success
securing critical
energy infrastructures

SUCCESS

D2.6 v1.0

The Survivability by Design concept V1

The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 700416.

Project Name	SUCCESS
Contractual Delivery Date:	April 30, 2017
Actual Delivery Date:	April 30, 2017
Contributors:	RWTH
Workpackage:	WP2 – Security, Resilience and Survivability by Design
Security:	PU
Nature:	R
Version:	1.0
Total number of pages:	19

Abstract:
This document describes the SUCCESS survivability by design approach, which is based on the exploitation of distributed energy resources for service restoration for the case of a power blackout. In the deliverable will be described the state of the art of service restoration after blackout and the challenges posed by the new network paradigm resulting from the evolution of classical power distribution grids into smart grids.

In the second part of this deliverable, a new service restoration strategy is described and the results from real time simulations are presented.

Keyword list:
Security, Communication, Utility, Survivability, Reliability, Restoration, Reconfiguration, Distribution Systems, Power Distribution Network, Microgrids

Executive Summary

This first version of this deliverable illustrates the survivability by design concept developed in the framework of the SUCCESS project.

Survivability is, by definition, the ability of a system to continue to function during and after a natural or man-made disturbance. In case of power grids, this affects the ability to provide service to customers in case of disturbance, either minimising the area affected by the resulting outage or minimising the recovery time after a blackout.

Present survivability strategies applied in power grids present a top-down approach: in case of blackout the first step is to restore operation of bulk generation units and then gradually restore the power supply to the end users. This approach, however, is bound to become deprecated due to the growing penetration of distributed energy resources, which will soon replace most of the centralized bulk generation power plants.

For this reason, new survivability approaches are needed to keep up with the evolution of the power grid infrastructure.

In this deliverable, we propose a new survivability strategy, based on the exploitation of distributed energy resources in islanded microgrid configurations. In chapters 3 and 4 we describe the reference scenario and the proposed survivability strategy, while in chapter 5 we will show the results of the simulations performed in RWTH laboratory.

Authors

Partner	Name	e-mail
Rheinisch-Westfaelische Technische Hochschule Aachen (RWTH)		
	Gianluca Lipari	glipari@eonerc.rwth-aachen.de

Table of Contents

1. Introduction

This document reports on the SUCCESS survivability by design concept and its application for grid functionality restauration in the event of a blackout. The survivability by design concept developed in the SUCCESS project focuses on the exploitation of the distributed energy resources, nowadays widely available in the distribution grids. The resulting power restauration strategy has a bottom-up approach, energising small microgrids first and then reconnecting them together incrementally, which is the opposite of the currently employed grid restoration methodologies, that are top-down based, reflecting the traditional concept of a centralized power grid.

The first version of the survivability by design concept, presented in this deliverable, describes the proposed grid restoration methodology and presents the results obtained in a real-time simulation environment.

1.1 How to read this document

The reader should be familiar with the content of D4.2 before reading this document. Some general knowledge of D2.2, D4.4 and D5.1 is required to understand the references to these documents.

This document provides a description of the survivability by design concept, first introducing the possible causes and effects of blackouts in power distribution grids and the state of the art of the grid functionality restoration techniques. In the second part of the document, a new methodology for grid service restoration, based on islanded microgrids, is described and related simulation results are presented.

1.2 Relation to other activities

The work presented in this deliverable is part of the overall WP 2 concept of enhancing security, resiliency and survivability of modern power distribution grids, by developing new concepts and methodologies that better cope with security issues and possible new threats that undermine present and, to an even greater extent, future distribution grids.

On one hand, the security by design concept, presented in Deliverable D2.2 [1], describes possible attack detection and mitigation schemes, focusing in particular on time synchronization attacks against Phasor Measurement Units (PMUs).

On the other hand, Deliverable D2.4 [2] presents a resilience by design concept, based on the cloud computing paradigm, where system resilience is ensured by enabling fast relocation of cloud virtual resources when a security incident (attack) is identified.

However, despite the efforts put in designing a reliable and robust SUCCESS Security Monitoring Solution, as presented in Deliverables D4.2 [3] and D4.4 [4], the possibility of successful attacks, which could lead to grid instability and even to large scale blackouts, cannot be ruled out.

For this reason, the survivability by design concept presented in this deliverable is intended to mitigate the possible effects of such power outages in situations that are still envisioned as possible in the general view of the project, as provided for example in the Irish trial site scenario, described in Deliverable D5.1 [5].

2. Blackouts and grid restoration

2.1 State of the art

A power blackout is a short-term or a long-term loss of the electric power to a particular area, which can be caused by different reasons. Possible causes, for example, can be faults at power stations, damage to electric transmission lines, substations or other parts of the distribution system, a short circuit, or the overloading of electricity mains. However, with the growing digitalisation of the distribution grids automation and the increasing number of field devices, like measurement and control devices distributed on field, the power distribution grid is turning into a so-called Cyber-Physical System (CPS). A CPS is a system controlled or monitored by computer-based algorithms, tightly integrated with the internet and its users. In cyber-physical systems, physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioural modalities, and interacting with each other in a myriad of ways that change with context.

Given the dependence of almost any other system on continuous supply of electricity, the power grid can be considered the most important of all critical infrastructures [6].

Hence, with the power grid becoming more and more a cyber-physical infrastructure, the effects of failures affecting one component have implications also for the others. One example of this is the Ukrainian blackout of December 2015, also described in Deliverable D1.1 [7], which is considered to be the first known successful cyber-attack on a power grid. Hackers were able to successfully compromise information systems of three energy distribution companies in Ukraine and temporarily disrupt electricity supply to the end consumers.

Blackouts that result from or result in power stations tripping are particularly difficult to recover from quickly and outages may last from a few minutes to a few weeks depending on the nature of the blackout and the configuration of the electrical network. In such cases bulk generators (e.g. hydroelectric, fossil-fuel or nuclear stations) are shut down and need to be powered up again in order to restart the service. Normally, the electric power used within the plant is provided from the station's own generators, and if all of the plant's main generators are shut down, station service power is provided by drawing power from the grid through the plant's transmission line. However, during a wide-area outage, off-site power from the grid is not available. In such situation, a so-called black start needs to be performed to bootstrap the power grid into operation.

A black start is, indeed, the process of restoring an electric power station or a part of an electric grid to operation without relying on the external transmission network [8].

To provide a black start, some power stations have small diesel generators, normally called the black start diesel generator (BSDG), which can be used to start larger generators (of several megawatts capacity), which in turn can be used to start the main power station generators. Often hydroelectric power plants are designated as the black-start sources to restore network interconnections. A hydroelectric station, in fact, needs very little initial power to start, and can put a large block of power on line very quickly to allow start-up of fossil-fuel or nuclear stations.

Generating plants using steam turbines require station service power of up to 10% of their capacity for boiler feedwater pumps, boiler forced-draft combustion air blowers, and for fuel preparation. It is uneconomical to provide such a large standby capacity at each station, so black-start power must be provided over designated tie lines from another station.

Once the black-start of several power stations is completed, the available power is then used to power up other bulk generation plants and simultaneously to restore the service is small areas; this is needed to maintain the power balance between generation and consumption.

One example of a black start sequence might be as follows:

- A battery starts a small diesel generator installed in a hydroelectric generating station,
- The power from the diesel generator is used to bring the generating station into operation,
- Key transmission lines between the station and other areas are energized,
- The power from the station is used to start one of the nuclear/fossil-fuel-fired base load plants, and then
- The power from the base load plant is used to restart all of the other power plants in the system.

Power is finally re-applied to the general electricity distribution network and sent to the consumers. Often this will happen gradually; starting the entire grid at once may not be feasible.

In a larger grid, black start will often involve starting multiple "islands" of generation (each supplying local load areas), and then synchronising and reconnecting these islands to form a complete grid. The power stations involved have to be able to accept large step changes in load as the grid is reconnected.

In general, actual survivability and power restoration strategies follow a top-down approach, from bulk power generation plants to final customers.

Generally, the service disruption time for customers can last for hours or even days, like in the Italian 2003 blackout [9] or the Indian 2012 blackout [10].

2.2 Survivability in future smart grids

Analysis of recent blackouts shows that their causes are largely similar. When one segment of the system fails, the segments near it cannot cope with the increased load caused by the failure, so they fail as well. The resulting outages cascade through the grid and leave large areas without power. It is impossible to replace even small portions of the power grid infrastructure each time an outage occurs, as doing so would necessitate expending significant time and effort, which can be prohibitively expensive. Practical and innovative solutions are required that allow the grid to tolerate localized outages without collapse. One possible solution is to integrate cyber infrastructure (such as communication, computing, and control elements) that provides the intelligence requirements of a smart grid. The goal is to create a fortified and efficient power grid that outperforms its predecessors.

The Smart Grid concept encapsulates the current ongoing efforts to modernize the ageing and unreliable conventional power grid into a flexible, more efficient power network that will [11] [12]:

1. Increase the reliability of electrical supply to the customers,
2. Enhance the system performance and reduce transmission losses,
3. Improve the resilience to disruptions, and
4. Allow for automated maintenance and operation.

Moreover, the Smart Grid concept introduces an updated architecture and new elements to the traditional power grid. The key component in this transformation is an information and communication technology infrastructure that enables the various entities within the network to communicate with each other in a fast and reliable way. Besides a communication link, the modern grid relies on a vast number of sensors and actuators that are distributed throughout its transmission and distribution network; these “smart” agents monitor the health of the system on a constant basis and are able to automatically act upon a disturbance in order to prevent a failure, or minimize its impact if it is unavoidable. Finally, distributed renewable energy generators help reduce transmission losses by bringing generation closer to consumption, while promoting the use of clean, low-carbon energy. These distributed generators give rise to an important concept within the Smart Grid domain, the so-called microgrid. Microgrids are small-scale, medium/low voltage electric power systems that also include distributed storage units and loads, and cover a limited geographic area.

As a result, existing survivability schemes, which have been designed with a centralized architecture in mind, are either inefficient or no longer applicable. Most of them, in fact, emphasize the survivability of the entire grid rather than an individual node (i.e. substation or feeder). For future smart grids, a bottom-up approach, starting from decentralized energy resources exploitation, is more appropriate.

With that assumption in mind, the proposed survivability by design concept considers the formation of microgrid clusters, where a microgrid that produces more energy than currently needed may supply electricity to another microgrid that faces the prospect of a blackout. The resulting formation provides complete robustness under single-failure conditions, and partial robustness under multi-failure conditions.

It is obvious that the coordination and smooth operation of the Smart Grid is far from an easy task. For instance, while renewable resources may supplement the generation capability and address environmental concerns, they also aggravate reliability due to their volatility [13]. New mechanisms and protocols are required that will ensure the proper function of the network and guarantee its reliability in case of system disturbances, while running in a non-hierarchical and essentially decentralized way.

An effective network voltage regulation is of paramount importance for the survival of the power grid. However, this is a process that is becoming more complex due to the increasing penetration of distributed generation systems in electrical grids; since these generators rely on renewable energy sources, their power injections are random and may alter the voltage profiles on the network buses in a non-scheduled fashion.

Hence, in the following chapter an innovative survivability strategy, based on small-scale distributed generators exploitation, will be presented. The proposed methodology uses the local energy resources in order to create an islanded microgrid, regulating the voltage and the power flow inside the microgrid using a consensus based algorithm.

3. Scenario Definition

For the testing of the proposed survivability strategy, a simple test microgrid was defined and simulated with a Real-Time Digital Simulator in the RWTH laboratory. The goal was to verify how the simulated microgrid would behave in a blackout situation, caused by an extensive grid failure at physical/device level, trying to repower up in islanding mode. The cause of such failure could be a successful attack on the grid infrastructure able to generate a massive instability in the grid. This scenario contemplates the possibility that both the SUCCESS Security Solution functions and the resilience by developed design features failed to block or mitigate the effects of such attack.

The test scenario focused on an isolated microgrid where loads and Distributed Energy Resources (DERs), acting as local generators, are present. The goal is to restore the service in the isolated area, rebuilding the grid using energy provided by the DERs.

After identifying the fault extension, the isolation process of the area is performed acting on circuit breakers, switches and microgrid interconnection switches located inside the portion of the grid that is being tested.

The final objective is to demonstrate how the SUCCESS solution is able to recover after a wide area attack or a physical failure, acting in a “special” rescue mode.

We want to prove that, even if the security and resiliency strategies fail, the SUCCESS architecture is still capable of maintaining the service on a local microgrid scale and eventually being able to rebuild the whole grid by bringing together all the single microgrids.

Another outcome of this use case will be an evaluation of the correlation between the attack extension and recovery time, in order to prove how the SUCCESS framework can withstand larger and harmful attacks with respect to traditional power grid structures and achieve normal operating mode in shorter times.

This use case analyses the behaviour of the SUCCESS architecture and the power grid when the extent of the attack/failure is wide enough to compromise the operation of the architecture even after the recovery attempts operated by the security and resiliency functions.

The survivability use case starting point is determined by the failure of both security and resiliency functions in case of a successful attack.

In such cases the grid, or a wide section of it, is not able to guarantee the normal operating mode.

Assuming that the communication network is still available, at least on a local scale between single local generators in order to allow the field devices to communicate each other, the restoration process can be started.

The complete sequence of the grid restoration sequence would be as follows:

1. An individual microgrid is created, including neighbouring generators and loads,
2. Several microgrids are synchronized and then joined together, and then they
3. Synchronize with the main MV or HV grid. The main grid can be assumed to have been restored and the connected set of microgrids needs to be synced to it.

4. Decentralized Control Strategy

The proposed Secondary Control for this black-start scenario is the consensus-based distributed algorithm, which, among the ones presented in literature [15], has been considered a suitable algorithm for this kind of scenario [16] [17]. Purpose of the control is to reach an *agreement space* for all the agents that participate in the cooperative task [16]. The definition of the control begins with the definition of the graph ***G***. In the scenario under test the graph comprehends four nodes communicating with their neighbour. The schema of ***G*** is represented in Figure 4.1.

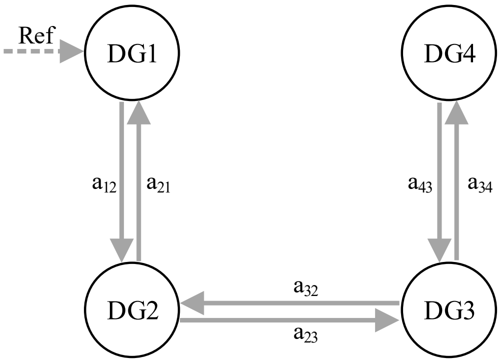

Figure 4.1 - Graph of the test nodes

The communication links of the graph, the so-called edges, are represented by the time-invariant adjacency matrix A [16] [17], where every element of the matrix a_{ij} defines the weight of the edge from the node i to j. The adjacency matrix of ***G*** is the following:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad a_{ij} = a_{ji} = 1 \qquad (1)$$

The in-degree and out-degree matrixes are defined in [16] and [18] and they are described as $D^{in} = diag\{d_i^{in}\}$, where $d_i^{in} = \sum_i a_{ij}$ and $D^{out} = diag\{d_i^{out}\}$, where $d_i^{out} = \sum_i a_{ji}$. Since $a_{ij} = a_{ji}$, the two degree matrixes are identical and the graph is balanced and undirected [16] [18], resulting in the following expression of the matrix $D = D^{in} = D^{out}$:

$$D = diag\{1,2,2,1\} \qquad (2)$$

The matrix highlights that the maximum graph degree is two, because it is the highest number of neighbouring connections of the nodes.

Once the matrixes A and D are defined, the *Laplacian* of ***G*** is immediately obtained:

$$L = D - A = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix} \qquad (3)$$

The distributed consensus algorithm is applied to the graph, in the form expressed in [16]:

$$\dot{x}_i = \sum a_{ij}(x_j(t) - x_i(t)) \qquad (4)$$

which can be expressed in the compact form as:

$$\dot{x} = -Lx \qquad (5)$$

As described in [16], in case of an undirected graph the algorithm (5) can be represented as a gradient-descendent algorithm, where $\varphi(x) = 1/2 \cdot x^T L x$:

$$\dot{x} = -\nabla\varphi(x) \qquad (6)$$

demonstrating that the consensus is asymptotically reached.

An input bias can be also introduced in order to apply an objective that must be achieved by the nodes.

$$\dot{x}_i = \sum a_{ij}(x_j(t) - x_i(t)) + r_{ij} \qquad (7)$$

As defined in [16], the input bias plays no role in the stability.

The consensus theory has been applied to the isolated AC microgrids in the last years. The paper [17] has presented an application of the distributed control interacting with the well-known droop control-based primary controls. The same approach has been recently improved by means of a finite-time control protocol [19].

The distributed and cooperative approach of the theory briefly described demonstrates to be a suitable approach for the black-start scenario, since there is no need for a central master controller, which allows for a local control strategy without needing a centralized controller that may not be available in a black-start scenario. Moreover, the distances for the communication are smaller, since the transmission of the data is involved only among the neighbours.

The control structure reflects the distributed consensus algorithm and it is described by the following equations [18]:

$$\dot{u}_{v_i} = c_{v_i} \sum a_{ij}(v_{od_j}(t) - v_{od_i}(t)) + g_i(V_{ref} - v_{od_i}(t)) \qquad (8)$$

$$\dot{u}_{q_i} = c_{q_i} \sum a_{ij}(n_j q_j(t) - n_i q_i(t)) \qquad (9)$$

$$\dot{u}_{\omega_i} = c_{\omega_i} \sum a_{ij}(\omega_j(t) - \omega_i(t)) + g_i(\omega_{ref} - \omega_i(t)) \qquad (10)$$

$$\dot{u}_{p_i} = c_{p_i} \sum a_{ij}(m_j p_j(t) - m_i p_i(t)) \qquad (11)$$

The equations are applied to the graph ***G*** where it appears evident that only the voltage and frequency control present a reference value to be tracked, whereas the objective for the active and reactive power control is to achieve the power sharing determined by the droop control.

Referring to the graph described in Figure 4.1, the only distributed generator that receives the references is the first one and the others follow it, as it is described later.

The combination of (8) - (11) results in the following control outputs:

$$\delta v_{\mathrm{n}_i} = \int \left(\dot{u}_{v_i} + \dot{u}_{q_i}\right) \mathrm{d}t \qquad (12)$$

$$\delta\omega_{\mathrm{n}_i} = \int \left(\dot{u}_{\omega_i} + \dot{u}_{p_i}\right)\mathrm{d}t \qquad (13)$$

The result of the secondary control corrects the reference values of the primary control by adding δv_{n_i} and $\delta\omega_{\mathrm{n}_i}$ to the set-point value v_{n_i} and ω_{n_i}. The scheme of the secondary control and its interaction with the primary control is described in Figure 4.2.

4.1 Control of the Inverter

The inverter control reflects the typical droop-based control for the voltage-controlled voltage-source inverter (VCVSI) [20]. The voltage and frequency references, eventually modified by the secondary control, are adjusted through the droop equations and then combined together, generating the three-phase reference signal for the voltage control. The result of the voltage control is compared with the current measurements and it is sent to the current control, generating the references signals for the PWM. The control scheme of both primary and secondary controls are depicted in Figure 4.2. On the left side, the secondary control is responsible of voltage and frequency regulation, by applying equations (8), (9), (10) and (11). Here v_{od_i} represents the d-component of the voltage, ω_i the frequency measurement, q_i the reactive power measurement and p_i the active power measurement at the point $i = 1, \dots, 4$. The coefficients n_i and m_i are the droop coefficients of the reactive and active power.

The primary control, on the right side, is responsible of generating the correct voltage reference for the generator and then use this value to calculate the needed inputs for the current control.

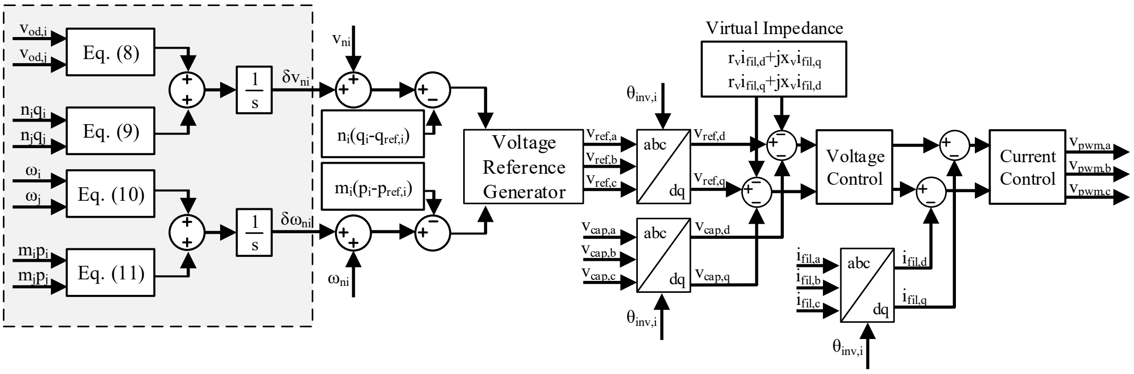

Figure 4.2 - Secondary and Primary control

4.2 Synchronization issues in the black-start scenario

The synchronization reveals it to be a peculiar aspect of the black-start scenario. The main reason for this is the fact that the inverters are disconnected from the microgrid before the reconnection procedure, as depicted in Figure 4.3. Recently, it has been demonstrated that the microgrid characterized by DC/AC inverters controlled with power-droop regulators possesses a unique synchronized and stable solution [21]. This important result allows the design of the control to be independent on a synchronization algorithm during the normal operation. Moreover, it has been demonstrated that the droop control and PLLs can be re-elaborated in a common structure, highlighting that droop controllers can achieve the same function of the PLLs without a dedicated synchronization unit [22]. This cannot be considered valid anymore in case of black-start scenario. During the blackout, the inverters, disconnected from the rest of the system, are keeping the voltage of the output capacitance constant, because of the action of the primary control. In this situation, the voltage reference generator output is modified by the droop action, which, in the general, can be different for each inverter, as shown in Figure 4.2. Moreover, the calculation of the phase angle $\boldsymbol{\theta_{inv,i}}$ is modified by the droop control, as described by the following equation:

$$\theta_{inv,i} = \int \left(2\pi\left(m_i\left(p_i - p_{ref,i}\right) + \delta\omega_{\mathrm{n}_i}\right) + \omega_{\mathrm{n}_i}\right)\mathrm{d}t \qquad (14)$$

The second synchronization issue is related to the time delay of the reclosing commands.

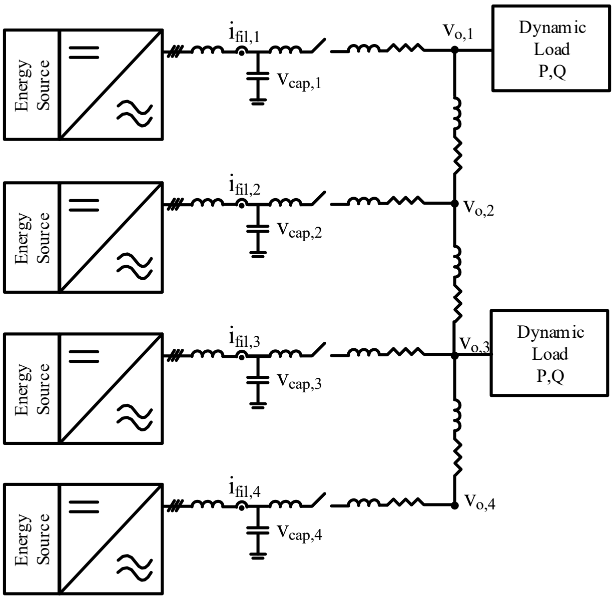

Figure 4.3 - Islanded Microgrid Model

5. Simulations implementation and results

A sample grid model has been implemented before running the real time simulations. The model of the grid under test was implemented in RSCAD, a commercial software for power grid modelling, and then deployed on a Real Time Digital Simulator provided by RTDS technologies.

The scheme of the microgrid is depicted in Figure 5.1:

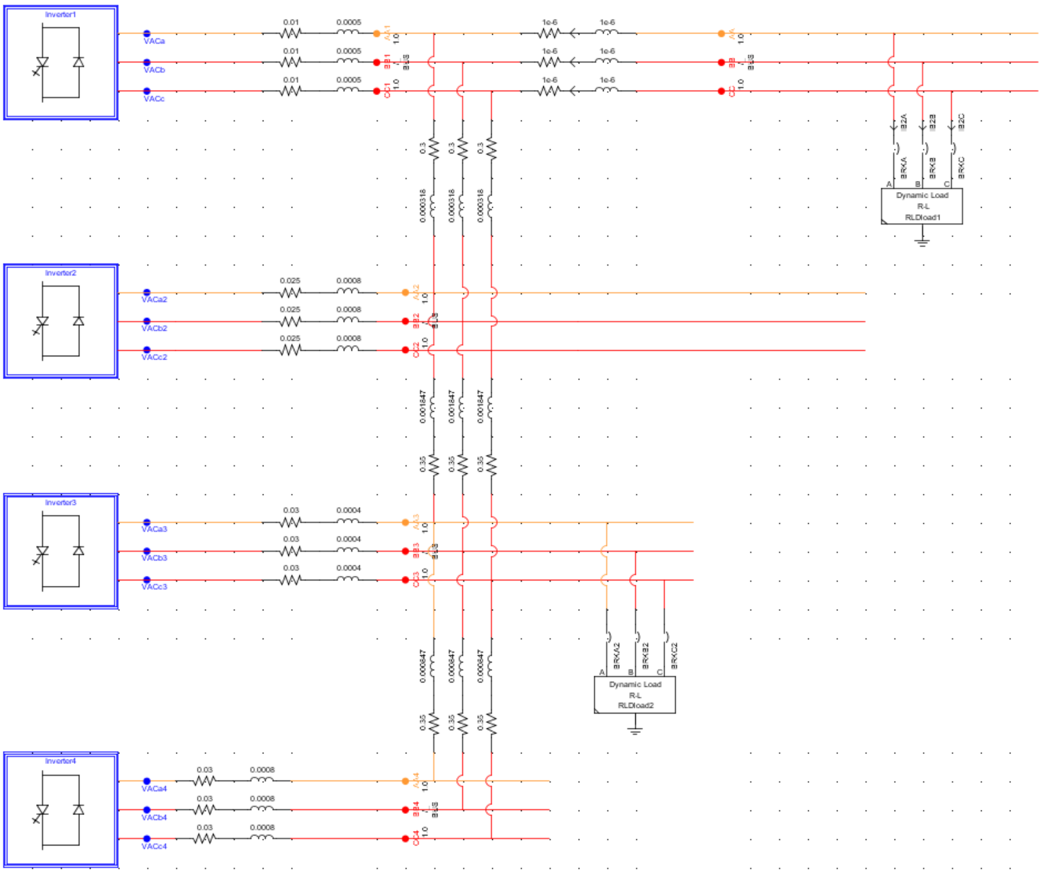

Figure 5.1 - Simulated microgrid implemented in RTDS

As shown in Figure 5.1 the reference grid includes four distributed generators, composed by solar PV panels and their inverters, and two loads.

The inverter model is depicted in Figure 5.2:

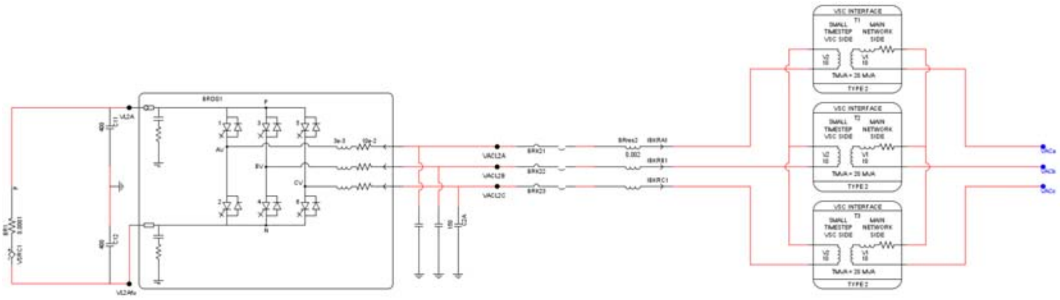

Figure 5.2 – Inverter model implemented in RTDS

The first set of simulations was carried out without deactivating the droop control of the inverters. As explained in the previous chapter, this leads to synchronization issues among the inverters that causes unneglectable peak currents. The action of the droop results in a lack of synchronization among the inverter voltages before starting the reconnection, because both the reference voltage and the phase calculation are modified by it. Reclosing out of phase VCVSIs determines a very high transient value of the currents, as described in [23] [24], in case of out of phase reclosing with the grid, as shown in Figure 5.3 and Figure 5.4.

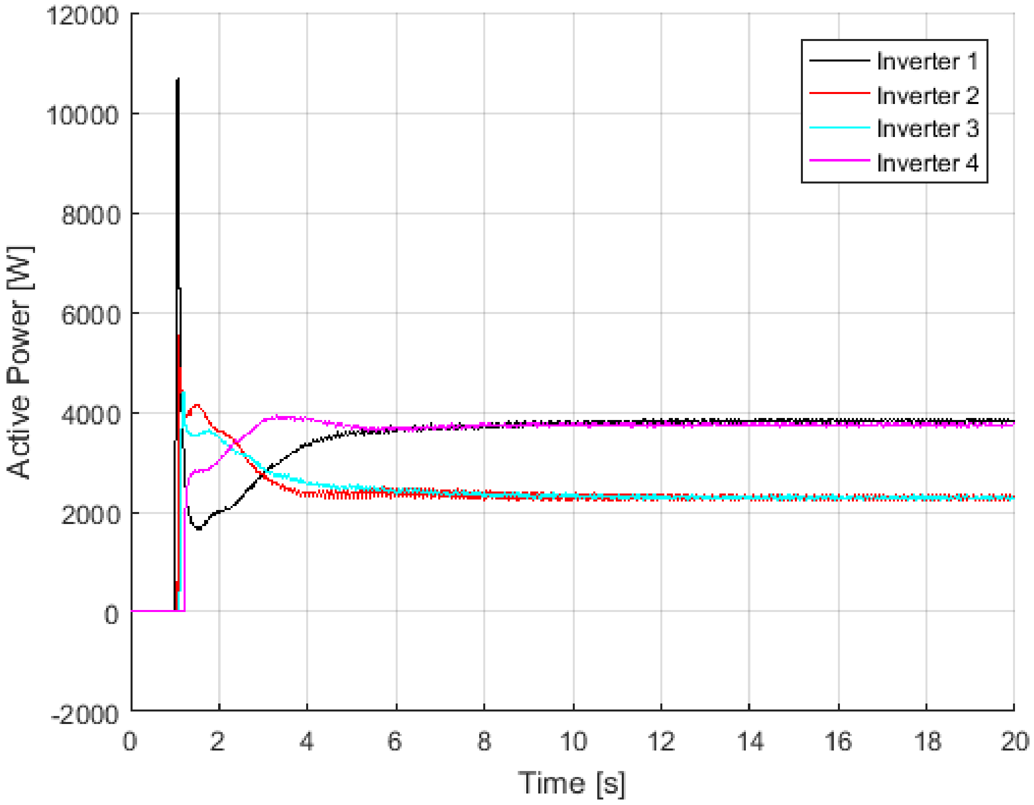

Figure 5.3 - Inverter reconnection with droop control enabled (Active Power)

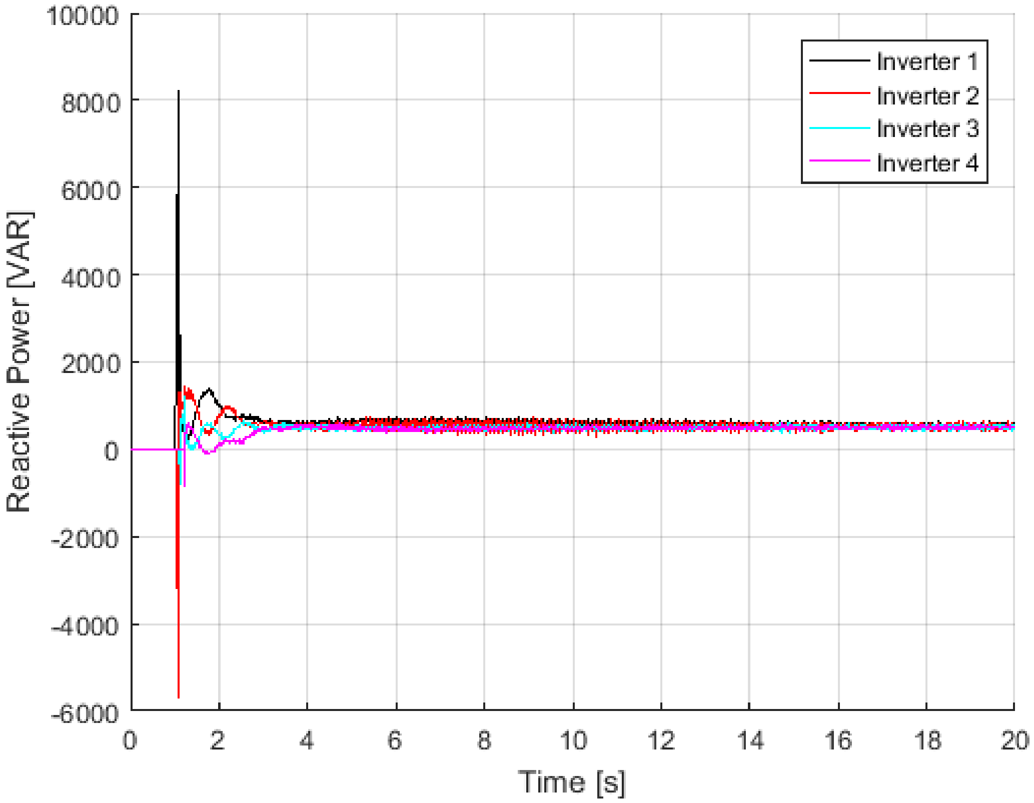

Figure 5.4 - Inverter reconnection with droop control enabled (Reactive Power)

Following the analysis of the results obtained in the first set of simulation, we decided to disable the drop control during the reconnection phase, in order to avoid the undesired peak currents.

The disabling of the droop control ensures the voltage to be in phase before the reconnection, avoiding the out of phase current peak. Once the inverters are reconnected, the droop control can be enabled, in order to guarantee the correct power sharing and the synchronization among the inverters, as reported in Figure 5.5 and Figure 5.6.

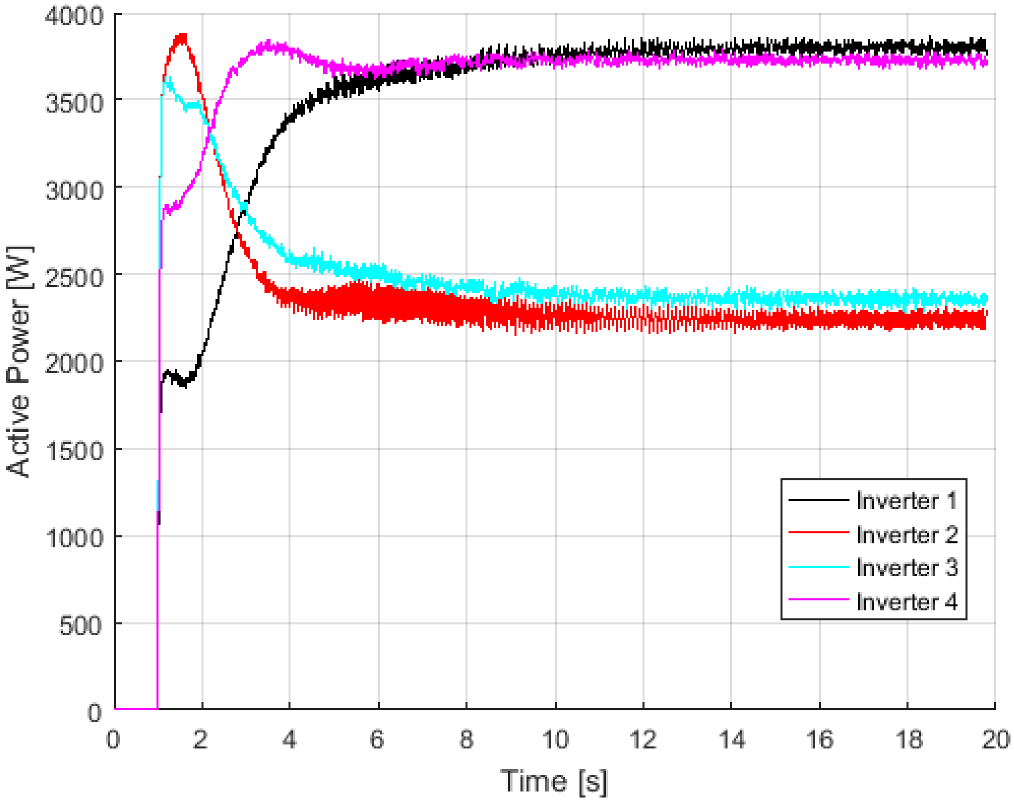

Figure 5.5 - Inverter reconnection with disabled droop control (Active Power)

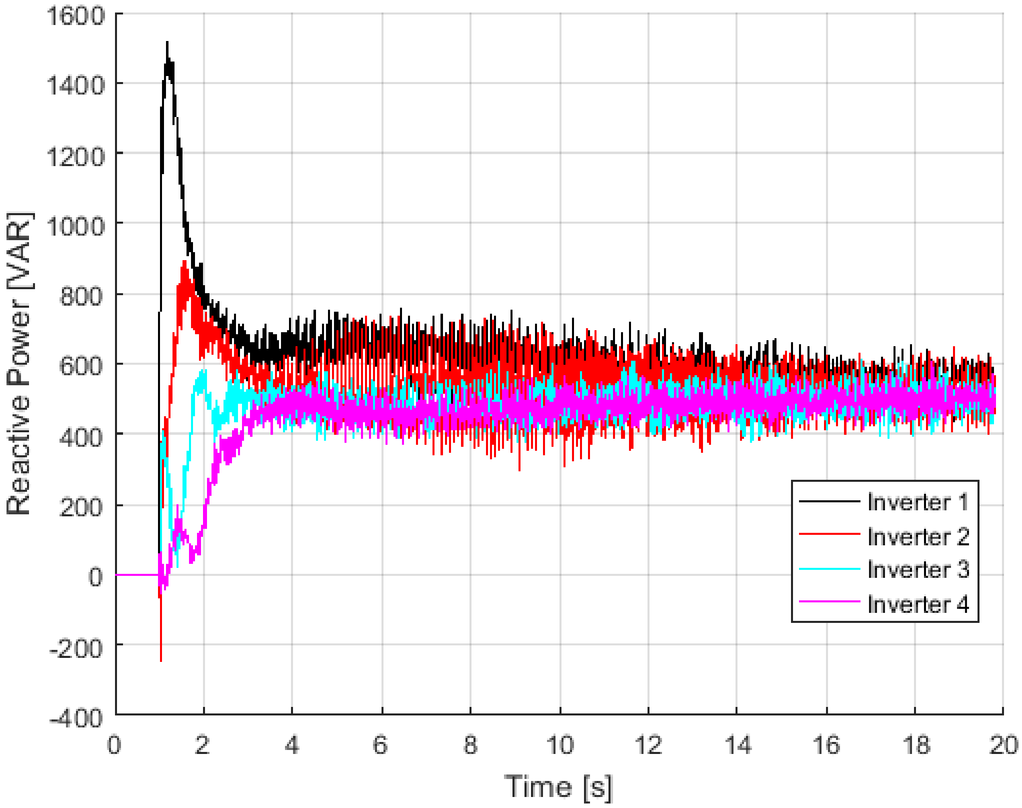

Figure 5.6 - - Inverter reconnection with disabled droop control (Reactive Power)

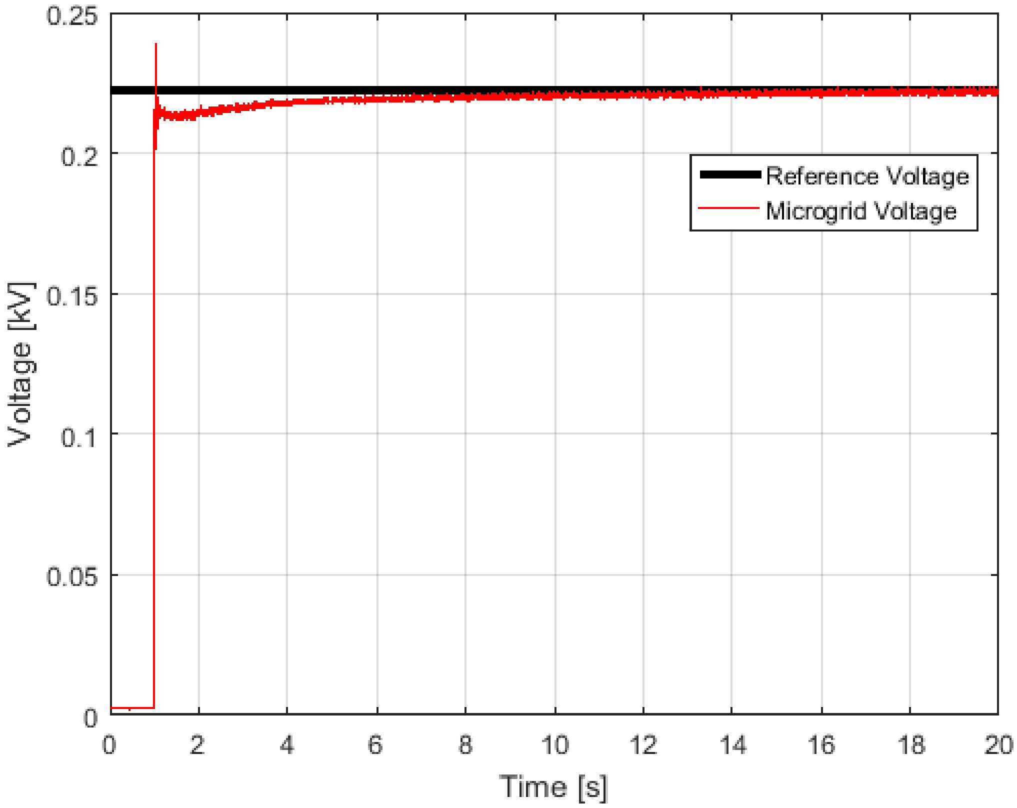

Figure 5.7 - Interconnection point voltage value

Additionally, the voltage value at the main bus during the reconnection phase presents a small peak, caused by the sudden unbalance between generation and consumption, shown in Figure

5.7. This peak is, however, small enough to be tolerated by protections and other devices connected to the grid.

Finally, as can be deduced from the simulation results, the creation of the microgrid and the reconnection of loads and generators is completed in less than 20 seconds. This would mean that, for the customers connected to the microgrid, the power outage duration is dramatically reduced, if compared to those of traditional power restoration strategies.

6. Conclusion

This deliverable presents a grid survivability concept based on the exploitation of distributed energy resources in microgrids, providing the needed energy for the islanded mode operation of the microgrid.

The main result of the work done in the related project task 2.3 focused on the study and the implementation of the technical solutions to be adopted to synchronize and coordinate the locally distributed generator in an essentially decentralized way. The main technical issue tackled was the synchronization of the AC component provided by the inverters. In fact, since there is no global reference coming from the main grid, the inverters have to synchronize in order to generate the required voltage and current waveforms that allow the normal behaviour of the grid.

The results obtained through the real-time simulation carried out in the RWTH laboratory showed how the proposed approach is able to provide the required performance in order to power up a reference microgrid in islanding mode, reducing the power outage duration for customers.

The next steps of our work, in the second part of task 2.3, will be the implementation of the proposed controllers on real hardware, including both control boards and communication devices, and the execution of hardware-in-the-loop simulations. This kind of tests will allow to verify whether the proposed algorithms are able to properly operate even if presence of measurement uncertainties and communication delays.

Moreover, a further development of the survivability concept will be the implementation of a coordination algorithm able to bring together and connect small neighbour microgrids, with the goal to expand the restored section of the grid, and ultimately reconnect the already restored sections with the main distribution grid, once it is fully operational.

7. References

[1] SUCCESS D2.2, “Security by Design Concept, V1”, April 2017

[2] SUCCESS D2.4, “Resiliency by Design Concept, V1”, April 2017

[3] SUCCESS D4.2, “Solution Architecture and Solution Description, V2”, April 2017

[4] SUCCESS D4.4, “Description of Available Components for SW Functions, Infrastructure and Related Documentation, V1”, April 2017

[5] SUCCESS D5.1, “Trial Sites Planning”, April 2017

[6] L. H. Tsoukalas and R. Gao. From smart grids to an energy internet: Assumptions, architectures and requirements. Presented at Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on. 2008.

[7] SUCCESS D1.1, “Identification of Existing Threats”, October 2016

[8] Knight, U.G. Power Systems in Emergencies - From Contingency Planning to Crisis Management John Wiley & Sons 2001

[9] "Huge blackout cripples Italy". BBC News Online. Published 28 September 2003. Available online at: http://news.bbc.co.uk/2/hi/3146136.stm

[10] "India blackouts leave 700 million without power". The Guardian. Published 31 July 2012. Available online at: https://www.theguardian.com/world/2012/jul/31/india-blackout-electricity-power-cuts

[11] J. A. Momoh. Smart grid design for efficient and flexible power networks operation and control. Presented at Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES. 2009.

[12] X. Fang, S. Misra, G. Xue and D. Yang. Smart grid — the new and improved power grid: A survey. Communications Surveys & Tutorials, IEEE PP(99), pp. 1-37. 2011.

[13] K. Moslehi and R. Kumar. A reliability perspective of the smart grid. Smart Grid, IEEE Transactions on 1(1), pp. 57-64. 2010.

[14] S. Rinaldi, J. Peerenboom, and T. Kelly, “Identifying, understanding, and analyzing critical infrastructure interdependencies” IEEE Control Syst. Mag., vol. 11, pp. 11–25, December 2001.

[15] IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems" in *IEEE Std 1547.4-2011* , vol., no., pp.1-54, July 20 2011.

[16] Olfati-Saber, Reza, J. Alex Fax, and Richard M. Murray. "Consensus and cooperation in networked multi-agent systems" *Proceedings of the IEEE* 95.1 (2007): 215-233.

[17] Bidram, Ali, et al. "Secondary control of microgrids based on distributed cooperative control of multi-agent systems" *IET Generation, Transmission & Distribution* 7.8 (2013): 822-831.

[18] Nasirian, Vahidreza, et al. "Droop-free distributed control for AC microgrids" *IEEE Transactions on Power Electronics* 31.2 (2016): 1600-1617.

[19] Zuo, Shan, et al. "Distributed Finite-Time Voltage and Frequency Restoration in Islanded AC Microgrids" *IEEE Transactions on Industrial Electronics* 63.10 (2016): 5988-5997.

[20] M. Kumar, S. C. Srivastava and S. N. Singh, "Dynamic performance analysis of DC microgrid with a proposed control strategy for single-phase VCVSI" *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, 2014, pp. 1-6.

[21] Simpson-Porco, John W., Florian Dörfler, and Francesco Bullo. "Synchronization and power sharing for droop-controlled inverters in islanded microgrids" *Automatica* 49.9 (2013): 2603-2611.

[22] Zhong, Qing-Chang, and Dushan Boroyevich. "Structural resemblance between droop controllers and phase-locked loops" *IEEE Access* 4 (2016): 5733-5741.

[23] de Aguiar, Cassius R., et al. "Out-of-phase automatic reclosing in distributed generation systems with voltage source inverters" *Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), 2015 IEEE 13th Brazilian*. IEEE, 2015.

[24] Kumpulainen, L. K., and K. T. Kauhaniemi. "Analysis of the impact of distributed generation on automatic reclosing" *Power Systems Conference and Exposition, 2004. IEEE PES*. IEEE, 2004.

8. List of Abbreviations

CENELEC	European Committee for Electro technical Standardization
CPS	Cyber-Physical System
EMS	Decentralised energy management system
DER	Distributed Energy Resources
DMS	Distribution Management System
DSO	Distribution System Operator
ESCO	Energy Service Companies
ESO	European Standardisation Organisations
HEMS	Home Energy Management System
HV	High Voltage
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IED	Intelligent Electronic Device
IoT	Internet of Things
KPI	Key Performance Indicator
LTE	Long Term Evolution
LV	Low Voltage
MV	Medium Voltage
NIST	National Institute of Standards and Technology
NORM	Next generation Open Real time Meter
PLC	Power Line Communication
PLL	Phase-Locked Loop
PMT	Project Management Team
PMU	Phasor Measurement Unit
PS	Primary Substation
PWM	Pulse Width Modulation
RTDS	Real Time Digital Simulator
SCADA	Supervisory Control and Data Acquisition
SG-CG	Smart Grid Coordination Group
SGSG	Smart Grid Stakeholders Group
SME	Small & Medium Enterprise
SS	Secondary Substation
VCVSI	Voltage-Controlled Voltage-Source Inverter
TL	Task Leader
TM	Technical Manager
TSO	Transmission System Operator
VPP	Virtual Power Plant
WP	Work Package
WPL	Work Package Leader