# PROTECTION SYSTEM ANALYSIS IN LV GRID, WITH HIGH DG PENETRATION, IN PARALLEL AND ISLANDING OPERATION

Nuno Lopes Filipe
EDP Labelec - Portugal
nuno.lopesfilipe@edp.pt

Andreia LEIRIA
EDP Labelec - Portugal
andreia.leira@edp.pt

Ricardo André
EDP NEW R.&.D - Portugal
ricardo.andre@edp.pt

José Damásio
SIEMENS SA - Portugal
jose.damasio@siemens.com

Matthias Gerlich
SIEMENS AG - Germany
matthias.gerlich@siemens.com

Salvador Rodriguez
GPTECH - SPAIN
srodriguez@greenpower.es

## ABSTRACT

*The ambitious 20-20-20 targets of the European Union (EU) have been fostering the development of several projects aiming to help to comply with these goals. SENSIBLE – Storage-enabled sustainable energy for buildings and communities is a Horizon 2020 funded innovation action aiming at integrating small-scale electro-chemical, electro-mechanical and thermal storage technologies, together with Distributed Renewable Energy Sources (DRES), into distribution grid, homes and buildings.*

*One of the main objectives of the Portuguese SENSIBLE demonstrator is to test the islanding operation of a LV with grid embedded storage devices.*

*This paper presents the short-circuit studies that were performed for the distributed resource (DR) island system. For that purpose the actual secondary substation LV grid was modeled with MATLAB Simulink software, with real grid data provided by the DSO and with the grid embedded storage models provided by the manufacturers. The studies were performed for all foreseeable configurations (parallel and island) to ensure clearing of faulted conditions, and with different load scenarios.*

## INTRODUCTION

EDP LABELEC is an EDP Group company whose mission is to be the technical excellence centre for all EDP. Accordingly, EDP Labelec has been an important EDP NEW R&D partner, providing technical support and helping on solving the challenges it faces, such as the one presented in this study.

The increasing penetration of Distributed Renewable Energy Sources in the Low Voltage (LV) network, located close to demand can deliver electricity with minimal losses, which can have a higher value in comparison with the traditional distribution infrastructure. However, under today's grid codes, all distributed generation must disconnect during utility grid power outages. This is precisely when these on-site sources could offer the greatest value to both generation owners and end costumers, by optimizing: power quality and continuity-of-service. Sustainability aspects shall also be considered since it may run continuously in off-grid or on-grid mode.

Under SENSIBLE project, EDP will test – in the Portuguese demonstrator of Évora – one use case dedicated to the operation in islanding mode, which consists in the disconnection from the main grid (due to planned and unplanned events), without interrupting the service to the final LV costumers.

This study gives a response for the new challenges that this operating mode brings in terms of protection schemes and principles.

## SYSTEM ARCHITECTURE

The system architecture of the Évora demonstrator dedicated to the islanding operation is shown on Figure 1.

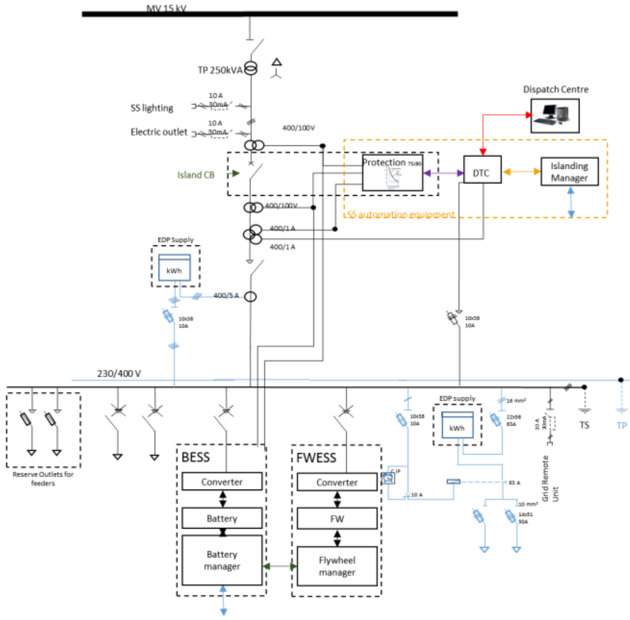


*Figure 1 - System Architecture [1]*

The secondary substation (SS) is supplied by a 15kV line, that provides energy to a pole mounted 250kVA transformer with a Dny5 configuration and a voltage ratio of 15kV/400V.

This SS has 3 feeders, one used for the public illumination circuit, and two main feeders to provide energy to the LV end clients. It will be installed in feeder 1 a 30kW Battery Storage Unit (ST 30kW - GPTech), at a cable distance of about 520m, from the SS.

The 50kW Battery Storage Unit (ST 50kW - GPTech) and

the 125kW Flywheel Unit (FW - Siemens) will be installed at the SS directly connect to the LV bus.
The SS will have automation equipment to manage the whole operation (grid->island->grid): there will be the protection relay, a DTC (Data Collector Centre), which will be connected the dispatch centre, and an Islanding Manager. This last device, the most important one, is able to control the droop characteristic of the Flywheel and the 50kW battery. It is connected to analogue sensors and to the protection relay and interacts with the DTC to successfully achieve the transition between grid-connected operation and islanding.

## Flywheel Unit 125kW (Siemens)

In order to provide power in complement to batteries in case of transient regimens providing short time peak active power. This device will have droop control, island detection and its operation is coordinated with the other energy storage systems (ESS).

## Battery Storage Units [2]

Electro-chemical storage (Li-Ion batteries) in order to provide flexibility in islanding operation, both at SS level and at feeder level. At SS level, the ST 50kW will be operated with V/f control and at feeder level the ST 30kW in P/Q control. Droop control strategies will be implemented at ESS level. ESS batteries were sized so that an islanding could be possible in 80% of outrages/failures in MV grid side. In terms of energy, 30 min would cover also 95% of the outages, based on historical data. This results in a required capacity of about 80kW and energy of at least 40kWh.
For the ST 50kW the maximum inverters current in case of a fault on the grid was specified to be 220A, which will be tested in the simulation.

## System Operation

The FW 125kW and ST 50kW are connected to the LV busbar and operate in V/f mode all the time (in grid-connected mode and islanded mode).
For preliminary transient operation tests, it will be considered to use external loads instead of energy demand from houses. Those tests will take place in EDP Labelec laboratory and they are aimed to test all the operation process with focus on the coordination between the equipments, as well as the effective coordination in the protection system.
The studies performed in this work do not consider the household storage devices neither the PV systems, because they have little influence in the short-circuit current contribution to trip the circuit breakers. Besides that, for a complete simulation of the system, which will be done for other tasks, it is necessary to scale up modelling and simulation tasks and integrate the other batteries, loads and PVs.

**Grid-connected to islanding operation**
If there is a high load demand and the storage devices do not have the capacity to produce enough energy, it could be a possibility to open a switch in order to disconnect non-critical loads (load-shedding process), keeping the frequency and voltage at acceptable levels.
Both, flywheel and battery systems can detect islanding autonomously, but the whole process will be guided by the islanding manager.

**Islanding operation to grid-connected**
The secondary substation will have a synchro-check relay from SIEMENS SA that allows a connection with a discrepancy of 5-10º 20mHz. This relay will inform the islanding manager if connection to MV grid is possible or not. This device will perform the synchronization between MV and LV and inform the DTC when it is done.

## Protection Devices

As it is possible to see on Figure 1 for the overcurrent protection of the whole system we have:

- Island circuit breaker, controlled by a overcurrent time protection relay (Siemens 7SJ80);
- Each of the three storage devices have an interface protection device, as demanded by the Portuguese DSO, with an overcurrent relay (7SR11 and 7SR12 Argus, Siemens) that operates a circuit breaker;
- The two main feeders will have 3VL3, Siemens, circuit breakers, with a nominal current $I_N$ = 200A and a rated current $I_r$ = 80-200A.

The interface protection of the storage devices will have many different protection functions besides the overcurrent (over/under voltage, over/under current, maximum zero sequence voltage). This study will be focus on the short-circuit currents that will appear on the grid in the result of a fault, and the capacity/behaviour of the storage devices on those situations. The results will help the Portuguese distribution system operator (DSO) to define the settings for the overcurrent relays.

# DIGITAL SIMULATION

## Grid Topology and Elements

In this simulation, it is assumed a peak consumption of around 70kW, a typical value for this secondary substation. The feeders are modelled using three-phase pi section and RLC branches to represent the lines and cables. The clients are modelled as a RLC load. The load profile of each client was obtain from real load diagrams provided by the DSO.
The feeder 1, (which has the ST 30kW) has a consumption of around 25kW and the feeder 2 of around 45kW. This last one will not have a grid-embedded storage unit, so it will be simulated as an equivalent three-phase RLC Load with the equivalent impedance seen from the SS (Figure 2).

*Figure 2 - Simulation Model*

**ESS Devices**

All the models used for this study were developed and validated by the manufacturers and will also be used for other studies in the SENSIBLE project.

## SIMULATION SCENARIOS

The simulation scenarios tested the grid behaviour for the following topics:

- Transitory variation of the grid's parameters, voltage, frequency, current, in the transition between islanding and parallel mode;

Grid-connected Mode

- Storage behaviour in case of a fault (phase-ground and phase-phase-ground) in the LV busbar and at a distance of 200m from the storage;

Islanding Mode

- The inverters response for different fault conditions: phase-ground, phase-phase and a phase-ground fault at a distance of 200m from the secondary substation in feeder 1;

## SIMULATION RESULTS

### Transition Grid -> Island -> Grid

In this scenario, only the grid provides energy to the household loads until second 1. At this time, all the ESS are switched on. At t = 2s the grid circuit breaker opens and the grid is operating in islanding mode, with the FW operation just on the transient and the ST 50kW providing the energy that previously came from the electrical grid. At t = 7s the synchronization process begins and the circuit breaker is closed on the zero crossing of the current to guarantee a smooth transition between operating modes. In Figure 3, Figure 4 and Figure 5 it is possible to see the active power, frequency and voltage profiles for the whole simulation. The frequency levels are within the permissible values 49.5-50.5Hz. The same happens for the voltage levels that stabilize within the permissible values 90-110% $V_n$. The difference between the phase voltage levels are due to the load unbalance.

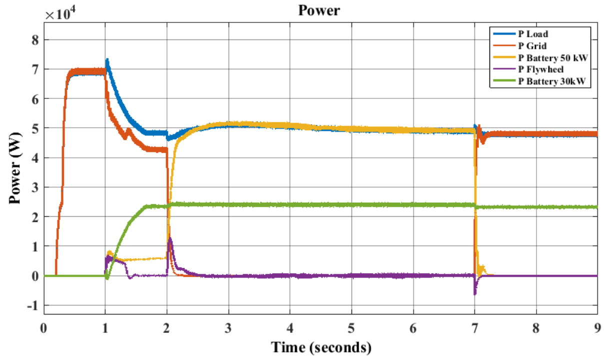


*Figure 3 – Active power profile on the grid on transition grid-connected/islanding operations*

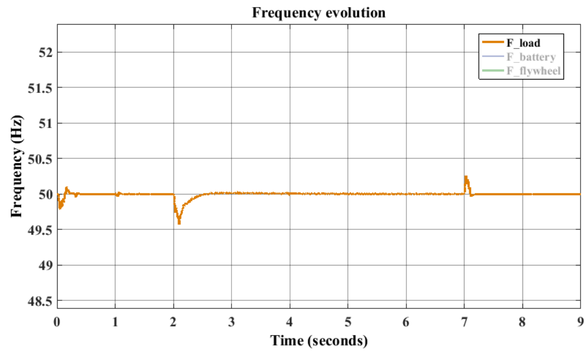


*Figure 4 - Frequency profile on the grid on transition grid-connected/islanding operations*

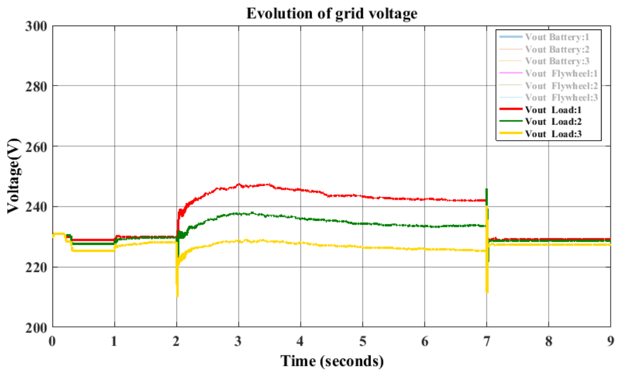


*Figure 5 – Voltage profile on the grid on grid-connected/islanding operations*

On the Simulink FW model it was used a battery connected to the inverter because there is no model to represent the electro-mechanical device that has the much faster time response and produces a higher current peak. In reality, we may observe a slower response from the ST 50kW with the FW ensuring the smooth transition. For the purpose of this study, which focus is on the short-circuit simulation, this fact does not affect the results.

### Grid-Connected Mode

For the grid-connected mode all the storage devices are switched on at t = 1s, and at t = 3s, a fault occurs at the LV busbar (worst case scenario). This fault remains on the network for 500ms, at that time the fault disappears and the network returns to normal operation with the ST 30kW in PQ mode and ST 50kW and FW in V/f mode. The aim of this simulation is to determine the behaviour of the storage devices in fault conditions.

**1. Fault conditions -> Phase-Ground on LV busbar**

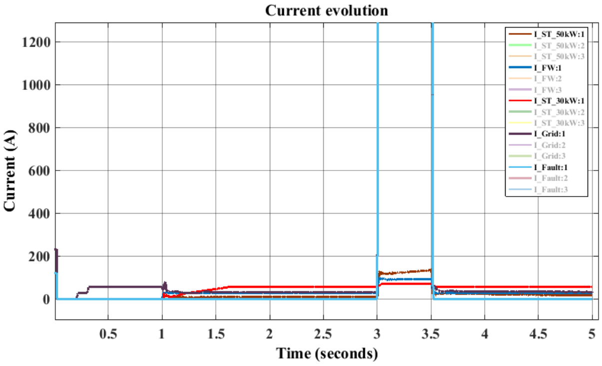


*Figure 6 – Phase to ground fault on the LV busbar, grid-connected mode*

At t = 3s, a solid phase A to ground fault occurs. In Figure 6 it is possible to observe, between t = 3-3.5s, the current contribution of each device to the fault current. The currents injected by the storage devices increase during the fault condition which will be higher for the ST 50kW, 140A, and the FW, 96A. The ST 30kW is operating on PQ mode which limits the current output, 73A.

In this operating mode, the current that trips the overcurrent protection relay of the island CB has to be provided by the grid, which can be seen on Figure 6, where the grid current is higher than 1kA. Although the current values of the storage devices are not very high, in grid operating mode the inverters should limit the injection of current to the nominal value (or the pre-fault value), to minimize the thermal stresses that affect the equipments, this could extend their lifetime. In case of a busbar fault, the island CB should trip and the ESS CB should receive an order to trip also, in order to stop feeding the fault.

The remarks made here are applicable for other types of fault conditions on the busbar. For a fault on a feeder, its CB should trip faster than the island CB so the other feeder continues to provide energy to the end clients. If the fault is on feeder 1, the ST 30kW should also trip.

## Islanding Mode

For the islanding mode all the storage devices are switched on at t = 1s. At t = 1.5s the island CB opens and the grid starts to operate in islanding mode. At t = 3.5s fault occurs and remains on the network for 500ms. After that, the fault disappears and the network remains with the ESS operating. The aim of this simulation is to determine the behaviour of the storage devices in fault conditions, especially the current provided. This will help to determine the settings for the overcurrent relays and for the CB.

**1. Fault conditions -> Phase-Ground on LV busbar**

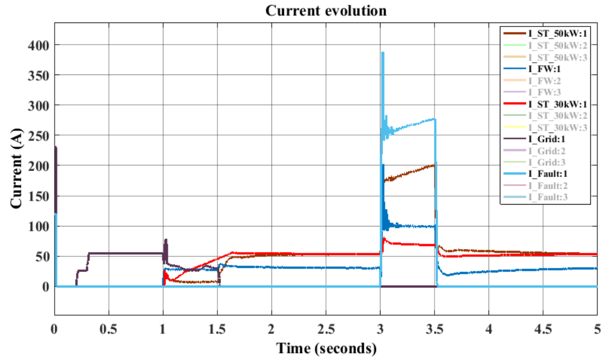


*Figure 7 - Phase to ground fault on the LV busbar, islanding mode*

In fault condition t = 3-3.5s, Figure 7, the majority of the fault current is provided by the ST 50kW, followed by the FW. The ST 30kW is in PQ control mode which limits the current output.

As it is possible to see, the ST 50kW current spikes to 170-200A, so its overcurrent relay should detect the fault condition for this range of current. With a fault in this location (busbar), every interface protection of the storage devices have to trip and stop feeding the fault, this is applicable also for the ST 30kW. Note that there will be storage devices and PV on household clients so it is important that their interface protection will trip in case of a busbar fault. This may be accomplished by the frequency and voltage drop that can cause the tripping of the interface protections for those devices.

In this study the ST 30kW has this current injection limitation, but in reality it should have the capacity to inject $3*I_n$ = 130A in case of a fault scenario. So its protection relay should trip at a value close to this.

The ST 50kW should in reality provide more current, in the order if $3*I_n$ = 216A. If the fault conditions persisted longer, the ST 50kW should reach this current value because its current was increasing, as it is possible to see on Figure 7.

**2. Fault conditions -> Phase-Phase on LV busbar**

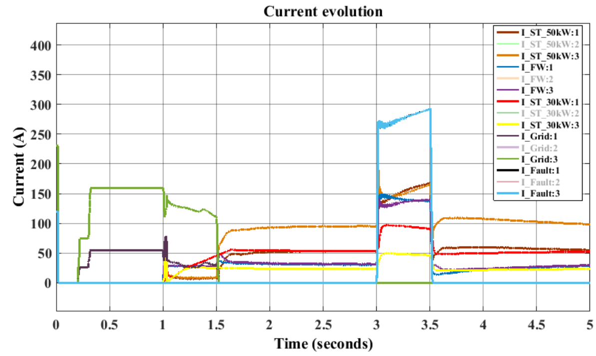


*Figure 8 - Phase to phase fault on the LV busbar, islanding mode*

For this scenario the ST 50kW could deliver more than 150A per phase for the fault contribution, nearly the same has the FW. Both devices provide more than 200A to the fault. In a fault condition like this and the previous one, the ESS devices have to stop providing energy and the corresponding circuit breaker has to trip.

**3. Fault conditions -> Phase-Ground 200m on feeder 1**

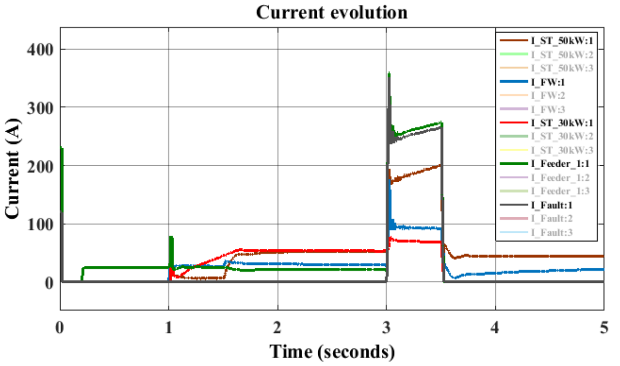


*Figure 9 - Phase to ground fault on feeder 1, 200 m from the secondary substation, islanding mode*

In this scenario, Figure 9, there is a solid phase A to ground fault located on feeder 1, at 200m cable distance of the SS. This scenario, similar to 1., is crucial to emphasise the importance of the protection coordination. It is necessary that in a situation like this, the feeder CB trips with the current provided by the ESS on the SS. For that, a setting lower than the current provided by the ST 50kW is needed, in the order of 180A.

The fault is on feeder 1, so the ST 30kW as to trip, and it will not feed the fault. This could be done by the trip of its overcurrent protection relay, which should be set for a value lower than the 130A, or by receiving an external tripping signal sent by the automation equipment. The ESS on the SS continues to provide energy to the second feeder, so the feeder's 1 CB should have a tripping time faster than the ESS overcurrent relays (protection coordination).

The settings of the feeder's CB need to be adjustable to the ST 50kW capacity to inject fault current. In the devices specifications it is stated that it can provide nearly 220A, but that may depend on the situation or it could not be fast enough to trip the circuit breaker in the time needed. So the setting has to be lower than that, around 170A. On the other hand, it has to be high enough, as it will not trip due to a peak load situation during the normal operation mode, during the winter for example. The overcurrent ESS relays must be set for a value smaller than the maximum short-circuit current and must be coordinated with the feeders CB, as previously said. The ST 30kW should receive a tripping signal, if the feeder 1 CB trips due to a fault. The overcurrent relay for the island CB should also be coordinated with the feeder's CB (they should trip faster) and with the ESS, that should trip in case of a fault in a busbar.

## CONCLUSIONS

Under SENSIBLE project a study was conducted by EDP Labelec in order to assess the short-circuit currents in the Portuguese Évora demonstrator that is intended to perform island operation. The simulation scenarios tested the grid and ESS behaviours in islanding and grid-connected mode, and produced the results needed for the protection system setting and coordination.

The modelling and subsequent simulations were performed using MATLAB Simulink. The ESS behaviour was observed during the transition between the two operation modes. For the grid connected mode it was analysed the ESS contribution for the fault current, noting that those equipments should allow the control of their contribution to the nominal current value to limit the thermal stress. For the islanding operation it was determined the ESS capacity to inject the fault current needed to trip the circuit breakers, as well as their overcurrent relays.

The study presented here is just a small part of a more complete work performed.

The paper presents the technical solution for the protection system of the Évora Sensible Demonstrator, with the protection schemes, settings and a protection philosophy that can be applied for future LV grids that would have the capacity to be operated in islanding mode, compliant with the grid code requirements and assuring the quality of service.

## FUTURE WORK

All the Sensible equipment (storage devices, logical devices and communications) will be tested in laboratory environment, in EDP Labelec, before being installed in the field. The simulations results will be validated in laboratory and, if needed, the models will be tuned. After installation, the results here presented will be also compared with real data monitored on the field.

## REFERENCES

[1] - EDP Distribuição, LV secondary switchgear technical specifications

[2] - Ricardo André, Cired 2017, Low Voltage Grid Upgrades Enabling Islanding Operation