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D3.6 Decision Support for self-healing

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Description of the contribution of each partner organisation to the work presented in the deliverable.

Partner	Contribution
UdG	Main contributor:
CS	
JR	-
EYPESA	Pilot grid operation details
UPC	PED contributions to Self-healing
SIN	-
ICOM	-

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Acronyms and abbreviations

AMI	Advanced Metering Infrastructure
DMS	Distribution Management System
ESB	Enterprise Service Bus
HLUC	High Level Use Case
ICT	Information and Communication Infrastructure
ILP	Integer Linear Programming
LV	Low Voltage
MV	Medium Voltage
PED	Power Electronic Device
PMU	Phasor Measurement Unit (Synchrophasor)
PUC	Primary Use Case
SCADA	Supervisory Control and Data Acquisition
SG	Switch Gear
SM	Smart Meter
OF	Optic Fibre
WAMS	Wide Area Monitoring System

Executive Summary

The document introduces the challenge of the self-healing concept in smart grids, as a natural extension of protection strategies and considering the additional complexity of distributed generation. The chapter 1 includes the formulation and associated state of the art to follow with specific considerations derived from the RESOLVD pilot. Chapter 2 is devoted to present the self-healing problem and formulating it as a general optimisation problem applicable to any smart grid. Self-healing is a general concept that denotes the resilience of power systems. It embraces the control and scheduling strategies to ensure reliability of power grid and uninterrupted power supply. Implementing a complete self-healing strategy in a grid requires redundancy at sensing and acting levels. At sensing level redundancy is required to perform fault detection and isolation, whereas at control/acting level it is required to provide alternative configurations to maintain supply in presence of outages. In presence of faults, the purpose of self-healing is to minimize the outage area and system operating loss. In this first part, the document also wides the scope of self-healing to enhance normal operation, by optimizing the operation to reduce the apparition of critical events. The section includes a detailed state of the art of self-healing. The particularities of the RESOLVD pilot grid are also analysed in this chapter, considering the reconfiguration possibilities that the 3 newly installed switchgear offer. This analysis is based on the study of possible transitions that the operation of these switchgears can create and presented in a state diagram. This allows to consider both radial and ring exploitation of the grid and the consequences it supposes for the protection schemes.

Next, chapter 3, analyses capabilities of the power electronic devices during specific scenarios related to RESOLVD use cases related to self-healing and islanding. The power electronic device developed in RESOLVD provides an additional degree of flexibility, since it can manage island solution supported by the storage elements. In particular, the following High Level Use Cases are analysed:

- HLUC05: Self-healing after a fault: once a fault is located, they alert the self-healing application to initiate corrective actions, acting on switchgears and the PED, e.g. exchanging power.
- HLUC06: Power management in intentional and controlled-island mode: Main service is to help to minimize both types of supply interruption, planned and accidental. The PED can energise the isolated low voltage grid.
- HLUC07: Detection and interruption of unintentional uncontrolled island mode. The riskiest situations that can occur in the LV grid is uncontrolled islanding. This means that part of the network, despite being disconnected from the main grid (due to maintenance activity or protection elements actuation after a fault), keeps being powered by DG sources in an uncontrolled way.

During outages, usually the information flows increase considerably and communication can also be affected reducing the reaction capabilities. In the RESOLVD architecture, the power electronic device will have autonomy to implement some self-healing operations; consequently, the required information to support decisions support has to be available.

1. Introduction

1.1. Scope of the document

This document reports the activity of T3.5 related to capabilities RESOLVD technologies to provide self-healing properties to the grid and extends to other considerations related to self-healing resulted during the project development. The task includes the general problem formulation of the self-healing problem; and a particular investigation on specific capabilities of RESOLVD hardware (i.e. synchrophasors and power electronics device) to support local and autonomous decision making and acting during outages (self-healing). During outages, usually the information flows increase considerably and communication can also be affected reducing the reaction capabilities. In the RESOLVD architecture, the power electronic device will have autonomy to implement some self-healing operations; consequently, the required information to support decisions support has to be available. This issue will be examined during the demonstration.

The document aims to report the general problem formulation to implement a centralised self-healing application (Figure 1). With this aim the document revises the self-healing concept and the state of the art of the problem statement and solving procedures. However, the document extends the analysis to the identification of operations that the power electronic device can perform locally and it includes a study on data/information requirements for decision support during outages.

This document describes the RESOLVD approach for self-healing. In particular, it addresses three main issues that self-healing imply:

1) General approach to self-healing, formulated as an optimization problem to decide the better system reconfiguration in presence of outages.
2) Contribution of the power electronic device (PED). That is the local capabilities that Power electronic offer to manage energy during outages or islanding episodes.
3) Data and communication requirements in wide area monitoring and self-healing applications

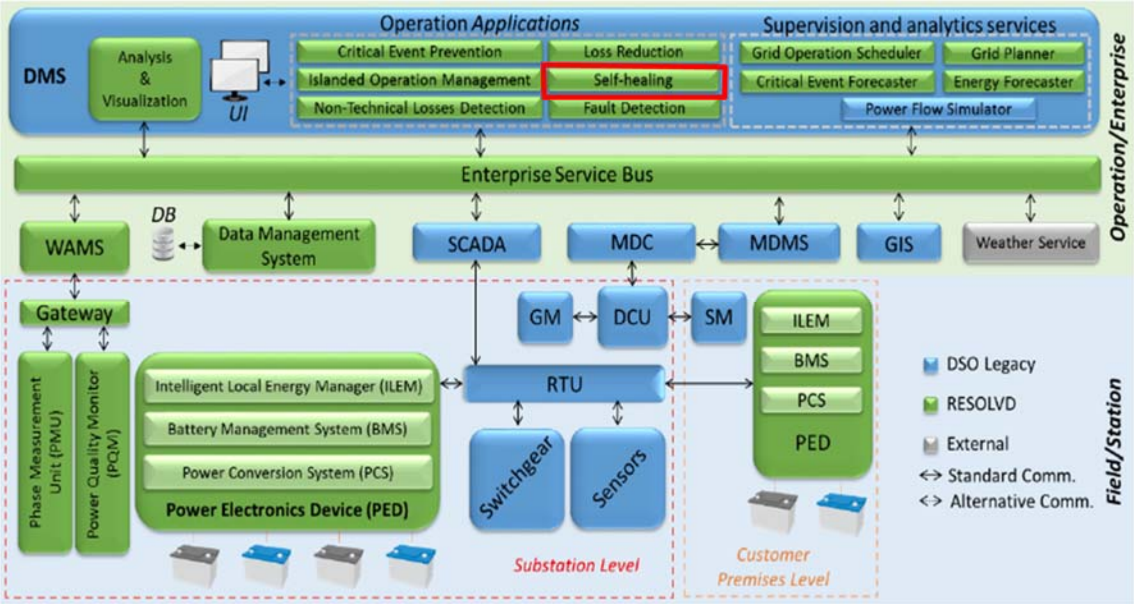


Figure 1 Identification of self-healing application in the RESOLVD architecture.

The general self-healing approach can be defined as an optimisation problem constrained to the operation boundaries imposed by the grid, safety operation and quality of supply criteria, during outages.

The power electronic device developed in RESOLVD provides an additional degree of flexibility, since it can manage island solution supported by the storage elements. This particular issue is also being discussed in the document.

Finally, major observability of RESOLVD, provided by the deployment of synchrophasors in the grid, provides enhanced fault detection and isolation capabilities but requires of communication infrastructures and bandwidth not always available. Reduction of this data flow can reduce the reaction capabilities when decision making procedures are centralised at the control room for a further mapping into the switching elements and/or power devices for acting. Limitations in the RESOLVD pilot are analysed in the chapter.

This document aims to set the basis for self-healing in the RESOLVD project previous to the integration of components. After this integration the project aims to test self-healing possibilities based on this analysis. Conclusions will be reported in further deliverables.

1.2. Report structure

The document is organised in five chapters. Introduction is the present chapter and presents the objectives and structure. Next, follows a chapter devoted to formulate the self-healing problem and discussion on the state of the art. The chapter also includes the analysis of the pilot grid and possible states to perform self-healing. Third chapter analyses the role of power electronic device in specific self-healing operations, in the pilot grid, by performing local actions where it is connected and autonomously when operating in the self-healing mode. Fourth chapter aims to discuss on the data and communications requirements for the implementation of self-healing methods in a centralised way (e.g. wide area monitoring with PMU networks) and the capabilities that distributes solutions offer. Finally, the last chapter is devoted to the conclusions.

2. Self-healing of smart grids: from concept to actual challenges

Self-healing is a general concept that denotes the resilience of power systems. It embraces the control and scheduling strategies to ensure reliability of power grid and uninterrupted power supply [27]. Implementing a complete self-healing strategy in a grid requires redundancy at sensing and acting levels. At sensing level redundancy is required to perform fault detection and isolation, whereas at control/acting level it is required to provide alternative configurations to maintain supply in presence of outages.

During, normal operation, the purpose of self-healing control is to optimize the operation and eliminate hidden troubles; whereas in presence of faults, the purpose of self-healing is to minimize the outage area and system operating loss. In this second scenario, it encompasses the fault location, isolation and reconfiguration of the grid to restore as much as possible power in order to minimise the impact of a failure in the affected are. The first, fault location, requires field information, from sensors and basically consists on checking consistency of the information they provide according to normal operation conditions. Second, fault location, stands for delimitating the affectation by analysing which sensors observe the fault and using that information to bound the possible location to specific pinpoint location in a line or identifying misbehaving components. Finally, the third step, reconfiguration, implies modifications on the grid operation (topology, set points, etc.) to avoid the fault and preserving the operation conditions as close as possible to the normal operation. Reconfiguration usually attempts to maximise some pre-defined objective (e.g. amount of supplied power, number of costumers, quality of supply, etc.).

Although self-heling is still an open research field, some successful implementations already exist. The self-healing smart grid in Ho Chi Minh City (Vietnam) developed by Thu Thiem Power Company and Schneider Electric is a recent example [18]. It provides fault isolation and service restoration, reducing the duration and impact of any fault on the medium voltage network by reconfiguring the loop – which happens in less than a minute for 66% of customers.

2.1. The self-healing optimisation problem and state of the art

Self-healing is a grid reconfiguration problem that can be formulated as an optimisation problem and its solution consists on searching for the best solution that satisfies a set of equality and inequality operational constraints according to a fitness of cost function. Since the grid reconfiguration basically is possible through the actuation on switching elements, the problem is of combinational nature and the search space increases exponentially as the number of switches in the system increases. Thus, self-healing of grids involving a large number of switching elements usually are solved with metaheuristic methods capable to provide suboptimal solutions in reduced time.

A formal definition of the self-healing optimization problem can be formulated according to [2][15]. Based on these works, next subsection reports the general self-healing problem formulation as a fitness function related to the area that the grid is serving (specified for example in terms of supplied power, number of customers or buses) and the set of constraints that the problem should satisfy. Then, problem solving is reduced to explore the problem space using metaheuristics.

To quantify the out-of-service area (to be minimized) in the objective function, several representations can be used [15][2]:

Number of out-of-service buses:	$\min \sum N_{bus}^{OS}$
Number of out-of-service costumers:	$\min \sum N_{loads}^{OS}$
Amount of power/energy not delivered:	$\min \sum E_{loads}^{OS}$

Usually self-healing is defined to minimize at least one of these factors. However, the problem formulation may include a unique objective, combination of them or a main objective with additional considerations such as the reduction of the operation (switching) cost or the power losses, within a multi-objective formulation [7].

Priority loads can be also considered in the formulation, given different weights for each costumer or bus [11]. In addition, local generation from distributed energy resources can be prioritized to optimize the hosting capacity of the grid [3][10].

As in the scheduling optimization formulation (presented in deliverable D3.5 of this project [34]), the typical network and operation problem boundaries have to be considered, such as power flow balance, bus voltage, line current, and power transfer capacity constraints, as well as power production and consumption limits and the grid topology, usually radial or meshed. These and the other constraints, such as the number of switching actions, can be formulated as hard constraints or integrated in the objective function.

Once the formulation is defined, different solution methodologies can be adopted. For small systems, mathematical programing can provide the optimal solution of some formulations. Nevertheless, these formulations are usually non-convex and require heuristics or meta-heuristics methods to solve large systems. Although heuristics and expert systems have presented good results for some specific systems [12][13], meta-heuristics provide a better general methodology [14].

In this scenario, a decision support system framework shall be able to provide an optimal solution for effective self-healing and grid reconfiguration, considering distinct objectives and operating conditions. Overall, decision support systems consider numerous (conflicting) evaluations in a multi-criteria analysis, enabling choice of action in an uncertain environment [4], and also rely on information about alternatives, which may include the network topologies and operating constraints aforementioned and also multi-day-ahead operation models to enable an adequate self-healing planning over time [5][9]. However, some multi-objective problem formulations may have no feasible solution or multiple (sub-optimal) feasible solutions over a range of scenarios.

As an option, if the data are decentralized, communication and cooperation strategies can be used to supply services to out-of-service areas within a multi-agent system framework [6]. In this scenario, the agents are autonomous entities representing distinct parts of the system. For instance, network components are local agents, whereas aggregators are zone agents and the system operator is the orchestrator agent [8].

2.2. General formulation of the self-healing problem

In the following subsections the optimization problem presented in the previous section is completely formulated based on [15]. First, the representation of the network and their elements is presented aiming to introduce the constraints that electrical laws impose in the system. After, the optimisation problem is presented as a multi objective fitness function and additional constraints imposed by operation are added.

2.2.1. Network representation and electric constraints

The network is defined by a directed graph, (G), with a set of attributes and constraints. The constraints are due to electrical laws (see below) and engineering/operational constraints (2.2.2/A). They may apply globally to the graph or only to nodes or arcs. The graph (G) is defined as a set of n arcs (A) and a set of m nodes (N):

$$G = \{A,N\} \tag{1}$$

The n arcs are usually denoted by two subscripts representing the nodes they are connecting. So, A_{ij} by convention represents an arc connecting nodes N_i and N_j.

$$A = \{A_{ij}\} \tag{2}$$

By using the notation in (2), there is not need to explicitly specify the set of nodes (they are represented by i and j). Fig. 2 shows a drawing of a simple graph.

Power balance equations and Kirchhoff voltage rule apply to the network. The sum of the total demand of power ($\Sigma P_d(t)$ and losses ($\Sigma P_{losses}(t)$) must be equal to the total supply ($\Sigma P_s(t)$).

$$\Sigma P_d(t) + P_{losses}(t) = P_s(t) \tag{3}$$

Moreover, for a network without islanding, the total demand of power ($\Sigma P_d(t)$) may not exceed the maximum capacity of the supply ($\Sigma P_{s,max}$). This constraint is important to take into account while reconfiguring the network.

$$\Sigma P_d(t) + P_{losses}(t) \leq \Sigma P_{s,max} \tag{4}$$

The total demand is defined as the power consumed ($\Sigma P_c(t)$) and stored ($\Sigma P_{stored}(t)$):

$$\Sigma P_d(t)=\Sigma P_c(t) + \Sigma P_{stored}(t) \tag{5}$$

The total supply is the sum of the power supplied by the substations ($\Sigma P_{CG}(t)$), the distributed generation ($\Sigma P_{DG}(t)$) and the power released by the energy storage ($\Sigma P_{released}(t)$).

$$\Sigma P_s(t) = \Sigma P_{CG}(t) + \Sigma P_{DG}(t) + \Sigma P_{released}(t) \tag{6}$$

Moreover, the Kirchhoff voltage law applies for every loop:

$$\Sigma v(t) = 0 \tag{7}$$

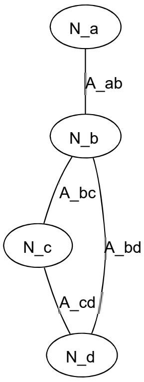


Figure 2 Graph: Circles represent nodes and lines denote arcs.

Table 1 Main parameters of arc elements

Arcs	Parameters	General laws
A_L	Z_{ij}	$v_j(t) - v_i(t) = Z_{ij} i_{ij}(t)$
A_S	Actual state, Normal state, Operability with current, Remote control, Healthy/unhealthy state	$Z_{ij,closed} \simeq 0$ $i_{ij,open} = 0$

A. Arcs

Arcs are element where the current is constant for every time instant:

$$i_{jk}(t) = C \tag{8}$$

Arcs can be subdivided in a set of lines (A_L) and switches (A_s), and only the last can be operated:

$$A = \{A_L, A_s\} \tag{9}$$

Some switches can be remotely controlled. Switches are also characterised by their normal status and current status as their ability to work. The power consumption for the arc element is very low, negligible for the self-healing problem.

B. Nodes

The set of nodes is made up of the main feeder from the substation (N_{CG}), the distributed generators (N_{DG}), the loads (N_{loads}), the static distributed storage ($N_{statstorage}$) and also possible mobile distributed storage ($N_{mobstorage}$) and the Var control devices (N_{VAR}) and nodes that do neither represent supply, consumption nor VAR control (N_{others})

$$N_{leaf} = \{N_{CG}, N_{DG}, N_{loads}, N_{statstorage}, N_{mobstorage}, N_{VAR}, N_{other}\} \qquad (10)$$

Take into consideration that the distributed generation may be intermittent (e.g. photolvotaics) or not (e.g. generation with biofuels) and the distributed storage may be mobile (i.e. electrical vehicles) which complicates the self-healing problem. The loads are characterised by their observability (e.g. smart meters), their priority (which in turn defines load shedding strategies), their nominal power and actual current and voltage.

Table 2 Main parameters of nodes

Nodes	Parameters
NCG, NDG	$ik(t)$, $ik,max(t)$, Vk,nom, $Pk(t)$, $Qk(t)$, real-time observability
$Nloads$	$i_k(t)$, $i_{k,max}(t)$, V_{nom}, $Priority_k(t)$, load shedding capabilities , $P_k(t)$, $Q_k(t)$, real-time observability
$Nstatstorage$, $Nmobstorage$	$ik(t)$, $ik,max(t)$, Vk,nom, Ek,max, $P_k(t)$, $Q_k(t)$, real-time observability
$NVAR$	V, $cos\varphi$, controlability capabilities, realtime observability
$Nother$	$i_k(t)$, $V_k(t)$, $P_k(t)$, $Q_k(t)$, real-time observability

The parameters of other nodes are illustrated in the Table 2. The electrical parameters of all nodes may be observable (in real-time) if a monitoring device with telecommunication capabilities is installed at the node; otherwise the value has to be assessed by power flow calculation using power flow solvers or similar tools.

For the nodes N_{CG}, N_{DG},N_{loads}, $N_{statstorage}$, $N_{mobstorage}$, the current has to be below the maximum:

$$i_k(t) \leq i_{k,max}(t) \qquad (11)$$

For the static and mobile storage, the released energy ($E_{k,released}$) may not exceed the stored energy ($E_{k,stored}$) :

$$E_{k,released} \leq E_{k,stored} \qquad (12)$$

with the stored energy being the integral of power($P_k(t)$) over time:

$$E_{k,stored} = \int P_k(t).dt \qquad (13)$$

C. States

The network (G) evolves from an initial state ($S_{start}{}^G$) to the final state (S^G_{end}), through a sequence of intermediate states:

$$S^G(t) = < s^G_k(t) > \tag{14}$$

with $t_{start} \le t_k \le t_{end}$

and where $s^G{}_k(t)$ is a set of power measurements ($I_{ij,k}$, $V_{m,k}$) at arcs (A_{ij}) and nodes (N_m), and arcs switch states ($A_{s,k}$) at t_k

$$\exists N_{load,k} \in N_{load} : P_k = 0 \tag{15}$$

The final state can be defined implicitly by reaching the maximum of the objective function $f(t) = max[f(t)]$, or a pseud-maximum over a specific threshold $f(t) \ge C$.
Next subsection details how can be defined the objective or fitness function.

2.2.2. Self-healing: constraints and fitness function

A. Additional constraints

Beside, electrical laws (see above), the maximum capacity has to respected for the central and distributed generation as for the distributed storage.

$$i_k(t) \le i_{k,max}(t) \tag{18}$$

Some switches may not operate under current, thus $i_k = 0$ while operating them.
The network may be constrained to work under some topology (unidirectional or bidirectional radial, meshed, islands). Moreover, for reconfiguration, power quality (e.g. voltage limits) or cost reduction (e.g. good power factor) may be asked.

B. Fitness function

Grid reconfiguration during self-healing consists on optimizing some objectives. The following are the most common. They can be used alone or in combined to define multi-objective functions:

- Number of supplied consumers by priority level: $max(Nc,priority_k)$
- Supplied power/energy: $max(\Sigma E_c)$ or $max(\Sigma P_c)$
- Frequency of outage by zone (area k) and time period (Δt): $min(numberOutagearea\ k, \Delta t)$
- Power quality (voltage and reactive power) (e.g. Vmin ≤ V ≤ Vmax, c ≥ cosφ): EN50160 is used as a standard in Europe, but some countries have implemented stricter limits.
- Operational costs (Power balance between elements)

The operators should choose one or several of this goals in which case it combines them using weights to build a multi-objective function. Alternatively, reliability indexes which are combination of the goals may be made compulsory in application of regulations. However, give reward/penalty differs across countries [6].

C. Reliability indices

Despite, reliability indexes and the monitored parameters are not standardised across countries, some indicators usually adopted in the European countries, according to the Council of European Energy Regulators (CEER) include the following:

$SAIFI$ (system average interruption frequency index).

$$SAIFI = \frac{\Sigma N_i}{N_t} \tag{19}$$

where ΣN_i is the total number of interruptions and N_t the number of total customers in the network.

- $SAIDI$ (system average interruption duration index):

$$SAIDI = \frac{\Sigma N_i r_i}{N_t} \tag{20}$$

where r_i is the duration of the interruption N_i

- $MAIFI_E$ (momentary average interruption frequency index): for measuring frequency of short interruptions:

$$MAIFI_E = \frac{\Sigma IM_E N_{mi}}{N_T} \tag{21}$$

where IM_E is the number of momentary interruptions and N_{mi} is the number of interrupter customers during each interruption

- ENS (energy not supplied) due to interruptions in the transmission network

$$ENS = \Sigma E_i \tag{22}$$

where ENS is the sum of unsupplied energy.

The focus on one or several goals can thus be based on reliability indexes.

D. Problem solving

The solution (Sol) is a temporal sequence of operations ($o_{k,t}$) that optimizes the goals and comply the constraints defined in the previous subsection

$$Sol = < o_{k,t} > = < A_{s,k}(t) > \tag{23}$$

where

$t_{start} \leq t \leq t_{end}$ and $o_{k,t}$ refers to a switch A_k operated at time = t.

Finding the optimal or pseudo-optimal solution is search problem that usually is solved by using evolutionary programming (genetic algorithms/programming), particle swam optimisation or simulated annealing methods.

2.3. Current challenges to implement self-healing strategies in distribution smart grids

Traditionally, in distribution networks, protection strategies implement self-healing actuations aiming to protect the assets to specific failures and on the basis of some operation assumptions, i.e. radial operation, no generation (or insignificant), oversized lines, voltage control, etc. It basically consists of a set of protection relays and fuses, distributed in substations and along the lines, with fixed and coordinated settings to automatically react to predefined pattern faults (magnitude and location) in reduced times. After this autonomous actuation, is the system operator who, remotely or supported by crews in the field restore the network for a suboptimal operation until the failure is repaired.

In current smart grid context with non-dispatchable distributed generation, storage elements, electric vehicles, power electronics, and active demand response, as representative technologies; the self-healing concept acquires a new dimension; and optimisation during both, normal and faulty operation, gains sense. Grid operation objectives are the same (grid safety, quality of supply, etc.) but operation possibilities can variate depending on the observability and availability of controllable assets (switchgear, storage, power flow control, etc.). Thus, episodes of high generation could require a reconfiguration to avoid congestions through the use of storage capacity or simply to facilitate evacuation through other circuits, as preventive self-healing operation. Similarly, the presence of distributed generation and storage suggest the possibility to temporarily create and operate islands, or microgrids, during specific fault events. And, this approach should coexist with traditional protection strategies. Thus, self-healing mechanisms have to provide resilience to short-circuits and severe failures but also support to the avoidance of critical events (e.g. congestions, grid stability, etc.) or possible affectations on the quality of supply (e.g. over/sub voltages).

Distributed generation and storage in the grid implies a more complex operation; since they can produce reverse power flow (from distributed generators to substations) at the same time that can reduce coupling stress between demand and generation. Thus, a smart grid has a more flexible operation, but it requires more observability (enhanced instrumentation infrastructures and anticipative capabilities) to be controlled and optimally operated, including self-healing capabilities.

Currently synchro-phasor (PMU) and smart-metering (assuming real time or near real-time communication capabilities, not currently available by many smart metering systems) infrastructures are the sensing infrastructures that complement traditional SCADA systems, providing a higher spatio-temporal resolution of electric magnitudes in the grid. This huge amount of data conveniently processed together with power flow simulators and forecasting tools constitute the input of a new generation of grid operation and self-healing systems aiming to provide anytime optimal operation, included in presence of faults, according to exploitation objectives.

However, this imposes new challenges on the ICT infrastructure that should supports smart grid operation; but also on the capabilities of the self-healing management system itself. During normal operation, ICT infrastructure should support distributed real-time data processing and computing; however, what it is really important is what should be the capabilities during abnormal episodes. In presence of a failure in the power grid, probably part of the ICT infrastructure will be also affected (for example PLC communications will be interrupted by a fault or during outage battery systems supplying ICT will have delimited autonomy). Thus, the new challenge is how to guarantee self-healing capabilities when failures can also affect the ICT infrastructure.

As in the traditional protection systems, self-healing solutions will imply decision capabilities at different levels and this this requires distributed solutions ([1]) based on multi-agent systems ([18]) and distributed computing approaches (edge, fog cloud). The Internet of things paradigm has also envisioned as integration technology to solve the current fragmentation of information in silos (substation automation, customer services, market, etc.) and facilitating data treatment (filtering, analysis and processing) from a vast number of sources in order to provide adequate access to information and providing the redundancy required by self-healing systems [23].

It is well known the impact of distributed non-controllable renewable generation (e.g. PV), due to the production variability and the consequent possibility to cause congestions or affect voltage profiles at supply points. However, the use of inverters (e.g. in PV generation or electrochemical storage) can provide active and reactive power management increasing the controllability of these grids. In [17], the performance of voltage regulation in distributed photovoltaic generation scenarios to assist grid reconfiguration after disturbances caused by severe faults is analysed. Results are based on a sensitivity analysis regarding the performance of voltage regulation, based on a co-simulation of PSCAD and MatLab.

Reconfiguration capabilities (although currently operated radially, distribution grids often present operable ring or meshed architectures), together with voltage regulation and reactive control can provide substantial self-healing capabilities to the distribution grid. However, an efficient communication infrastructure is required to observe and manage in real time these assets in order to guarantee operation requirements.

2.4. Considerations to implement Self-healing strategies in RESOLVD

Implementation of RESOLVD technologies will be demonstrated in a low voltage distribution grid that is represented by Figure 3. The grid is constituted by two secondary substations (SS-A and SS-B), several PV generators that are represented by the rounded G according to the position they can be grouped with respect to the switching points (GA/B). Load correspond to around thirty consumers, represented by the triangles in the different sections (LA/B). The grid has been equipped with a power electronic device (PED) capable to manage energy in batteries located at the substation SS-B and three 3 switchgears (SGi) allowing different configurations. SG1 and SG2 can disconnect the pilot lines from secondary substations, whereas SG3 allows and intermediate connection between the two lines in the pilot.

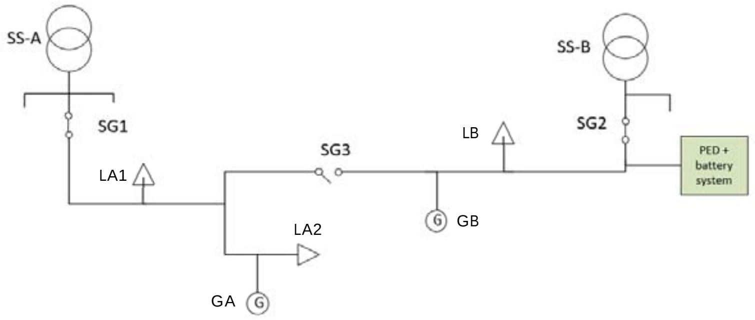


Figure 3 Simplified schema of the pilot grid

Traditionally, operation of the distribution grids is radial (e.g. pilot in Figure 3 with SG1 and SG2 closed and SG3 open). This is to ensure selectivity for protection systems and reduce the impact of protection tripping in presence of faults (only one radial circuit is affected by a trip), in terms of number of customers that are affected; however, a ring exploitation can reduce losses due to a better redistribution of power among feeders conforming the ring [33].

Figure 4 shows possible configuration states that could be achieved with the operation of the three switchgears (SG1, SG2, SG3) in the pilot, before considering the effect of the power electronic device (PED) and batteries. Traditional exploitation in radial feeders correspond to state (110) and line protections are reduced to fuses in substations. In the pilot, SG1 and SG2 allows preventive disconnection of lines, avoiding fuse actuation and at the same time provides additional flexibility to move load from one substation to another by acting also in SG3.

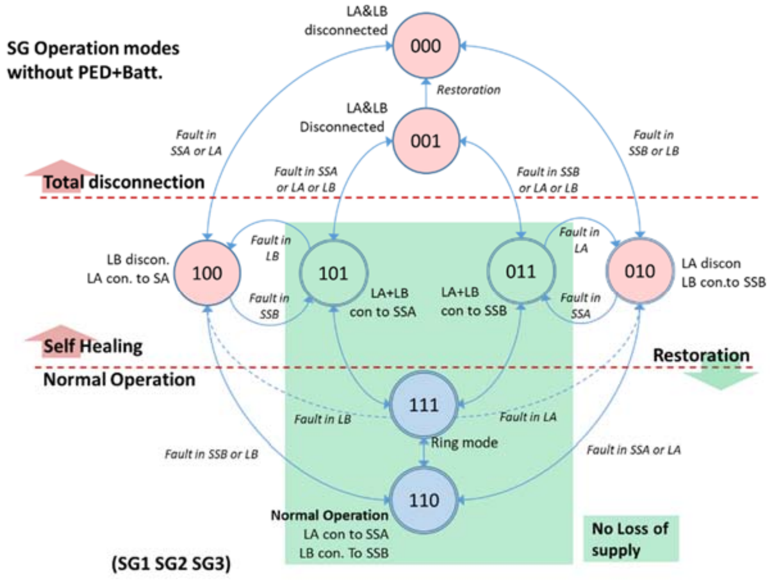


Figure 4 Configuration states of the pilot grid according to switchgear operation without PED and batteries

Tripping line protections at the secondary substations to protect feeders is equivalent to operate SG1 or SG2 resulting in the states (010) and (101) respectively (shadowed in red in the **Error! No s'ha trobat l'origen de la referència.**) with the consequence of loss of supply in the customers. The same consequence is derived from a fault in either SS-A or SS-B. However, in this last situation it would be possible to recover supply by acting on the intermediate SG3 (transition from 100 → 101, and 010 → 011). In case of a ring exploitation (state 111) of this grid, in presence of a transformer failure, either in SS-A or SS-B, it is possible to transfer load to the other substation by simply opening the SG of the affected substation (111→011 to disconnect SS-A or 111 → 101 to disconnect SS-B) preserving the continuity of supply in the whole grid. However, line fault requires two SG operations (111(→110)→100 for faults in LB or 111(→110)→010 for faults in LA).

States circled in double line represent those switchgear configurations that allow connecting the PED and offering additional energy management functionalities, through the scheduling and operation of storage (See RESOLVD deliverable D3.5 [34]), and power quality services, offered directly by the PED.

Figure 5 represents the same state diagram according to connection/disconnection of switchgears (SG1, SG2, SG3) but now considering the actuation of the PED. Again, states with double line represent those that allows a disconnection of the PED (**Error! No s'ha trobat l'origen de la referència.**). It can be observed that now the use of the PED together with appropriate configuration of SGs provides more flexibility to maintain the supply to all the customers (green area in both figures). However, some of these states correspond to island situation and reconnection to the grid is difficult and mainly it requires disconnecting the PED (single sense arrows), with the consequent loss of customers, to be reconnected again to the substations according to the normal operation mode.

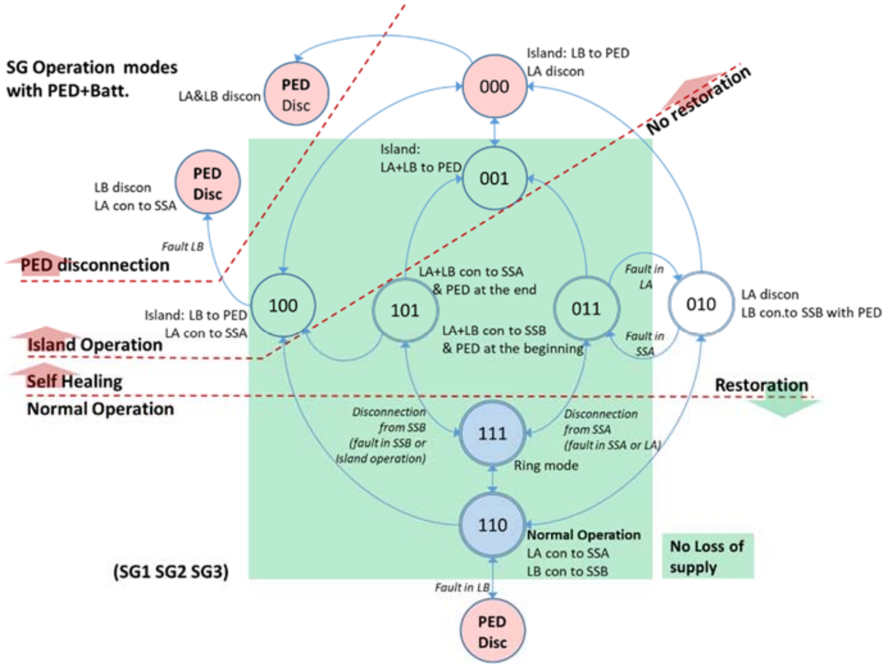


Figure 5 Configuration states of the pilot grid according to switchgear operation with PED+Battery in SB-B

Table 3, in the next page summarises the states that connecting and disconnecting the switchgear in the pilot can be reached and their operative when the PED is connected.

Next, in the following subsection, it is detailed how the PED can contribute to maintain maximum efficiency and quality of supply in presence of faults according to Use cases envisioned in RESOLVD.

Table 3 State description according to switchgears with PED connected

SG1	SG2	SG3 (ini)	State description	Observations
0	0	0	Island mode LB fed by PED + batteries (and GB). LA without service, GA cannot maintain LA.	GA should be disconnected. If possible, battery should be scheduled to maximum charge before changing to this state, during normal operation (110) or at least with LB connected to the main grid (010)
0	0	1	Island mode, without loss of customers LA1&2 + LB fed by PED + batteries (and GA+GB)	GA and GB operating normally. If possible, battery should be scheduled to maximum charge before changing to this state from normal operation (110) or with SS-B connected (010 and 011).
0	1	0	LB connected to SS-B Loss of LA1&2: disconnected from the main grid.	This state is reached from normal operation when a fault occurs in SSA or line A. In the former it can evolve to 011 and recover supply to LA. Batteries in SS-B can be optimally scheduled for peak shaving or similar optimization. GA should be disconnected. From this state it is possible to disconnect the PED without consequences and then follow state diagram in Figure 3.
0	1	1	LA1&2 + LB fed by SS-B.	This state allows feeding LA and LB from SSB and perform peak shaving and battery energy management. Opening SG2 (001) will result in island mode (loss of connection with SS-B) Opening SG3 (010) will result in loss of LA1&2 customers (for example in presence of a fault in LA1&2). Restoration to normal operation (110) implies connecting first SG1 (ring mode 111). From this state it is possible to disconnect the PED without consequences and then follow state diagram in Figure 3.
1	0	0	LB disconnected from the main grid. The only possible transition is to 110.	LA is supplied from SSA and LB is operated in island mode (disconnected from the grid and supplied from batteries by the PED). Reconnection of LB to the main grid is only possible if it is possible to control frequency at both sides of SG3 or SG2 (PED). So, in principle it is not possible to recover this state without disconnecting the PED and losing supply and LB.
1	0	1	LA1&2 + LB fed by SS-A.	LA and LB operated in island mode (disconnected from the grid and supplied from batteries by the PED). Reconnection to the main grid is not possible without disconnecting the PED, losing supply to the lines and restarting from 110.
1	1	0	Normal operation mode	This is the traditional model to operate lines radially: each one from its substation (LA – SSA, LB – SSB). From this state it is possible to disconnect the PED without consequences and then follow state diagram in Figure 3.
1	1	1	Ring configuration	Ring operation: all the loads supplied from both sides (SG3 connected). This configuration allows reducing losses in the grid. However, protection coordination is complex and it requires higher observability to coordinate them. It can be used in specific periods of time but it is not the common configuration. From this state it is possible to disconnect the PED without consequences and then follow state diagram in Figure 3.

3. Contribution of the Power Electronics Device to Self-healing

This section Discusses about how the power electronics devices can contribute to self-healing in low voltage grids; and, in particular, in the RESOLVD pilot grid. For that, the discussion starts from the definition of the use cases related to self-healing defined in WP1. The document describes the technical problem addressed in the identified use cases. Then it depicts how the PED is triggered for impacting on self-healing. After that, the capabilities of the PED to be exploited under such situation are listed. Finally, closing remarks on the actual impact of self-healing are stated.

3.1. Definition of self-healing

In RESOLVD project, self-healing refers to the capability for a network to be reconfigured in front of unexpected and sudden changes in both, loads (outages, connection/disconnection loads) and generation (out of services, sudden changes in renewable sources, etc.) with respect to schedule.

3.2. RESOLVD Use Cases related to self-healing and PED

HLUC05: Self-healing after a fault. According to D1.1 [36], the intense voltage swells (surges) can result in the activation of the overvoltage protections, while voltage drops can provoke a so-called voltage sag (or dip). The main service of this HLUC is using the high observability of the LV be able to detect and locate faults, and then when faults are located, they alert the self-healing application to initiate corrective actions, acting on switchgears and the PED, e.g. exchanging power.

HLUC06: Power management in intentional and controlled-island mode. According to the D1.1, the main service of HLUC is to help to minimize both types of supply interruption:

- Prearranged, that can be due to planned maintenance works of a part of the network.
- Accidental, usually caused by a fault of different natures (external event, equipment failures or interferences).

The main challenge of the PED is to energise the isolated (and non-affected, i.e. after self-healing actions have been succeeded) low voltage grid.

HLUC07: Detection and interruption of unintentional uncontrolled island mode. According to D1.1 one of the riskiest situations that can occur in the LV grid is uncontrolled islanding. This means that part of the network, despite being disconnected from the main grid (due to maintenance activity or protection elements actuation after a fault), keeps being powered by DG sources in an uncontrolled way.

3.3. PED activation and management for each of the Use Cases

HLUC05: Self-healing after a fault. The main idea in this case is contribute to the fault exchanging reactive (and also can be active) power to the fault in order to force the protections intervention.

- PED activation procedure: A instantaneous active and reactive power setpoint is sent by the DMS in order to exchange power. Note, the DMS has to deactivate the automatic operation mode and active the manual mode in order to respond to the fault.
- PED operation: The PED provides power according the demanded setpoint until the DMS changes the corresponding setpoints or the grid is in black out state (or the batteries cannot supply more energy).
- PED main performances to be exploited: The capability of providing power to the fault to facilitate the intervention of protections.

HLUC06: Power management in intentional and controlled-island mode.

- PED activation procedure: A instantaneous command is sent by the DMS in order to energize the low voltage grid. Note, the DMS has to deactivate the automatic operation mode and active the manual mode in order to start the grid forming operation.
- PED operation: The PED energizes the grid until the DMS stops the island mode, sends a command to resynchronized the low voltage grid to main grid, or the batteries cannot supply or absorb more energy and triggers an operation failure.
- PED main performances to be exploited: The capability of PED for creating and maintaining and stable electrical island compensating the variation between consumption and generation.

HLUC07: Detection and interruption of unintentional uncontrolled island mode.

- PED activation procedure: An instantaneous command is sent by the DMS in order to unbalance the low voltage grid equilibrium. Note, the DMS has to deactivate the automatic operation mode and active the manual mode of the PED in order to start the grid forming operation.
- PED operation: The PED performs a predefined power profile in order to break the equilibrium between generation and consumption.
- PED main performances to be exploited: The capability of providing power to the LV system in order to break the equilibrium between generation and consumption and facilitate the intervention of protections.

3.4. Final remarks on PED impact on self-healing

In general terms, the contribution of the PED is on exchanging energy with the grid when there is not grid support, thus ensuring the security of supply to customers. Such lack of mains supply can be because of various circumstances, i.e. a grid fault, or intentional and unintentional island operation. Under these circumstances, the key performance of the PED to be exploited in the capability of acting as a voltage source. Under this control mode, the PED is driving the voltage and the frequency of the grid. Connected loads rely on the performance of the PED to maintain such constants as stable over time.

It is important to note that the performance of the PED while maximizing self-healing aspect of the grid is related to how fast it is commanded to be activated. The duty of fast triggering the PED to act as a voltage source is for the DMS. Thus, it is principal for the DMS to prioritize these actions over other common activities, so it triggers the switchgears and PED in order to act fast for grid self-healing. In addition, it is important to notice the PED that should stop its scheduled operation (common operation mode) and be aware of acting according to these new setpoints and commands. The internal operations in the PED to switch between one control mode and the other should be also almost instantaneous.

4. ICT requirements and challenges for self-healing

Traditionally distribution systems are operated through Supervisory Control And Data Acquisition (SCADA) systems with an isolated access to grid information that make attacks very improbable; however, the development of smart grid technologies (e.g. smart meters, distributed generation, storage) and the associated services (e.g. demand response strategies, aggregation, flexibility operation) require opening communications to gather data from consumers and other stakeholders (aggregators, generators, etc.) making the system more vulnerable. Integration of advanced metering infrastructure (AMI) and other subsystems with participation of other stakeholders also suppose a vulnerability [22]. Thus, smart grid concept expands cybersecurity issues towards the interactions across the whole energy-data value chain and through the shared infrastructure it requires; and, tackling also privacy issues of involved stakeholders and in particular consumers. M. B. Line et al. point the following main critical issues [20]:

- *Connectivity*: Increased connectivity (internet-like) increases also vulnerability. That is, possibility to affect more and multiple components resulting in loss of control, but also facilitates propagation and cascade effect.
- *New trust models:* Increased connectivity and diversity in the ownership of energy assets cannot assure trustworthy among all participants due to different responsibilities and roles w.r.t to sensing elements.
- *Security management:* Increase in number of connected devices also implies complexity on cryptographic management of sessions among those devices and associated computational cost.
- *Software vulnerabilities-malware attacks:* Despite of efforts in reducing vulnerabilities these are still risky. Currently, many smart grids solutions are custom made software that not always have been submitted to rigorous security tests.
- *Consumer's privacy:* Smart meters are the cornerstone for the development of a smart home concept capable to identify appliances operation at sub-hourly time intervals, resulting in detailed lecture of user behaviour. This data need to be protected to avoid access to unauthorised people.
- *Human factor:* This is always a critical point when dealing with large systems that usually is solved with training and an appropriate design of applications and permissions in decision making applications.

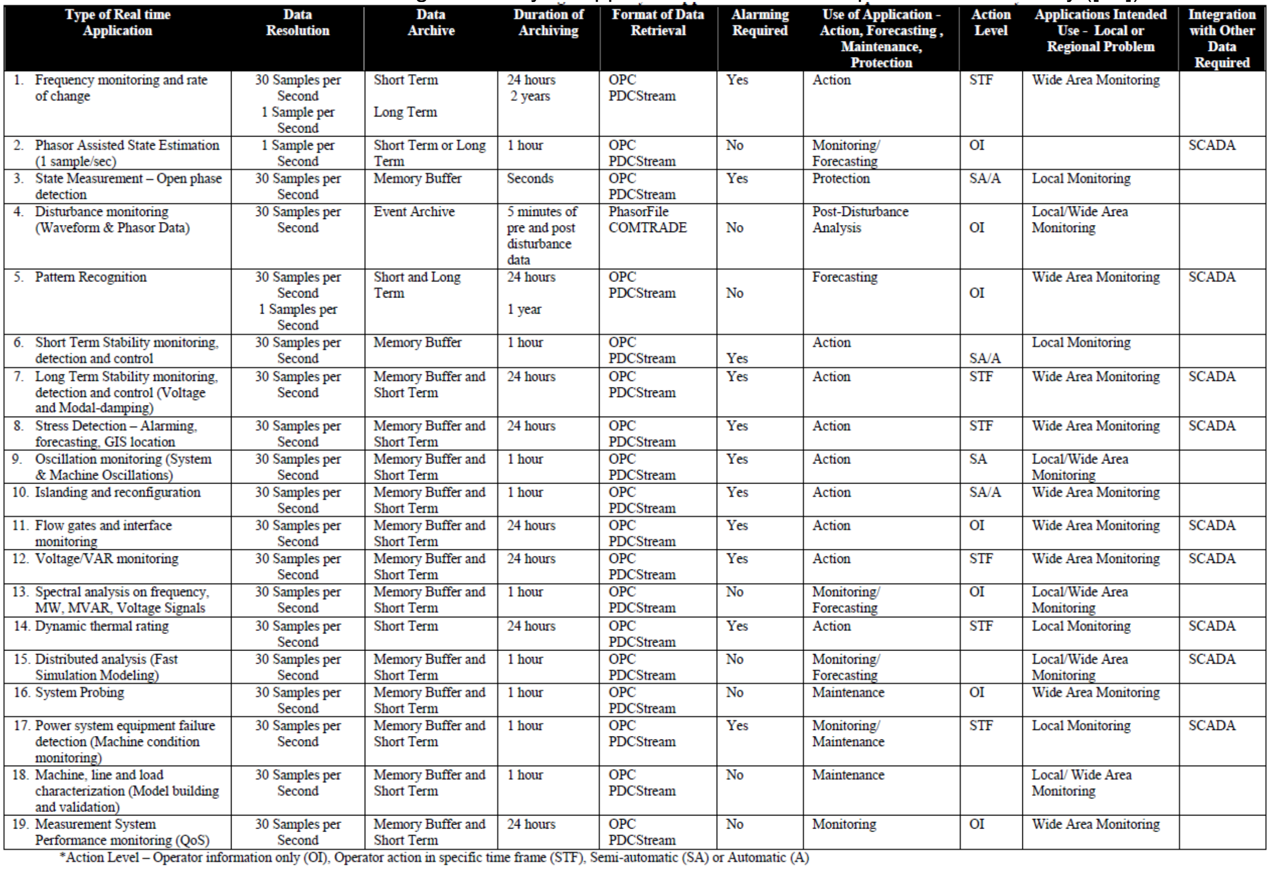
The communication infrastructure required to implement a smart grid should assure reliability and resilience to cyberattacks as stated in [24]; and a comprehensive set of standards (cryptography, access control, firewalls) has been proposed addressing this issue [25]. However, real-time decision making requirements imply a great observability of the network and the use of computation tools for state estimation, forecasting and optimisation.

Table 4 Survey on smart grid applications based on latency and data requirements (from [28])

Main Application	**Applications based on it**	**Origin of Data/Place where we need the data**	**Data**	**Latency requirement**	**Number of PMUs we may need to optimally run the application**	**Data time window**
State Estimation	Contingency analysis, Power flow, AGC, AVC, Energy markets, Dynamic/ Voltage security assessment	All substations/ Control center	P,Q, V, theta, I	1 second	Number of buses in the system	Instant
Transient Stability	Load trip, Generation trip, Islanding	Generating substations/ Application servers	Generator internal angle, df/dt, f	100 milliseconds	Number of generation buses (1/20 buses)	10-50 cycles
Small Signal Stability	Modes, Modes shape, Damping, Online update of PSS, Decreasing tie-line flows	Some key locations/ Application server	V phasor	1 second	1/10 buses	Minutes
Voltage Stability	Capacitor switching, Load shedding, Islanding	Some key location/ Application server	V phasor	1-5 seconds	1/10 buses	Minutes
Postmortem analysis	Model validation, Engineering settings for future	All PMU and DFR data/ Historian. This data base can be distributed to avoid network congestion	All measurements	NA	Number of buses in the system	Instant and Event files from DFRs

Nowadays, this observability is provided by PMU networks, deployed in specific quantities (number of PMUs) and locations to fulfil the requirements of these tools required for the operation management subsystems. With PMUs all over the system, the state of the grid (voltage phasors) can be directly measured and moreover can be measured many times per second with time-stamps giving insight into the dynamics of the system [28]. Table 4 summarises in a simple manner number of PMUs, location, data and window measurement length required for specific those applications involved in wide area monitoring for grid operation at transmission level. Real-time applications for wide area monitoring aims to identify critical events, to assess them and providing a self-healing response to the power system ([31][32]).

Table 5 Real time Wide-Area Monitoring and Analysis Applications and Data Requirements Summary ([31])



Type of Real time Application	Data Resolution	Data Archive	Duration of Archiving	Format of Data Retrieval	Alarming Required	Use of Application - Action, Forecasting , Maintenance, Protection	Action Level	Applications Intended Use - Local or Regional Problem	Integration with Other Data Required
1. Frequency monitoring and rate of change	30 Samples per Second 1 Sample per Second	Short Term Long Term	24 hours 2 years	OPC PDCStream	Yes	Action	STF	Wide Area Monitoring	
2. Phasor Assisted State Estimation (1 sample/sec)	1 Sample per Second	Short Term or Long Term	1 hour	OPC PDCStream	No	Monitoring/ Forecasting	OI		SCADA
3. State Measurement – Open phase detection	30 Samples per Second	Memory Buffer	Seconds	OPC PDCStream	Yes	Protection	SA/A	Local Monitoring	
4. Disturbance monitoring (Waveform & Phasor Data)	30 Samples per Second	Event Archive	5 minutes of pre and post disturbance data	PhasorFile COMTRADE	No	Post-Disturbance Analysis	OI	Local/Wide Area Monitoring	
5. Pattern Recognition	30 Samples per Second 1 Samples per Second	Short and Long Term	24 hours 1 year	OPC PDCStream	No	Forecasting	OI	Wide Area Monitoring	SCADA
6. Short Term Stability monitoring, detection and control	30 Samples per Second	Memory Buffer	1 hour	OPC PDCStream	Yes	Action	SA/A	Local Monitoring	
7. Long Term Stability monitoring, detection and control (Voltage and Modal-damping)	30 Samples per Second	Memory Buffer and Short Term	24 hours	OPC PDCStream	Yes	Action	STF	Wide Area Monitoring	SCADA
8. Stress Detection – Alarming, forecasting, GIS location	30 Samples per Second	Memory Buffer and Short Term	24 hours	OPC PDCStream	Yes	Action	STF	Wide Area Monitoring	SCADA
9. Oscillation monitoring (System & Machine Oscillations)	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	Yes	Action	SA	Local/Wide Area Monitoring	
10. Islanding and reconfiguration	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	Yes	Action	SA/A	Wide Area Monitoring	
11. Flow gates and interface monitoring	30 Samples per Second	Memory Buffer and Short Term	24 hours	OPC PDCStream	Yes	Action	OI	Wide Area Monitoring	SCADA
12. Voltage/VAR monitoring	30 Samples per Second	Memory Buffer and Short Term	24 hours	OPC PDCStream	Yes	Action	STF	Wide Area Monitoring	SCADA
13. Spectral analysis on frequency, MW, MVAR, Voltage Signals	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	No	Monitoring/ Forecasting	OI	Local/Wide Area Monitoring	
14. Dynamic thermal rating	30 Samples per Second	Short Term	24 hours	OPC PDCStream	Yes	Action	STF	Local Monitoring	SCADA
15. Distributed analysis (Fast Simulation Modeling)	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	No	Monitoring/ Forecasting		Local/Wide Area Monitoring	SCADA
16. System Probing	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	No	Maintenance	OI	Wide Area Monitoring	
17. Power system equipment failure detection (Machine condition monitoring)	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	Yes	Monitoring/ Maintenance	STF	Local Monitoring	SCADA
18. Machine, line and load characterization (Model building and validation)	30 Samples per Second	Memory Buffer and Short Term	1 hour	OPC PDCStream	No	Maintenance		Local/ Wide Area Monitoring	
19. Measurement System Performance monitoring (QoS)	30 Samples per Second	Memory Buffer and Short Term	24 hours	OPC PDCStream	No	Monitoring	OI	Wide Area Monitoring	

*Action Level – Operator information only (OI), Operator action in specific time frame (STF), Semi-automatic (SA) or Automatic (A)

According to [31], the time required to perform adaptive protection with wide area monitoring systems involves six main activities. On the assumption that optic-fibre network with dedicated channels is available, the corresponding times for these activities are estimated, resulting in 185ms.

a) Sensor Processing Time: 5 ms
b) Transmission Time of Information: 10 ms
c) Processing Incoming Message Queue: 10 ms
d) Computing Time for Decision: 100 ms
e) Transmission of Control Signal: 10 ms
f) Operating Time of Local Device: 50 ms

However, in distribution grids the OF infrastructure cannot be guaranteed and let alone at the low voltage grid, where usually a kind of wireless (LTE, 3G) or PLC communications can be present. Consequently, the transmission times b) and e) could be much higher and reconfiguration actions with this quick answer will not be possible. In such situations, a multi-agent system framework [6] provides a solution for distributed reasoning and locally acting. Moreover, during outages, communication systems and availability of PMUs can also be altered causing a degradation of the decision capacity during critical situations. Only, once the PMU is reconnected to the system the observability of the system is regained so that the network can self-heal [27]. In order to minimize the system's self-healing time integer linear programming models have been proposed in the literature in combination with heuristic and metaheuristic methods. For example, an intuitional algorithm is used to reduce complexity in calculations in [26].

4.1. RESOLVD scenario: Communication limitations for PMU data

In the project, 2 PMUs, will be installed in the Low voltage grid aiming to increase observability. However, communication infrastructure in secondary substations is not prepared for transmitting the elevate amounts of data the PMU can generate. No optical fibre infrastructure is deployed and data access is usually solved with dedicated LTE/3G communication. Consequently, the PMUs were adapted to allow TCP or UDP connection throughout the urban-pedestrian LTE network (details and deployment guidelines in [35]). In terms of latency, a one-way delay of between 10 to 20 ms was observed in the ideal case (without paquet loss), which is well within the margins set by IEEE C37.118-2014 standard and can be describe as real-time. Using UDP connection a packet loss between 10% and 40% was observed depending on the LTE channel conditions. The maximum throughput achieved was 7,3 Mbits/s well short of the stream bandwidth. One-way delay of between 280 ms and 310 ms was observed falling the real time requirement of the use case. During network sub scenario transitions one-way delay spikes can be observed which are probably caused by the way that uplink channel is modelled. Using TCP connection does not improve the results as the maximum throughput achieved was 7,6 Mbits/s. Measured one-way delay was between 100 ms and 200 ms, a slight improvement over UDP. Thus, considering the whole cycle (6 activities previously listed), the system could react with an estimate time of 750ms.

Communication limitation implies a reduction in the reaction time, but also a reduction on the amount of data that sent. This limitation implies that self-healing capabilities based on centralised decision making applications that use PMU data will be reduced to those that require data at second rates. In terms of proof-of concept this will be enough to demonstrate the feasibility of integrated solutions, whereas real time capabilities will be tested locally by adding an embedded computer together with the PMUs in order to perform fault detection and sending only information once events were detected.

5. Conclusions

The document reports the study performed to implement self-healing application for low voltage grid within the RESOLVD project. The report includes the self-healing problem formulation to implement a centralised solution based on the state of the art of the problem statement and solving procedures and analyses possible grid configurations that the pilot can adopt based on the operation of switchgears deployed in the pilot. Special consideration is given to the capability of the power electronic device to manage energy locally during specific configurations that include islanding. Finally, the document includes the study on data/information requirements for decision support during outages and discusses about limitations of communication infrastructure in the pilot and the implications to exploit PMU data directly in the DMS.

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RESOLVD Deliverables

[34] RESOLVD Deliverable D3.5 "Scheduling. Strategy and methodology"

[35] RESOLVD Deliverable D3.3 "Advanced sensor infrastructure: from design to installation guidelines"

[36] RESOLVD Deliverable D1.1 "Use Case Definition"

[37] RESOLVD Deliverable D5.1 "Validation set-up report: Description of scenarios, tests and validation indicators"