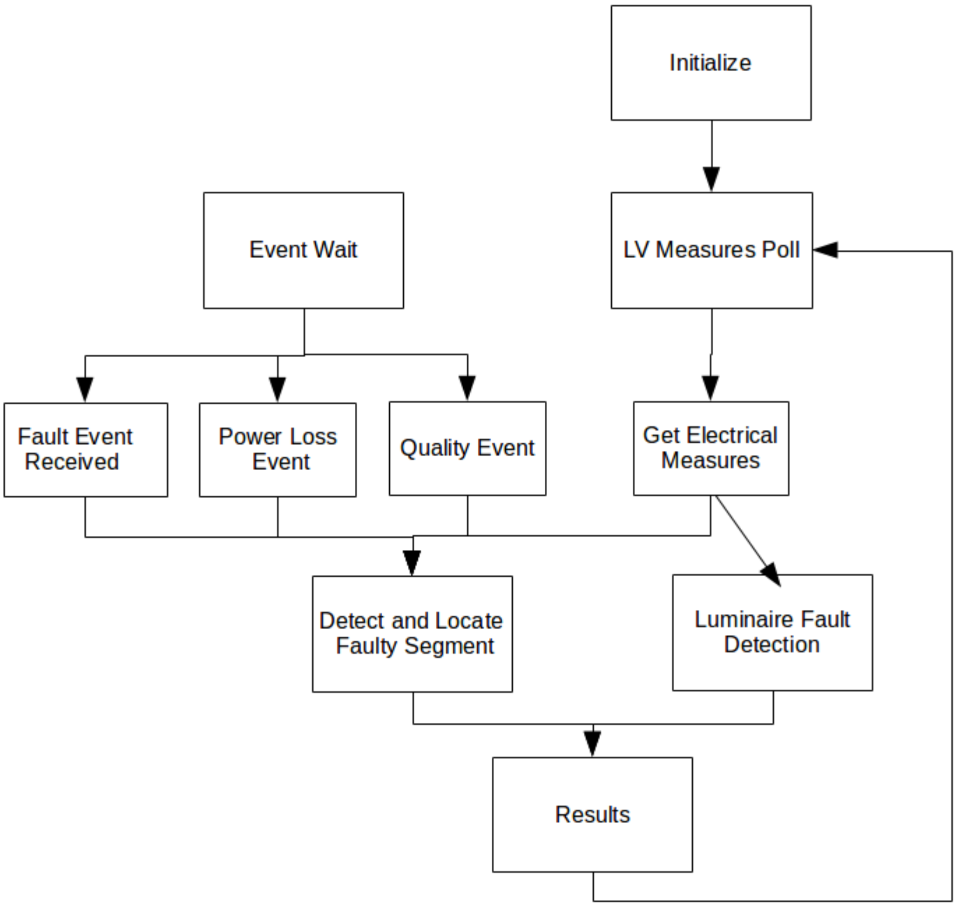


Figure 26: Fault Detection, Location and Fused Luminaires algorithm

In its initial state the LV Fault Management component is on idle, waiting for an Event input or for the finishing of the configured electrical measurements devices polling. When one of the inputs is present, the process will then treat the new data, decoding it, in four basic types of data:

- Fault Event – Event reported by a sensor, indicating the detection of a very high current (fault current) in the segment; when this event happens, usually it may be followed by a low voltage alarm, indicating the fusion of the protection fuse;
- Power Loss Event – Event indicating the loss of power in the segment;
- Quality Event – When voltage or current measured by a sensor exceeds the pre-configured threshold limits, the sensor will send an event;
- Electrical Measures Poll – Periodically, the DTC will request – by polling – the electrical measurements (voltage, current, active power, etc.) of all measurement devices.

For all kinds of events the component will await for confirmation, which means that when an event is received a timer will be launched. The event will only be considered valid after the event kept its state for the configured timeout.

In the Detect and Locate Segment stage, the component will analyse the LV grid based on the new data received. As output, the component provides the state of each segment in the LV grid.

The Luminaire Fault Detection and Location algorithm has as inputs the Public Street Light Measurements – voltages and currents – and after the analysis of these measurements it will report as output the state corresponding to the occurrence of a fused lamp fault – if it has occurred –, as well as the candidate number of fused luminaires for each PL segment.

The result is the full characterization of the PL grid in terms of alarms. The information is stored locally in the internal Real Time Database (RTDB) and is available to other software modules, such as for the local GUI/HMI or for any up-link protocol interfaces.

After the result is stored, the component will enter on idle mode, back to the initial state. When trigger conditions occur, the process main loop will resume.

The next subsections describe the main software components.

4.1.6.4.1 Initialize

Function: Initializes variables and configures the process
Algorithm:

```
Initialize all variables and setup of references – impedance or current, according to the detection method
Reads component's configuration file
Reads component's topology file
```

4.1.6.4.2 Get Electrical Measures

Function: Get Measures from devices
Algorithm:

```
Send DLMS measures request to the devices
Read response
IF Good response THEN
    Parse DLMS response
    Writes measures data into the internal Real Time Database
```

4.1.6.4.3 Events

Function: Event wait function
Algorithm:

```
Waits for spontaneous event
IF new event THEN
    Parse event
    Write event according to its type into the internal Real Time Database
```

4.1.6.4.4 Detect and Locate Faulty Segment

Function: Search all LV grid and tests fault conditions

Algorithm:

```
FOR FirstNode : LastNode DO
    IF FaultCurrentAlarm && !(ChildNode FaultCurrentAlarm) THEN
        Set Sensor Fault Alarm
FOR FirstNode : LastNode DO
    IF Sensor Fault Alarm Confirmed && (ChildNodeSensor Low Voltage || LastGasp) THEN
        Set Segment Fault Alarm
```

4.1.6.4.5 Luminaire Fault Detection

Function: Search all Public Street Lighting (PL) grid for fused luminaires

Note: the algorithm may perform using two different methods: Impedance or Current

Algorithm:

```
FOR FirstNode : LastNode DO
    IF ImpedanceMethod THEN
        Calculates next node impedance
        Calculates this node impedance
        Calculates this segment impedance
        IF Segment impedance > Reference impedance THEN
            Set fused luminaire alarm, in the segment
            The relation between the PL Segment Reference Impedance and the blown-up PL Segment
            Impedance gives an estimation number of fused luminaires, in the segment
    ELSE IF CurrentMethod THEN
        IF Sensor Current < Sensor Reference Current THEN
            Set fused luminaire alarm
            The relation between the PL Segment Reference Current and the blown-up PL Segment
            Current gives an estimation number of fused luminaires, in the segment
```

4.1.6.4.6 Luminaire Fault Detection Outputs

Function: Writes all output data in internal Real Time Database and in Internal Log

Algorithm:

```
IF Segment Fault THEN
    Write Segment Fault to RTDB
    Write Segment Fault to Log
IF Luminaire Fault THEN
    Write Luminaire Fault to RTDB
    Write Luminaire Fault to Log
IF Event THEN
    Write Event to RTDB
    Write Event to Log
```

4.1.7 LV Fault Management - LV Fault Prevention for Voltage Regulation

4.1.7.1 Functional Model

The inputs and outputs of LV Fault Prevention component for voltage regulation are presented in Figure 33.

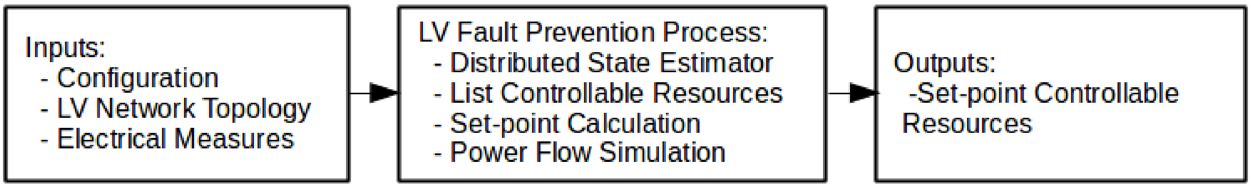


Figure 27: Inputs and outputs of the LV Fault Prevention algorithm targeted for voltage regulation

The component has as inputs the module configuration data setup, the complete LV grid topology, each grid device characterization and the LV grid existing sensors' electrical measurements.

The LV Fault Prevention component algorithm for voltage regulation periodically polls the grid electrical measurements from the available sensors and/or Smart Meters. After receiving the input data, the components verifies if there are any voltage limits violation on the grid. If one or more overvoltages are found, it calculates the necessary control set-point actions over the available Controllable Resources – e.g. a PV micro-generation inverter –, imposing power restrictions over each PV coupling node. The imposed restrictions will be removed from each node when the LV grid voltage is within the acceptable range, to release the restriction(s) without entering in voltage violation. As voltage levels cope with regulatory high and low limits, the algorithm uses a configurable hysteresis interval. The algorithm is triggered whenever the high voltage limit is violated; the needed power set-points are calculated using the Power Flow and State Estimator algorithms, aiming at bringing the voltage level – at the violating grid PV coupling nodes – to a value below the high voltage limit minus the hysteresis.

Once calculated the control set-points, the LVGMU sends them to the concerned PV installation, via the installation's Smart Meter. Locally, the Smart Meter communicates with the end user CMU which, in turn, sends the set-point controls directly to the PV inverter. In this scope, the PV inverter embeds a DMU, as defined in the e-balance architecture. Therefore, the control set-point issued by the LVGMU targets a DMU. By controlling – via set-points – the active power being injected by the inverter – normally, LV grids are predominantly resistive –, it is expected a local impact on the voltage level at the LV grid-injecting node associated to each microgeneration installation, meaning that such voltage will decrease. The controlling algorithm is iterative, thus dealing correctly with the stochastic nature of renewable energy sources and of end user consumption patterns. The algorithm is also suitable to deal with on-load tap changing, provided that this feature is available at each secondary substation transformer. The same applies for LV grid storage units.

4.1.7.2 Inputs

The LV Fault Prevention inputs can be organized in Configurations and Live Data – see Table 21.

Table 21: Configurations and Live Data for the LV Fault Prevention, regarding voltage regulation

Input	**Description**	**Source**
Configuration	Cyclic execution period;	LVGMU (Local)
Grid Topology – for algorithm 1	Includes the initial grid topology	LVGMU (Local)
Telemetered measurements from distribution grid	Real time voltages, currents and power	Sensors Smart Meters

4.1.7.3 Outputs

Table 26 summarizes the outputs of the LV Fault Prevention component regarding voltage regulation.

Table 22: LV Fault Prevention Outputs for voltage regulation

Control Variable	**Description**
Set-point Values	List of Set-points to the available Controllable Resources, e.g. PV inverters; these set-points comprise active power settings to be taken into account by the remote inverters

4.1.7.4 Algorithm

Upon voltage violation, namely as a result of overvoltage conditions arising from PV microgeneration, a voltage regulation feature is triggered at the LVGMU towards performing local control of PV inverters associated to the violating microgeneration installations.

Two algorithms were developed while one was implemented and the other was only simulated:

- The implemented algorithm 1
- The implemented algorithm 2

4.1.7.4.1 The Implemented Algorithm 1

As said, the LV Fault Prevention component runs on the LVGMU. For the purpose of voltage regulation, all features were developed to perform on the G Smart device, by Efacec.

The LV Fault Prevention component's voltage regulation algorithm is shown in Figure 28. The subsequent subsections present the algorithm steps through pseudo-code.

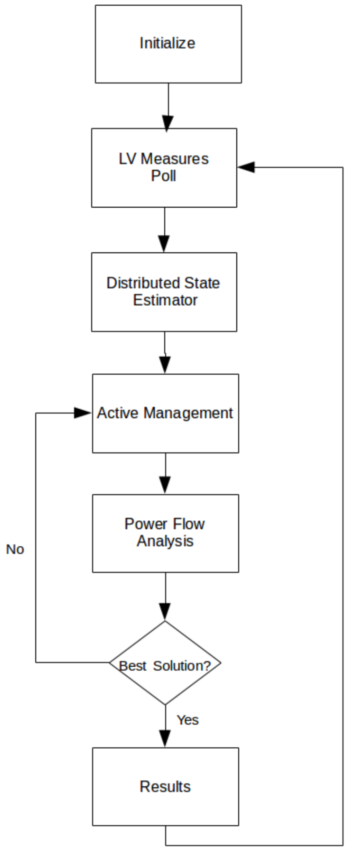


Figure 28: LV Fault Prevention component algorithm for voltage regulation

This process is divided in sequential stages:

1 - Initialize: Initialization of all algorithm variables and necessary configuration loading.

2 - LV Measures Poll: Collect the maximum possible real time measurements from the sensors or smart meters present in the LV grid.

3 - Distributed State Estimator (DSE): The DSE estimates the missing measurements from the original input data.

4 - Active Management: Active Management analyses the LV grid and identifies any overvoltage contingency. In case of detecting an overvoltage, it calculates a power set-point for each Controllable Resource – e.g. a PV micro-generation inverter –, so that the overvoltage could be properly managed. The calculated set-point will be used as input for the Power Flow analysis in a recursive manner so that it could determine the optimal solution.

5 - Power Flow: The previously calculated set-Point will be used in a power flow analysis and the results will be validated. The Power Flow is recursively calculated until the optimal solution is found.

6 - Results: The results consist in a list of optimal set-points for the Controllable Resources, with an associated error. If the error is above a limit the set-point(s) will be discarded and an error is returned.

4.1.7.4.1.1. Initialize

Function: Initializes variables and configures the process

Algorithm:

```
Initialize all variables
Reads component configuration file
Reads component topology file
```

4.1.7.4.1.2. LV Measures Poll

Function: Get measures from devices

Algorithm:

```
Send DLMS measures request to the devices
Read responses
FOR LV Grid Device 1 : Device N DO
    IF Good response THEN
        Parsing of the DLMS response
        Writes measures data into the internal Real Time Database
```

4.1.7.4.1.3. Distributed State Estimator (DSE)

Function: Performs local State Estimation, estimating unobservable relevant electrical data

Algorithm:

```
IF MissingElectricalMeasures THEN
    Estimation of missing electrical measures, based on historical data set
    Error checking
    Output estimated measures
ELSE
    Copy the Input data regarding the RTDB to the Output
```

4.1.7.4.1.4. Active Management

Function: Computes power set-points for all controllable grid devices

Algorithm:

```
Organize LV grid devices according to topology
FOR Controllable Resource DO
    Calculates the power set point, which, when applied to each controllable resource under the known LV grid state – that is an internal process of the LVGMU –, could result in a node voltage within the tolerable limits, comprising the mentioned hysteresis
```

4.1.7.4.1.5. Power Flow

Function: Computes electric variables after voltage regulation has been done

Algorithm:

```
FOR LV Grid Device 1: Device N DO
    Test power set point
    Calculate output voltage value
```

4.1.7.4.2 The implemented algorithm 2

The centralized approach specifically addresses a way of implementing dynamic voltage control of low voltage power grids with distributed generation.

4.1.7.4.2.1. Overview

The dynamic voltage control algorithm is applicable in Low Voltage (LV) power distribution grids to which various micro and mini producers are connected – designated in the literature as distributed generators (DG). The objective of the algorithm is to maximize the DG production, but it may also enforce fairness among DG producers, taking into account the contracts limitations with power grid operators or regulators and while keeping voltage levels within the standard operational limits in all coupling points in the power grid. This algorithm was submitted as a patent [16].

An e-balance LV power grid with distributed photovoltaic (PV) generation is depicted in Figure 29. Each PV generation site comprises one or more PV panels, an inverter and a CMU that interfaces with the e-balance system. The voltage control processing module runs the algorithm at the LVGMU, computing power generation set-points (SP) based on voltage (V), current (I) and power factor (PF) values measured at the PV coupling points and issued by the CMUs. The calculated set-points are then issued to the CMUs in order to dynamically adapt the PV inverter parameters, aiming at regulating the voltage profile at each coupling node.

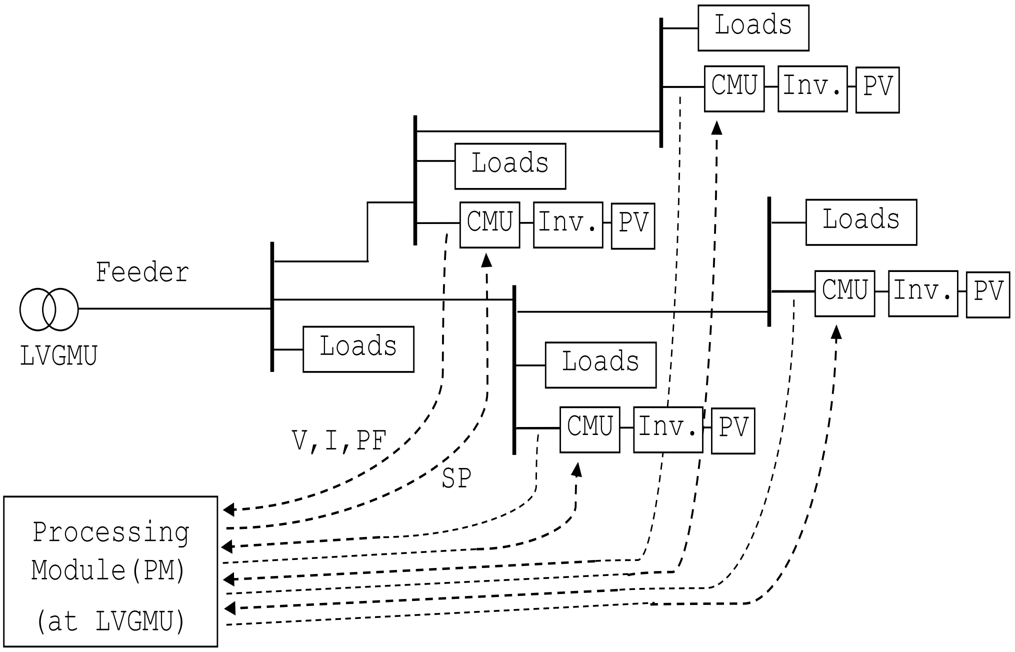


Figure 29: LV power grid architecture and data flow between the voltage control processing module and the CMUs at DG sites

4.1.7.4.2.2. Algorithm Description

Although existing algorithms in the state-of-the-art allow the calculation of the SP and to send it to the DG for voltage regulation in the distribution grid, they do it by successive approximations and usually they require some knowledge of the grid topology. Generally, they achieve approximate solutions. In the present invention, by contrast, knowledge of the grid topology is not required and an accurate solution is obtained by optimizing an objective function subject to a set of constraints to the currents and voltages at the output of DG coupling points.

As the proposed method relies on measurements performed only at the feeder where the DGs are connected, the number of measurements and equipment involved is reduced, resulting in a lightweight and scalable computational implementation, wherein the implementing complexity grows linearly with the number of applicable feeders. As there is no interference between the various feeders, the implementation to a larger grid is merely a replication of the same method to multiple feeders.

Another advantage of the locality of the proposed method is that one can select only the feeders that have DG installed, which reduces the number of grid equipment installed to an absolute minimum.

The pseudocode of the voltage control algorithm is listed in Figure 30.

```
FOR each DG in the feeder DO
    • Measure the Voltage (V), Current (I) and Power Factor (PF) at the output of DG;
    • Based on that measurements calculate the power that is produced by each DG
    • Send a setpoint (SP) to each DG with a slight decrease of the power that is
      currently injected in the grid by that DG.
    • Measure again the Voltage (V), Current (I) and Power Factor (PF) at the output of
      each DG;
DO
    • Based on the measurement made, calculate the sensitivity matrix (A) of that
      feeder, which shows how each DG affect the voltage in all the DGs.
    • Based on the sensitivity A matrix and in different constrains (maximum voltage
      level, maximum DG power, minimum DG power), calculate the power injected by
      each DG that optimize the global DG power. (SPoptimal)
FOR each DG in the feeder DO
    • IF the power currently injected by the DG in the grid is different of the calculated
      SPoptimal for that DG THEN
    • Send setpoint with the calculated SPoptimal value to that DG.
DO
Repeat the algorithm periodically.
```

Figure 30: Pseudocode of the voltage control algorithm

4.1.8 LV Fault Management - LV Fuse Fault Prevention

4.1.8.1 Functional Model

The LVGMU - LV Fuse Fault Prevention software process runs in a periodical way, processing incoming real time data (electrical current and alarms) from the LV Sensors or Smart Meters. The Sensors/Meters must be installed in the LVGMU control area. The Algorithm will output which fuses are relatively near a fault condition (over current, overloading, etc.), giving the DSO the possibility to programme a preventive maintenance on the indicated fuse, redistribute loads or even upgrade the Grid. The respective local log is generated at the LVGMU.

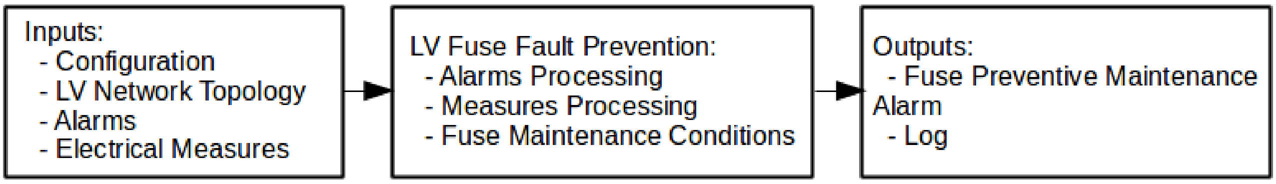


Figure 31: Inputs and outputs of the LV Fuse Fault Prevention algorithm

4.1.8.2 Inputs

The LV Fuse Fault Prevention inputs are indicated in Table 23.

Table 23: LV Fuse Fault Prevention component inputs

Input	Description	Source
Configuration	Cyclic execution period; Etc.	LVGMU (Local)
Grid Topology	Includes the initial grid topology	LVGMU (Local)
Telemetered measurements from distribution grid	Real time currents	Sensors Smart Meters
Sensor Alarms	Sensor Alarm indicating over current	Sensor

4.1.8.3 Outputs

Table 26 summarizes the outputs of the LV Fuse Fault Prevention functionality.

Table 24: LV Fuse Fault Prevention component outputs

Control Variable	Description
Alarms	Alarm indicating fuse substitution
Log	For each alarm is generated an entry on the LVGMU logbook

4.1.8.4 Algorithm

The LV Fuse Fault Prevention algorithm monitors the current at each point of the LV grid where a fuse and a current sensor exist. Figure 32 presents the LV Fuse Fault Prevention algorithm.

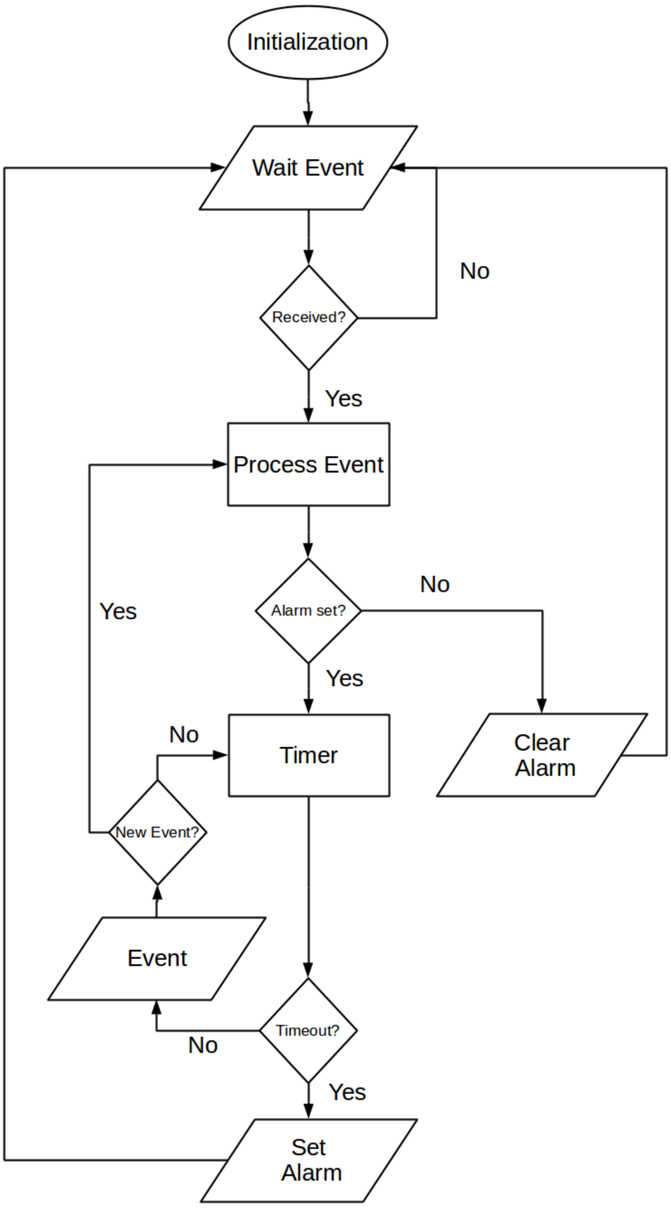


Figure 32: LV Fuse Fault Prevention algorithm

The algorithm, after initialization, awaits an incoming current alarm message, from the LV Sensors. When a message is received, the LVGMU will process it and validate if it is a set or clear alarm event.

Upon a set alarm event, a timer will start. If the timer reaches the timeout and the alarm is still present, the alarm is confirmed. Otherwise it will be discarded and the algorithm will go to the await state.

Upon a clear alarm event, the LVGMU will process it and will clear the fuse alarm. If there is a previously started timer it will be stopped.

The Set and Clear Alarm states generate log and statistical information, which will be updated and stored in the database.

4.1.9 LV Quality

4.1.9.1 Functional Model

The LV Quality component main goal is to collect information from grid sensors and smart meters connected downstream the secondary substation. Their role is to determine continuity and quality of service indices regarding the LV grid. The LV Quality component is targeted for being installed at the LVGMU.

The information required to characterize the grid technical quality has different sources:

- Smart Meters, which are able to detect and store information related to service interruptions and voltage disturbances. Depending on the severity of the disturbance, the Smart Meter may automatically generate an alarm which notifies the LVGMU.
- Grid Sensors, providing redundant information, which may help to identify and quantify the disturbance.
- DER advanced metering devices, when the devices are connected to the distribution level, such as in the case of distributed generation plants, it was assumed that the DER installation will be equipped with an advanced metering device which should have quality of service monitoring functions, similarly to the Smart Meter installed at consumer premises.
- Grid management units, namely LVGMU. The LVGMU is responsible for processing data related to the LV grid connected downstream the secondary substation. In addition, data from the DER devices connected at each voltage level and at the substation level can also be included.

The application includes three main functions:

- Pre-processing of data, responsible for creating the necessary data structures for the technical quality analysis and for managing the data received from the devices connected downstream the LVGMU.
- Continuity of service analysis, responsible for identifying interruptions and quantifying their duration. The function also determines the indices used by the energy regulator to evaluate distribution grid reliability. Adaptation of the indices may be required according to countries' regulations.
- As response to the Power Quality analysis, voltage regulation may be triggered to overcome grid overvoltage constraints

One of the main challenges of this component is the identification of interruptions and disturbances, since the smart meters and sensors connected to the same feeder are likely to be affected by the same disturbance. In order to correctly identify the disturbances, the component uses grid topology data.

The technical quality indices determined are stored locally at the LVGMU database.

When detecting overvoltage conditions, namely those associated to the impact of PV microgeneration, the LVGMU is able to trigger an algorithm suitable to deal with such conditions, thus promptly reacting to mitigate the overvoltage effects. Section 4.1.7 describes the mentioned algorithm.

The inputs and outputs of the LV Quality component are presented in Figure 33.

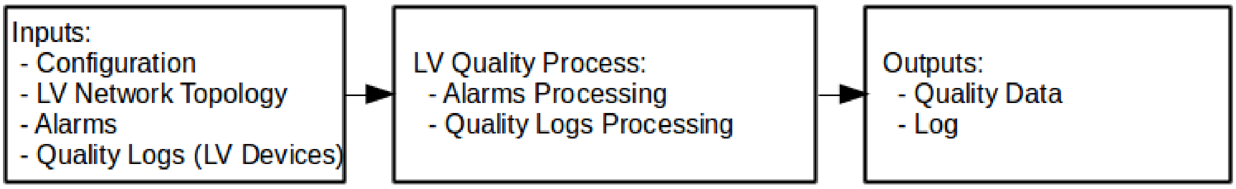


Figure 33: Inputs and outputs of the LV Quality algorithm

The Component has as inputs the component configuration data setup, the complete LV grid topology, as well as alarm and log data.

The LV Quality Component algorithm periodically polls the quality logs from the available sensors and/or Smart Meters. The data received is stored in the LVGMU database and then it is processed to generate quality reports.

4.1.9.2 LV Quality Inputs

The inputs of the LV Quality component are mainly related to the information provided by local advanced metering devices. Additional information from grid sensors can also help identifying and classifying service interruptions and disturbances. The information can be retrieved from the devices connected downstream in a weekly, monthly or yearly basis, according to the equipment data storage capacity and the periodicity of the analysis to be performed. The quality of service information collected by the LVGMU from the Smart Meter is more likely to be collected in a weekly or monthly basis, due to restrictions of communication infrastructure bandwidth. The quality of service information provided by Smart Meters is detailed in Table 25.

When retrieving the information from the different devices, proper identification and time stamping is required, in order to perform a synchronous analysis of the data.

Table 25 summarizes the additional data provided by Smart Meters regarding each specific secondary substation.

Table 25: LV Quality Component inputs – Information provided by Smart Meters

Technical quality	**Disturbance**	**Description**
Power Quality	Voltage magnitude variations	Detects when average voltage magnitude along a sliding pre-defined period (10 minutes according to EN50160:2000) is outside the admissible limits (pre-defined according to the voltage level considered). A time stamp is assigned to the beginning and to the end of the disturbance. The detection method includes the phase where the disturbance was detected.
	Number and duration of voltage magnitude variations	Counts the number of detected voltage variation disturbances and determines the total duration of this type of events.
	Overvoltage event	Generates an overvoltage event, identifying the phase where the disturbance has occurred in the case of three-phase connections.
	Undervoltage event	Generates an undervoltage event, identifying the phase where the disturbance has occurred in the case of three-phase connections.
Continuity of Service	Long interruptions of supply voltage	Detects long interruptions of supply voltage, meaning that voltage remains below 50% of the reference voltage during more than 3 min, according to EN50160:2000.
	Number and duration of long interruptions of supply voltage	Counts the number of detected long interruptions of voltage supply and determines the total duration of this type of events.

4.1.9.3 LV Quality Outputs

Table 26 summarizes the outputs of the LV Quality component. It includes continuity of service indices targeted for grid reliability assessment. Moreover, it includes power quality disturbances related indices.

Table 26: LV Quality Outputs for grid reliability and power quality

LV Quality results	Description
Availability index	Overall LV grid scope availability
SAIFI SAIDI CAIFI CAIDI MAIFI ENS	System Average Interruption Frequency Index System Average Interruption Duration Index Customer Average Interruption Frequency Index Customer Average Interruption Duration Index Momentary Average Interruption Frequency Index – for momentary interruptions Energy Not Supplied
Voltage	Overall grid supply voltage, for selected grid nodes, comprising log data enabling the presentation of a list of node voltage values or of trend displays associated to each node voltage. Alarms will be triggered upon threshold settings violation.
Voltage sags	Overall voltage sags, for all representative and measured grid nodes – e.g. as those with Smart meters –, comprising log data for enabling the presentation of a list of node voltage sags – per sag duration or per sag depth- Trend displays associated to each representative and measured grid node also allow the presentation of voltage sags.

4.1.9.4 LV Quality Algorithm

The LV Quality algorithm relies mainly in source information. Its approach is described as follows:

- Collection of input data from Smart Meters and from grid Sensors
- Data storage at the LVGMU
    - At the LVGMU, the downstream grid perspective is computed, taking into consideration the mentioned inputs and providing the mentioned outputs
- Presentation of grid availability and related outage – service interruption – data in the form of lists or trend displays, with filtering capabilities
- Presentation of power quality, comprising voltage values, voltage sag and swell data in the form of lists or trend displays, with filtering capabilities

4.1.10 LV Fraud

4.1.10.1 Functional Model

The Fraud Detection component is responsible for identifying possible fraud activities. It will run on the LVGMU. In case of fraud detection, the component will also try to identify the most probable locations for the occurrence of fraud activities, providing the identification of feeders, line segments and even end customers is provided.

The component will detect fraud activities by comparing the energy provided by the MV/LV transformer and by LV grid DER assets, with the energy consumption along the LV grid, removing the estimated technical losses, a configuration parameter. The Local Fraud Detection and Location algorithm can be implemented in order to generate a list of most probable locations for fraudulent activities. Different search levels can be implemented if sufficient measurements are available, namely:

- **Substation feeder level** – requires determining the non-expected energy consumption and losses differentiated by feeders. It will allow identifying the feeder with larger probability of fraud occurrence.
- **Feeder segment search** – requires metering equipment installed in the feeders. By analysing the energy measurements, currents or load diagrams – according to the sensor metering capabilities –, it might be possible to identify the line segments with larger probability of fraud occurrence. However, adequate mapping of Smart Meter along each single-phase circuit will be required.
- **Customer level** – by analysing the customers' energy and power consumption historian and processing meter fraud detection alarms. Sudden changes of power consumption behaviour, abnormal voltage and/or current values, consecutive errors of authentication, unauthorized changes of meter configurations will be taken into account. However, such data should be checked and validated with additional information from the LV grid feeders and/or from secondary substation sensors.

4.1.10.2 LV Fraud Detection inputs

The application will use data from the following entities:

- Smart Meters
- Local measurements at secondary substation
- Grid sensors, connected at the LV feeders

The key inputs of this component are described in Table 27. The LV Fraud component should enable the distribution grid operator to define the periodicity of the fraud detection analysis, which can run in daily, weekly or monthly basis, considering the periodicity of remote meter readings.

Table 27: Fraud Detection component inputs

Source	Input	Description
Smart meters	Energy Consumption / Injection	Provides the energy consumed and the energy provided by local DER. This information can be provided daily, weekly or monthly.
	Load diagram	Provides the local load diagram. This information can be provided daily, weekly or monthly, depending on the meter characteristics.
	Fraud Alarm	Generates a list of fraud events, corresponding to basic mechanisms such as user registration failure, strong magnetic field detected, meter enclosure unauthorized opening – tampering –, among others.

LV sensors	Instantaneous values of current, voltage and power.	LV sensors are not likely to include metering capabilities of smart meters. However, real-time data can be retrieved periodically and stored at the LVGMU. Smart meters can also be used as sensors when installed in the LV feeder, namely at distribution cabinets or at each secondary substation outbound feeder.
Secondary Substation	Total energy provided	Provides the total energy provided by the secondary substation. This value can be defined according to the period under analysis and be differentiated by each LV feeder.
	Load diagram	Provides the load diagram of the secondary substation. This information can be provided daily, weekly or monthly.

Besides the inputs described in previous tables, some parameters will have to be defined for the proper identification of fraud activities, namely:

- **Periodicity of fraud location**. The identification of clients or grid areas where fraud activities are more likely to have occurred, can be triggered considering a pre-defined period (e.g. weekly, monthly, every 6 months).
- **Mode of operation**. Two modes can be derived regarding the identification of possible fraud locations: an automatic procedure, where the fraud location will run automatically when non-expected energy events surpass a pre-defined limit. Otherwise, fraud location can run with a periodicity defined by the DSO.

4.1.10.3 LV Fraud Detection outputs

As outputs, the Fraud Detection component will provide the following:

- List of clients/meters where fraud activities are more likely to have occurred during the observation period.
- Historic database containing the events detected. For each event the following information should be associated:
    - Energy supplied by the secondary substation
    - Total energy provided by DER units placed downstream the secondary substation
    - Aggregated energy consumption derived from all Smart Meters downstream the secondary substation
    - Deviation of the energy balance to the defined non-expected energy consumption limit

The reports generated at the LV level by the LVGMU will then be analysed at the central services level. As outputs, the component will return a refined list of possible end customers, which may be involved in fraudulent activities.

4.1.10.4 LV Fraud Detection functional model

The Fraud Detection algorithm is represented at Figure 40 and consists of four main functional blocks.

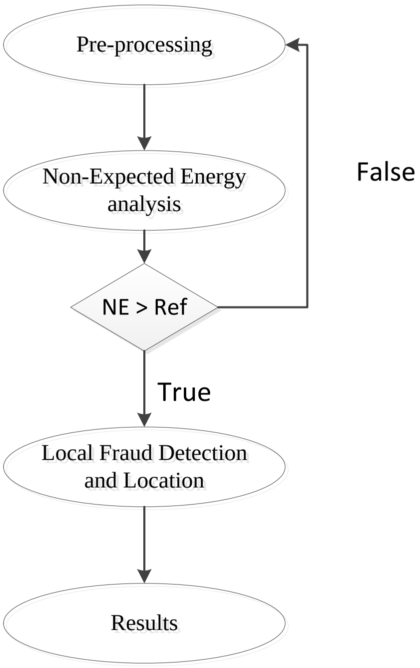


Figure 34: Process Diagram for LV Fraud Component

4.1.10.4.1 Pre-processing function

This process creates the necessary data structures for storing the data collected from the Smart Meters, grid sensors and secondary substation measurements and metering data. As referred previously, the data retrieved from the Smart Meter and sensors may be referenced to several days, weeks or months. Therefore, correct time stamping and synchronization has to be ensured. It is necessary to have at least the mapping of the meters regarding their placement at each phase of the 3-phase LV feeders.

4.1.10.4.2 Non-Expected Energy Analysis

The energy produced at the secondary substation and DER levels will be compared with the energy profiles provided by LV smart meters. When the difference exceeds the limit established, an event should be generated. If the number of events exceeds the number of admissible violations during the observation period, the local fraud detection and location algorithm is triggered. The non-expected energy for a given period of analysis can be determined based on the energy balance between the secondary substation, the DER assets and the LV grid end consumers:

$$NE = (E_{sub} + E_{der}) - (E_{cons\_lv} + E_{tec\_loss})$$

Where,

NE	Non-expected energy consumption
E_{sub}	Energy produced at the substation level
E_{der}	Energy produced by the DER
E_{cons_lv}	Energy consumption reported by the Smart Meters
E_{tec_loss}	Reference energy losses

4.1.10.4.3 Local Fraud Detection and Location

In order to detect probable locations of fraudulent activities, the component will first compare additional telemetered values of power and energy collected from the grid sensors against the data provided by the smart meters in order to first identify the feeder and/or segment with the highest probability of fraud occurrence.

4.1.10.4.4 Results

This process will build the results structure containing the outputs of the algorithm as described.

5 Energy resilience using energy balancing

5.1 Introduction

Energy resilience has been subject to a detailed description, regarding its purpose, the related algorithms and simulations. All those aspects are described in [6].

5.1.1 The energy resilience components within each management unit

In this section, all EMP's software related to Energy Balancing will be described, yet in relation to energy resilience only. Figure 35shows those components.

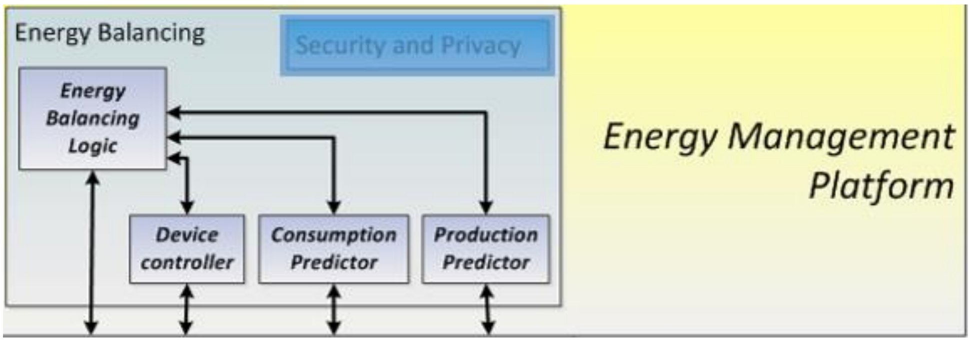


Figure 35: The Energy Management Platform (EMP) Energy Balancing components, supporting Energy Resilience

The mentioned components were developed under task T5.2 [6], as mentioned, but they impact also on the present D5.3 deliverable and its corresponding task T5.3.

Table 28: Relation between the e-balance architecture components and their energy balancing components

Management units and other devices	**e-balance architecture components name**			
	Energy Balancing Logic	**Device Controller**	**Consumption Predictor**	**Production Predictor**
TLGMU	performs		performs	performs
MVGMU	performs		performs	performs
LVGMU	performs		performs	performs
DERMU				
LV Sensors				
Smart Meters			supports	supports
CMU	performs	performs	performs	performs
DMU		is controlled by		

Note: For easing the above table understanding, one should interpret, e.g. LVGMU **performs** the **Energy Balancing Logic** component features, regarding energy resilience, , while DMU **is controlled by** the **Device Controller** component.

5.1.2 Use case and demonstration matrix

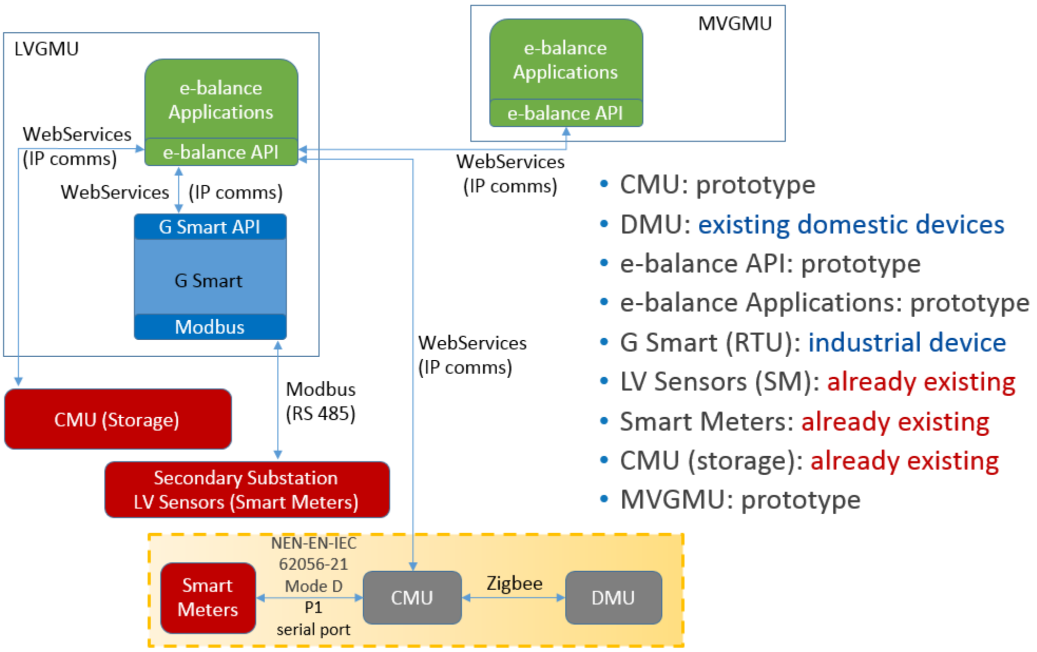
In Deliverable D2.1 [2], a set of use cases has been defined related to grid balancing towards energy resilience. Some of those use cases are to be demonstrated in Bronsbergen, which are given in Table 29. This table relates the use cases to be demonstrated with the Management Units and Devices planned for development within the e-balance project.

Table 29: Use cases related to energy resilience by balancing[2], planned for the Bronsbergen demo, in The Netherlands

use case #	Title	Related e-balance MUs and devices
3	Distributed generation balancing and resilience	MVGMU, LVGMU, CMU
11	Microgrid energy balancing	LVGMU, CMU
13	Neighbourhood power flows	LVGMU, Smart Meters as sensors
14	DER power flows	LVGMU, Smart Meters as sensors
27	Energy storage penetration simulation	In simulation
28	Electrical vehicle and distributed generation simulation	In simulation

5.1.3 A broader perspective of the e-balance components for the Bronsbergen demonstrator

Figure 36 and Figure 37 depict the main e-balance physical components of the Bronsbergen demonstrator, comprising Management Units (MU) and devices, as well as the main standards used for communication between them. A glimpse on the hardware and application/software modules is also given. Moreover, both images also highlight which Use Cases (UC) were covered, in line with what was described in Table 29.



- CMU: prototype
- DMU: existing domestic devices
- e-balance API: prototype
- e-balance Applications: prototype
- G Smart (RTU): industrial device
- LV Sensors (SM): already existing
- Smart Meters: already existing
- CMU (storage): already existing
- MVGMU: prototype

Figure 36: The physical components of e-balance and their role on supporting the Bronsbergen selected use cases for the Roelofs secondary substation

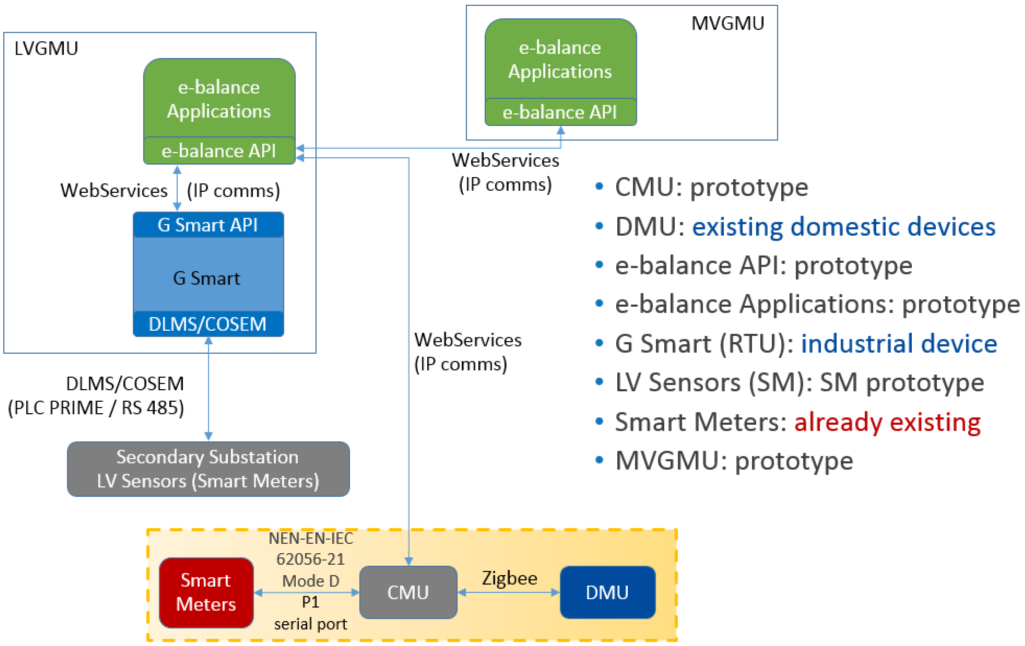


Figure 37: The physical components of e-balance and their role on supporting the Bronsbergen selected use cases for the Bronsbergenmeer secondary substation

5.2 Implementation Details of the Energy Balancing Components

The following sections describe the implementation details of the energy balancing components towards energy resilience.

5.2.1 Mechanism of resilience by balancing

The balancing algorithms use the flexibility in the production and demand in a neighbourhood to obtain a well-balanced grid. The use of the algorithms, thus, will by itself provide resilience against overloading the grid by either a peak demand or peak production.

Furthermore, when a grid failure may occur, the balancing algorithms can help in running a disconnected neighbourhood as a microgrid, independent of the main grid. Thus, additional resilience is provided against grid failures. Of course, this is only possible when enough locally generated energy is available.

In the following sections we present the model based analyses, using the models presented in D5.1 [3], in order to verify the algorithms and show the power of the approach. For the implementation details on the balancing algorithm itself we refer to D5.2 [6], which is dedicated to energy balancing.

5.2.2 Validation of resilience by balancing

This section is based on the work presented in the paper that will be presented at Power Tech 2015 [7].

When we add the grid topology to the outcome of the balancing algorithms, we can analyse the power flows within the grid, and check whether the balancing algorithms indeed help in providing a better power quality. With the Triana simulator (presented in D5.1 [3]), we can do this analysis offline and easily compare a scenario with and without the use of our balancing algorithms.

In the following we address two scenarios, and compare the e-balance profile-based steering algorithm with two other demand side management algorithms.

5.2.2.1 Scenario 1

In the first scenario we consider a detailed, three phase model of a Dutch LV grid with 121 houses. The demand is based on real life measurements. On top of this demand, an EV has been added to each house. We study the extreme case where all EVs are charged at maximum power as soon as they arrive at home in the evening at 18:00.

We compare the following strategies:

- No control: EV's are all connected at 18:00 and start charging.
- Optimal pricing, charging of EV's shift to time at which the price is the lowest. The prices are the same for all houses.
- e-balance profile based steering.

Figure 38 and Figure 39 show the evolution of the power at the transformer, and the minimum and maximum voltage in the LV grid during the day for the three control strategies. When no control is used, the EV's all start to charge at 18:00. This results in a peak demand of nearly 600 kW at the transformer, which lasts for approximately 3 hour. Grid analysis show overloaded cables in the case of no control, and voltage drops almost out of its legal bounds (207 V – 253 V). Losses add up to 89.6 kWh, 3.2%, in the single day.

When the optimal pricing control is used the peak is only shifted to the early morning, but it is hardly reduced. Although the voltage does stay within the permitted bounds, it is still close to the permitted lower bound when the EVs are charged. Due to the slightly improved balance, the losses decrease to 73.6 kWh, which is 2.7%.

Profile based steering, really reduces the peak by spreading the usage over the entire night. This results in that the voltage stays well within the bounds, and losses are reduced to 38.1 kWh (1.4%).

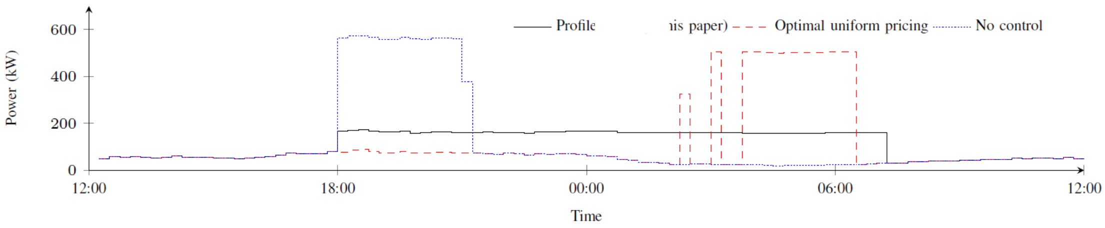
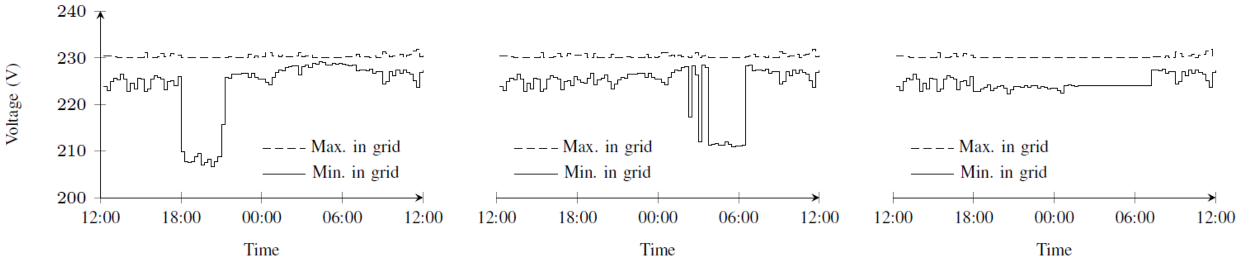


Figure 38: Power at the transformer (including losses) in optimal uniform pricing case study



(a) No control **(b) Optimal uniform pricing** **(c) Profile steering**

Figure 39: Lowest and highest observed voltage for optimal uniform pricing case study

5.2.2.2 Scenario 2

This scenario considers the same LV grid as in the first scenario. However, now in addition to the EV, each house is equipped with 3kWp PV panels, a 3kWh battery and a time-shiftable washing machine (to be scheduled between 8:00 and 17:00). The PV production is determined from Dutch weather data.

Now, we compare the following control strategies:

- no control
- a state-of-the-art DSM algorithm from [8]
- e-balance profile based steering

Figure 40 and Figure 41 show the evolution of the power at the transformer, and the minimum and maximum voltage in the LV grid during the day for the three control strategies.

Again, we see that when no control the charging of the EVs results in a large power peak at the transformer (Figure 40), and the voltage drops out of bounds several times during the day (Figure 41a).

The state-of-the-art algorithm improve the situation significantly; the power peak is flattened (Figure 40) and the voltage remains within the permitted limits (Figure 41b).

When we compare this to the e-balance profile steering approach, we can see that the peak is also flattened (Figure 40), and the voltage remains within the permitted limits (Figure 41c). In fact, profile steering is better capable of decreasing the peaks, and keeping the voltages within the permitted interval. Note, that one important reason for DSM is to keep the cable load low such that the expected life time of the cable increases. Whereas the state of-the-art approach keeps the load on all cables below 53% of their capacity, our algorithm keeps the load on all cables below 32.1% of their capacity. For a numerical comparison between the state of the art and our profile steering algorithm, see Table 30.

Another advantage of our algorithm is that it yields a more stable situation, as can be seen by comparing Figure 41b and Figure 41c. The reason for this is that the price signals used in the state-of-the-art algorithm result in aggressive steering, whereas our algorithm keeps the system state stable for a relatively long time.

Another important difference between both algorithms, is that the- state-of-the art algorithm requires detailed information of the grid, while our algorithm does not require this information and still achieves better results because it shaves the peaks at each level in the grid. We only used the grid topology after completion of the algorithm to calculate the voltages and losses that we presented in this evaluation, while the state-of-the-art research uses the topology in the optimization algorithm.

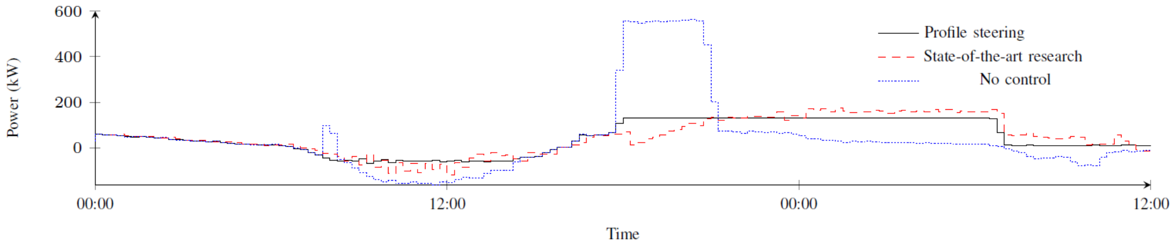
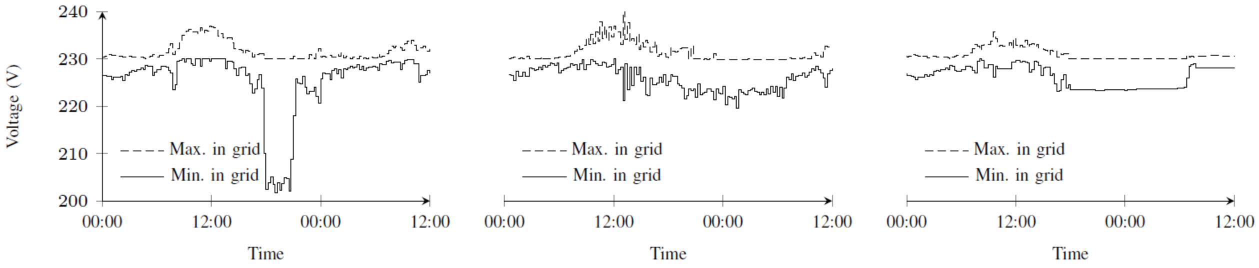


Figure 40: Power at the transformer (including losses) in the differentiated pricing case study



(a) No control **(b) state-of-the-art research** **(c) profile steering**

Figure 41: Lowest and highest observed voltages in the differentiated pricing case study

Table 30: Performance parameters of the DSM algorithms for the differentiated pricing case study.

	no control	**state-of-the-art**	**profile steering**
total losses (kWh)	26.6	3.0	1.5
lowest voltage (V)	201.8	219.6	223.2
highest voltage (V)	236.9	241.5	235.7
max. power (kW)	563.0	174.8	131.2
cable load (%)	143.2	53.0	32.1

The analysis of the two scenarios shows that the e-balance balancing algorithms indeed balance the demand well over time, which results in lower peak powers and flatter voltage profiles. Overall, the algorithm will reduce the strain on the grid elements, and thus enhance the resilience of the grid itself.

5.2.3 Validation of energy supply resilience

This section is based on the work presented in the paper that will be presented at the IEEE/IFIP International conference on Dependable Systems and Networks (DSN 2015) [9].

As we saw in the previous section, the energy balancing algorithms can help in reducing the load at the secondary substation. In case a grid failure occurs, a house or neighbourhood may even operate stand-alone, when enough local production is available. In D5.1 [3], we have presented a model that allows us to analyse the scenario of a grid failure, and compute the probability that enough energy is locally available to supply the demand.

In this section we present further results of our analysis. We discuss two scenarios. In the first we compare three battery management strategies for a single house. The second scenario gives a first analysis of the Bronsbergen demonstrator.

5.2.3.1 Model

Figure 42 depicts an abstraction of the used hybrid Petri net model, as was presented in D5.1 [3]. Recall that the model consists of three main parts.

The first part models the energy flows in the house or neighbourhood (middle part in Figure 42). The local production ($prod(t)$), supplies its energy to the demand ($demand(t)$). The battery can store the excess production until it is fully charged, and, reversely, supply extra energy when the local production is too low. Only, when the battery is full the excess production is exported to the grid, and, reversely, when the battery is empty the grid is used to supply the needed energy.

The second part models the battery management (top part in Figure 42). With battery management module we can limit the allowed depth of discharge when the system is grid connected. Thus, some back-up power is always available in case a grid failure occurs. Furthermore, we can choose to charge the battery from the grid, in case the local production is low.

The third part models the grid failure (bottom part of Figure 42). In the model a grid failure is introduced at time $T = a$. The grid is repaired in a randomly distributed time. We then compute the probability that the local production, together with the energy stored in the battery, is enough to supply the demand. Thus, the energy supply is made resilient to grid failures.

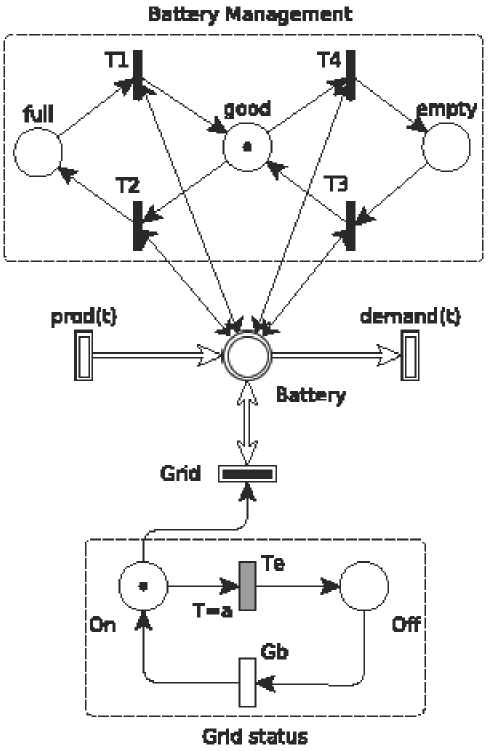


Figure 42: Abstraction of the Petri net model

5.2.3.2 Scenario 1: A single house

In the first scenario we consider a single house, which is equipped with PV panels and a battery. With the web tool PVWatts [10] we obtain the production profiles for the PV-system. The PVWatts profiles are computed for a system located in Amsterdam with twelve 250 Wp (Watt peak) solar panels (3 kWp total), facing south with a 45 degree tilt. The system losses, and all advanced parameters have been kept to the default values. These input values result in a yearly production of approximately 2750 kWh. We consider production profiles for sunny and cloudy days, in both winter and summer. The used profiles are shown in Figure 44.

The demand profiles are based on the EDSN profiles [11] for a total yearly demand of 3000 kWh. However, to reduce the computational complexity for the hybrid Petri net model, we use a more coarse grained approximation. The EDSN profiles and the used approximation profiles are given in Figure 43.

The battery size is varied from 500 Wh to 3000 Wh usable capacity.

We define three different battery management strategies:

- *Greedy*: The battery is always discharged for its full available capacity. The battery is charged only with locally produced energy.
- *Smart*: When the grid is available, the battery is never fully discharged. It is discharged only to a state of charge SoC_1. Part of its usable energy is kept as back-up energy. This energy is available when a grid failure occurs. Like the *Greedy* strategy, the battery is charged only with the locally produced energy.
- *Conservative*: Like in the *Smart* strategy, the battery is discharged only to the level of SoC_1 when the grid is available. However, when this state is reached, the grid is used to partially recharge the battery, to SoC_2. This results in additional back-up energy, when the grid fails.

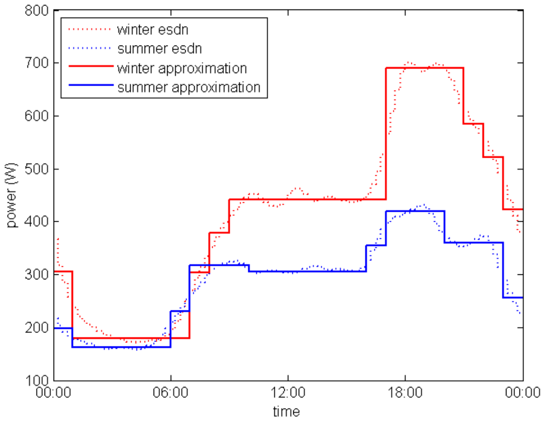


Figure 43: ESDN demand profiles for a winter and summer day and the approximations used in the model

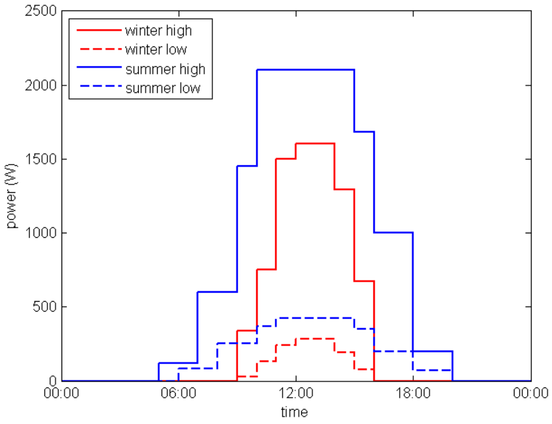


Figure 44: Summer and winter day production profiles

Table 31: Choice of threshold levels

Strategy	$\boldsymbol{SoC_1}$	$\boldsymbol{SoC_2}$
greedy	0	0
smart	$0.3C_u$	$0.3C_u$
conservative	$0.3C_u$	$0.5C_u$

Table 31 gives the choice of the levels of SoC_1 and SoC_2 in the three strategies.

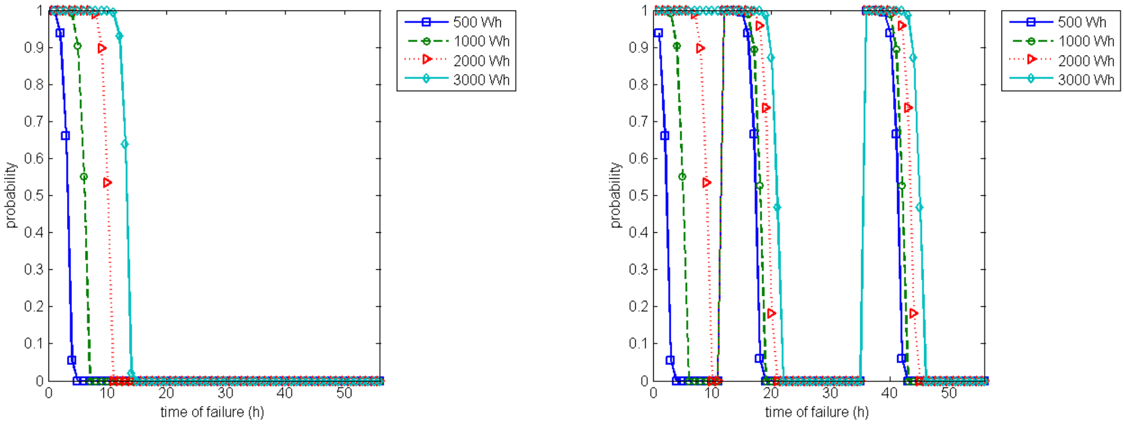
The rate at which the battery is charged from the grid in the *Conservative* strategy is set to $\frac{0.2C_u}{8}$. Thus, the battery will be charged by the grid from 0.3 C_u to 0.5 C_u in 8 hours. The battery is charged by the grid in such a relatively low rate in order to reduce the additional load on the grid, and to prevent a large number of partial charge-discharge cycles during the night.

5.2.3.2.1 Survivability results

In the following we consider the impact of a grid failure on the smart house for all three battery management strategies and the four production profiles as discussed in the previous Section. The grid may fail at different times of the day and comes back after a random repair time, that is distributed according to a folded Normal distribution, with average 2 and standard deviation of 1 (hour). Power outage times are monitored and reported by the Council of European Energy Regulators (CEER). In their recent benchmarking report on the continuity of electricity supply [12], one can see that the unplanned system average interruption duration index (SAIDI) differs largely per country, in 2012 ranging from only 10 and 14.5 minutes for, respectively, Luxembourg and Denmark, to as much as several hundreds of minutes in the Baltic states and Poland and Malta. The unplanned system average interruption frequency index (SAIFI) is well below 1 for some countries (like Luxembourg, the Netherlands and Denmark) and ranges to, for example, 2.33 for Italy and 2.99 for Slovenia.

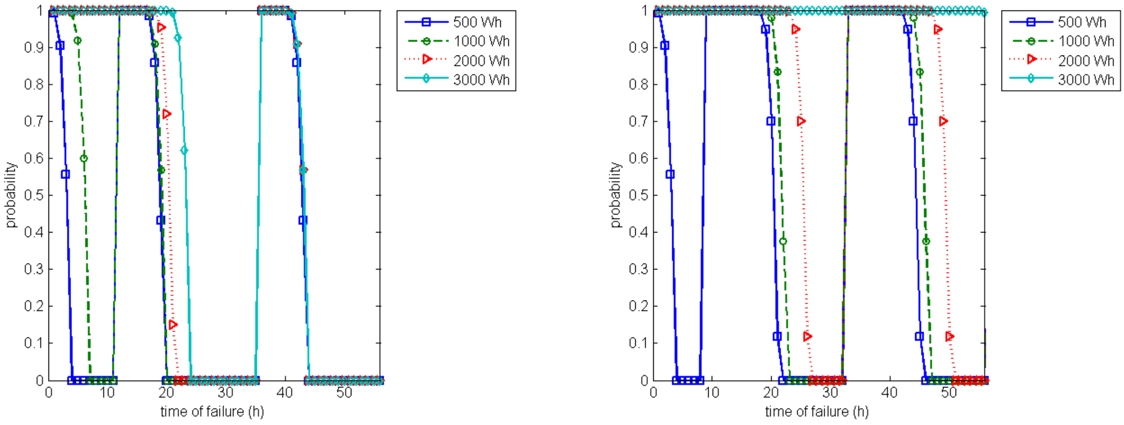
We show the survivability of the system, that is, the probability that the house can be powered continuously in the presence of a power outage, for battery sizes between 500 and 3000 Wh. We start with a full battery at midnight (which corresponds to time 0 in the figures). These results are computed using the FluidSurvivalTool[13].

5.2.3.2.1.1. Greedy



(a) Winter low

(b) Winter high



(c) Summer low

(d) Summer low

Figure 45: Probability of surviving a grid failure as function of the time that the failure occurs for the Greedy strategy. The following four scenarios are considered, (a) winter day with low production, (b) winter day with high production, (c) summer day with low production, and (d) summer day with high production

Figure 45 presents the survivability of the system, when the *Greedy* strategy is used for the four different production profiles. The time of failure is depicted on the x-axis and the probability that the system is survivable, that is, the probability the demand can be fulfilled without interruptions, on the y-axis. The time of failure (on the x-axis) corresponds to the firing time of the failure transition T_e in the HPnG model and does not represent the transient evolution of time. Clearly, the state of charge of the battery changes over time, hence, the time of failure has a direct impact on the survivability of the system.

In winter when the production is low the available energy from the battery is quickly consumed, since the *Greedy* strategy always first empties the battery before it imports energy from the grid. Together with the state of charge of the battery the survivability of the system drops rapidly, and as shown in Figure 45(a). Depending on the size of the battery, the probability that the system is survivable reaches zero for grid failures occurring between 5 to 15 hours. As the production in this setting is always lower than the demand, the battery will never be recharged on a winter day with low production. Hence, the system can not recover, once the battery has been drained.

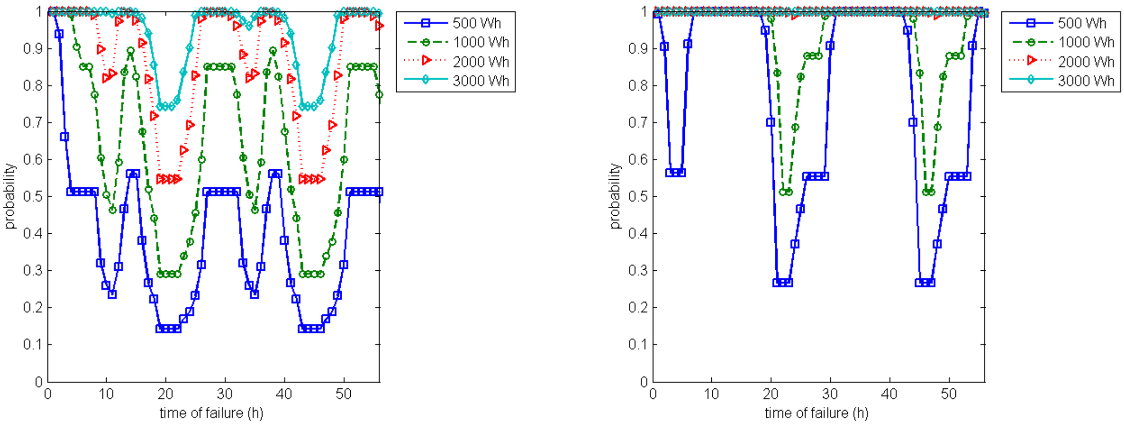
The situation changes when the production is higher, e.g., on a sunny winter day. The results for this setting are shown in Figure 45(b) and one can see that the survivability is high after noon (12 p.m.), but drops in the evening between 7 p.m. and 9 p.m., depending on the size of the battery. The reason is that the larger production during a sunny afternoon allows to recharge the battery and a full battery provides the means to survive a power outage for a couple of hours. However, during the night and the early morning the battery is always empty due to the *Greedy* strategy, hence, the probability to survive an outage at these times is zero. The described pattern repeats for consecutive days with this setting. The differences with the first 12 hours are due to the chosen initial condition of the full battery which increases the probability to survive in the beginning.

In summer when the production is low, e.g., on a rainy day, one can see in Figure 45(c) that the initial transient phase takes a full day. During this first day the survivability highly depends on the size of the battery, since a larger capacity provides more backup in case of a grid failure. However, after the battery has been emptied once (after the first 24 hours) one can see that the survivability is independent of the battery capacity. The reason is that although the battery is charged during the day, due to the low production, it is never charged above 600 Wh. Hence, additional battery capacity does not have an advantage with respect to the survivability.

On a summer day with a high production Figure 45(d) the start-up phase is much shorter, i.e., less than 10 hours. The reason is that the production is so high that an empty battery is quickly charged in the morning. It is interesting to see that in this setting, with the highest battery capacity of 3000 Wh, the system is survivable with probability one for all considered failure times. With the battery of 2000 Wh the system is not survivable for a couple of hours during the night. Hence, in this setting it is preferable to have a larger battery, while on a summer day with a low production the additional capacity does not increase the survivability in the long run.

Overall, the *Greedy* strategy results in a poor survivability for three out of four production profiles, i.e., with the exception of a summer day with high production. In all other cases the complete draining of the battery leads to a zero probability to survive a power outage for large parts of the day. In the following we will look at the two remaining strategies, *Smart* and *Conservative*, for the two settings *Winter low* and *Summer high* to contrast the impact of the production profiles on the battery management strategies.

5.2.3.2.1.2. Smart



(a) winter low

(b) summer high

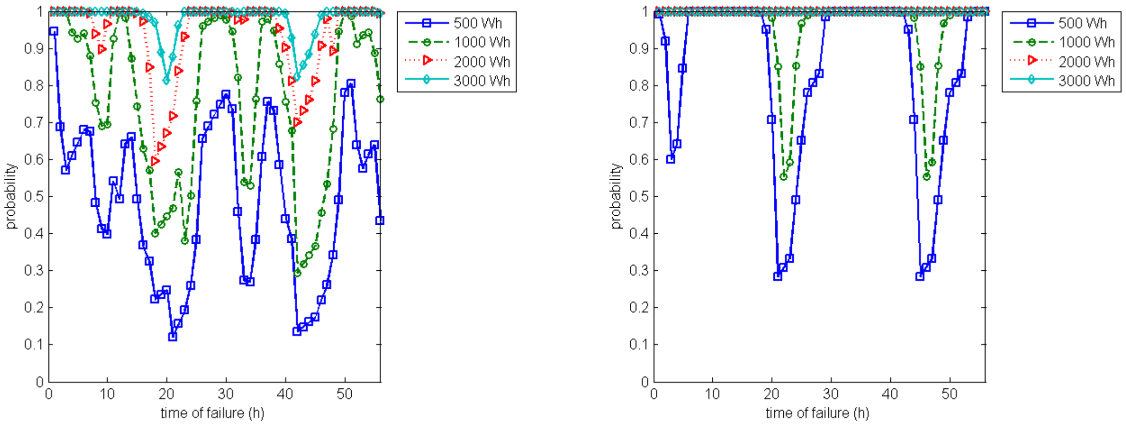
Figure 46: Probability of surviving a grid failure as function of the time that the failure occurs for the Smart strategy. The following two scenarios are considered, (a) winter day with low production, and (b) summer day with high production.

Figure 46 shows the survivability of the system when the *Smart* strategy is used. Recall that this strategy never drains the battery completely while the grid is available and always reserves 30% of the battery capacity to survive power outages. On a winter day with low production, as depicted in Figure 46(a), the survivability highly depends on the overall capacity of the battery. With this strategy the largest battery ensures a survivability of at least 70% for failures occurring at all times of the day, which is a large improvement with respect to the greedy strategy, where the survivability was zero, once the battery had been drained. When a smaller battery, e.g., 500 Wh, is used, the survivability drops to 10% during the night, which is clearly very low. This figure also exhibits a start-up phase, which is, however, rather small (less then 10 hours), after which a pattern repeats with a high survivability during the day and a dip during the evening hours. It is interesting to see that the survivability increases during the night even though the battery cannot be charged with local energy and will not be charged from the grid due to the strategy employed. This is due to the drop of the demand during the night, hence the system can survive longer on the remaining 30% battery capacity than during peak evening hours.

On a summer day with high production (cf. Figure 46(b)) the two largest batteries lead to a survivability of 100% for all potential failure occurrence times. For the two smaller batteries a pattern emerges after the initial start-up time of 10 hours, where the survivability is again high during the day, drops during the evening hours when the demand is very high and local energy is not available. During the night, the survivability then again increases due to the decreasing demand and returns to one as soon as the local generation produces energy again during the day.

When comparing the two strategies presented so far, the minimum survivability with the *Smart* strategy is, depending on the size of the battery, much better than when *Greedy* is used. However, the time intervals where the survivability is *not* good remain the same.

5.2.3.2.1.3. Conservative



(a) winter low (b) summer high

Figure 47: Probability of surviving a grid failure as function of the time that the failure occurs for the Conservative strategy. The following two scenarios are considered, (a) winter day with low production, and (b) summer day with high production.

Finally, we also analyse the *Conservative* strategy, where the resilience of the system is increased by additionally charging the battery from the grid, when its state of charge is lower than the predefined threshold SoC_2.

The resulting survivability is presented Figure 47. Especially on a winter day with low production, the variability is much higher than in the other settings. The reason is that we observe a relatively high number of state changes between the states *good* and *empty* of the battery management unit. As soon as the state of charge is less than 30% of the overall battery capacity, the grid is used to power the house, and it *also* charges the battery until it reaches 50% of its capacity. If this occurs at a point in time where the local generation is still not producing enough energy, the house is then powered from the battery until again the state of charge hits the 30% threshold. Especially for smaller battery sizes these state changes occur relatively often since the difference between 30% and 50% state of charge is smaller. As a result of the large amount of variability in the system, also the results do not reveal a clear pattern for the different battery sizes.

On a summer day with high production, the survivability is much more regular, as shown in Figure 47.(b). The start-up phase takes about 10 hours and we observe a survivability of one for the two large batteries and a minimum survivability of 30% and 55% for battery sizes 500 Wh and 1000 Wh, respectively, during the evening dips. When compared to the results for the *Smart* strategy one sees that the time intervals where the survivability is relatively low are much smaller for the *Conservative* strategy.

Overall one can conclude that achieving a high survivability is especially difficult on a winter day with low production. Having a larger battery only increases the survivability in this setting if one reserves backup power in the battery, which is only used in the case of a power outage. Additionally charging the battery from the grid in case of a low state of charge also improves the overall survivability and decreases the intervals of time where the survivability is low.

In contrast, on a summer day with high production the two large batteries are enough to ensure a survivability of 100% for the strategies *Smart* and *Conservative*, and even for *Greedy* the largest battery capacity ensures the same. One can conclude that in order to ensure a relatively high survivability, a smart house with the presented parameter settings would need a battery with at least a capacity of 2000 Wh and would employ at least strategy *Smart*. Note that, when the *Conservative* strategy is used, the thresholds SoC_1, SoC_2 and the additional charge from the grid have to be chosen carefully to reduce the number of state changes in the battery management unit, hence, to avoid cycling behaviour.

Table 32 summarizes the results of all the computations. The table shows the range and average survivability probability over a 24 hour period for all analysed scenarios. Here, the battery capacity was set to 2000 Wh. From this table we can clearly see the differences in survivability for the three strategies.

Table 32: Range and average survivability probabilities for all analysed scenarios with a battery capacity of 2000 Wh.

strategy		**winter low**	**winter high**	**summer low**	**summer high**
Greedy	min – max	0 – 0	0 – 1	0 – 1	0 – 1
	average	0	0.33	0.31	0.70
Smart	min – max	0.55 – 1	0.53 – 1	0.85 – 1	0.99 – 1
	average	0.84	0.90	0.98	1
conservative	min – max	0.70 – 1	0.59 – 1	0.92 – 1	1 – 1
	average	0.93	0.94	0.99	1

5.2.3.3 Bronsbergen demonstrator

In the Bronsbergen demonstrator we have a large set of houses equipped with PV-panels, and one large battery with 350 kWh usable capacity [14]. When we aggregate the demand and production of the entire Bronsbergen area, we can use the same model as for the single house to analyse the probability the area can survive a grid failure and operate as a microgrid.

Figure 48 and Figure 49 give the used demand and production profiles, respectively. The demand profile is, again, based on the ESDN profiles. However, now it is scaled to the demand of the entire Bronsbergen area. We have estimated, based on Figure 6 in D6.1 [12], the yearly demand of the holiday park to be 578,000 kWh.

For the production profiles we assumed that all PV-panels, total 315 kWp, are faced SW. This leads to a slightly skewed peak, with a higher production in the afternoon than in the morning.

In this scenario, we only consider the smart management strategy. Instead of changing the battery capacity, which is a given, we parameterize the fraction of the battery that is kept as back-up.

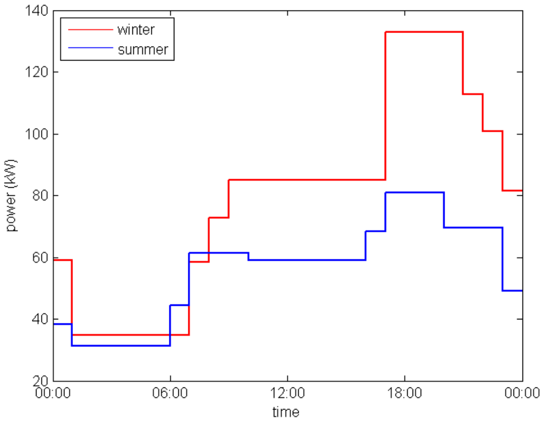


Figure 48: Demand profiles for the Bronsbergen scenario

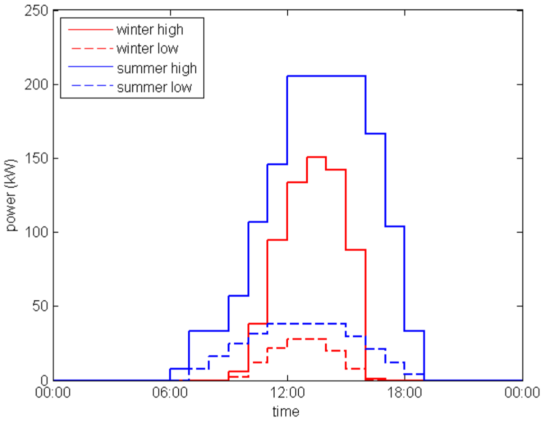


Figure 49: Production profiles for the Bronsbergen scenario

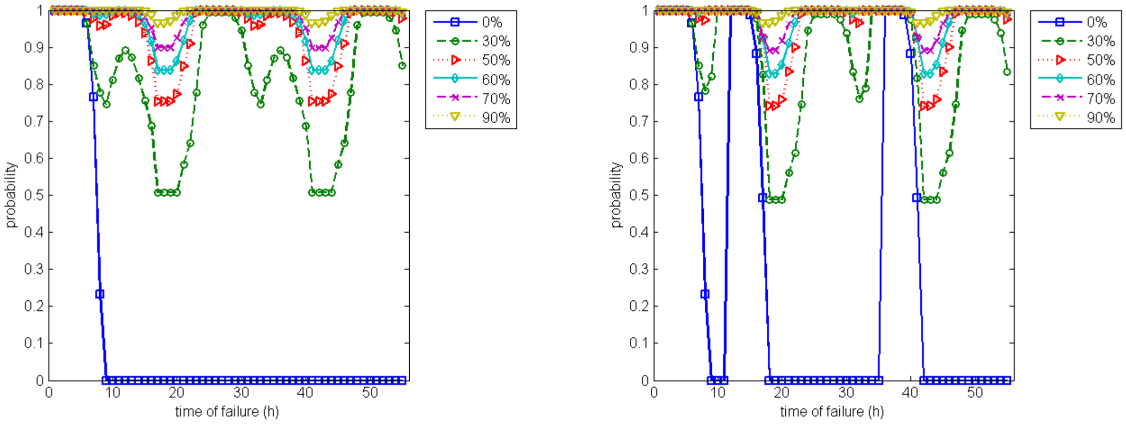
5.2.3.4 Survivability results

Like in the single house scenario we consider a random repair time, that is distributed according to a folded Normal distribution with average 2 and standard deviation of 1 (hour). The results of the analysis of the Bronsbergen scenario are given in Figure 50.

On a winter day with low production, Figure 50(a), we see that when no back-up energy is kept in the battery the survivability probability remains zero, after the battery is empties in the first night, since, in this case, the demand always exceeds the production. When 30% of the battery energy is reserved for back-up, the minimum survivability probability is increased to approximately 50%/ This minimum is achieved during the evening hours, when the demand is the largest. Reserving more back-up energy results in higher survivability probabilities. However, even when 90% of the battery is used as back-up, one cannot be fully sure to survive a failure during peak demand hours.

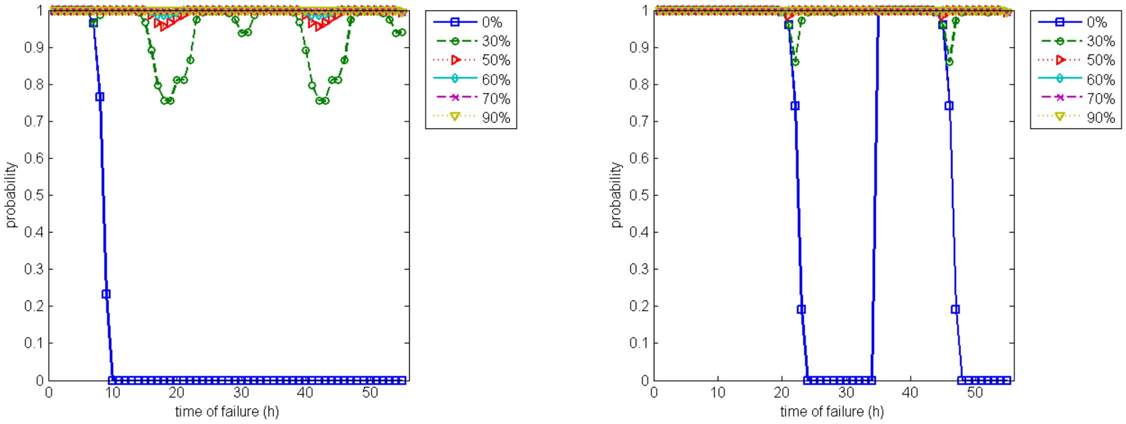
On a winter day with high production, Figure 50(b), we observe similar survivability probabilities during the nights. In both case, low and high production, the battery will be emptied until the back-up level during evening, thus the scenarios are actually the same during the nights. However, during the day, the local production is big enough to ensure survivability for a couple of hours, even without any back-up energy.

For the summer days, Figure 50(c) and Figure 50(d), we see that it is possible to survive the grid failure with probability 1 at any time of the day. On days with low production it is sufficient to reserve 70% of the battery capacity for back-up, and on days with high production 60% is enough.



(a) Winter low

(b) Winter high



(c) Summer low

(d) Summer low

Figure 50 Probability of surviving a grid failure as function of the time that the failure occurs for the Bronsbergen scenario. The following four scenarios are considered, (a) winter day with low production, (b) winter day with high production, (c) summer day with low production, and (d) summer day with high production.

5.2.4 Discussion

When comparing the three strategies Greedy, Smart and Conservative, we see that while Greedy allows using the battery in the most flexible way, it also provides the lowest survivability. In contrast, when a certain percentage of the battery is only used in case of a power outage, the survivability increases considerably, but this part of the capacity cannot be used in a flexible way. This clearly shows the trade-off between using the battery for balancing purposes and providing backup in case of a grid failure. The Bronsbergen scenario shows how this trade-off is dependent on the time of year, and level of production.

An additional trade-off for this system is the one between the investment costs, for the battery and additional equipment, and the earnings you can get by using the battery for balancing purposes. We want to investigate this trade-off further in the last part of this project.

6 Summary and Conclusions

The activities carried out in task T5.3 and described in this deliverable have permitted to obtain a list of conclusions and recommendations for the next demonstration steps of the e-balance project, which are commented as follows:

- The current implementation state of Grid resilience Components of the Energy Management Platform is suitable for being deployed in the demonstrators, e.g. in Batalha, Portugal – grid resilience and self-healing – and in Bronsbergen, The Netherlands – energy balancing towards energy resilience.
- Moreover, their design was performed so that their integration will be straightforward, as off-the-shelf industrial products and embedded devices, as well as industry systems – namely by Efacec – were selected to welcome the new software prototypes. The new software prototypes enhance the former range of features already available by those systems and devices.
- The implementations grants a high technology readiness level – actually, TRL 7 – to the improved industrial solutions and devices, meaning that the prototyped solutions will be demonstrated in a real grid operational environment.
- The energy management platform (EMP) development, comprising all **energy resilience and self-healing** features, developed and implemented for the Grid Management Units serving the **Batalha demonstrator**, are as follows:
  - Improving the energy efficiency of MV grids, by mitigating active power losses:
    - **Optimized Power Flow (OPF): performed by the TLGMU**
    - **Validation of Optimized Solutions (VOS): performed by the TLGMU**
  - Quickly detecting and locating faults and short-circuits occurring at MV grids, subsequently performing fault isolation and service restoration:
    - **Fault Detection, location, Isolation and service Restoration (FDIR): performed by the MVGMU**
  - Monitoring of LV grids, comprising power flows, voltage and losses calculation, as well as monitoring of public street lighting circuits:
    - **LV Neighbourhood Power Flows (LV NH Power Flow): performed by the LVGMU**
  - Monitoring of LV and MV grids, comprising the impact of DER assets:
    - **Distributed Energy Sources Power Flows (DER Power Flows): performed by the LVGMU and by the MVGMU**
  - Detecting and locating faults and short-circuits occurring at LV grids:
    - **LV Fault Management (LV Fault Mng): performed by the LVGMU**
  - Detecting and locating faulty light bulbs:
    - **LV Fault Management (LV Fault Mng): performed by the LVGMU**
  - Fault prevention at LV grids, comprising voltage level control and thermal stress mitigation:
    - **LV Fault Management (LV Fault Mng): performed by the LVGMU**
  - Fault prevention at public street lighting circuits:
    - **LV Fault Management (LV Fault Mng): performed by the LVGMU**
  - Service quality assessment at LV grids:
    - **Key performance indicators (LV Quality): performed by the LVGMU**
  - Fraud detection at LV grids:

    - **Fraud Detection (LV Fraud) : performed by the LVGMU**

- The energy management platform (EMP) development, comprising all **energy** resilience using energy balancing features, developed and implemented for the Grid Management Units serving the **Bronsbergen demonstrator**, are as follows:
  - Improvement of power quality by energy balancing:
    - **Energy balancing logic: performed by MV-GMU, LV-GMU and CMU**
  - Lowering the stress on transformers and cables:
    - **Energy balancing logic: performed by MV-GMU, LV-GMU and CMU**

The implemented algorithms serve the purpose of e-balance, namely the defined architecture and the expectation for accomplishing the defined use cases, while matching the demonstration goals for both Bronsbergen and Batalha demonstrators, respectively in The Netherlands and in Portugal.

The option for developing and subsequently integrating the software prototypes in industrial electronic devices, namely by Efacec, depicts the Consortium intention to value and to leverage the e-balance outcome towards enhancing the current solutions available in the industry, towards improving the Smart Grids.

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