H2020 SENSIBLE PROJECT – LABORATORY RESULTS FOR THE SHORT-CIRCUIT BEHAVIOUR OF THE STORAGE DEVICES. UNDER ISLANDING CONDITIONS

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ABSTRACT

The continuous increase of Distributed Generation (DER) along the electrical grid can offer several benefits, such as microgrid operation. However, microgrid operation requires special attention and introduces new challenges to the distribution operators, in particular for the protection systems.

In the SENSIBLE project, a H2020 project funded by the European Commission (EU), one of the objectives of the Portuguese demonstrator is to test the islanding operation of a LV secondary substation (SS) with grid and residential storage devices.

In the context of this paper, the results of the protection tests performed under laboratory conditions at EDP Labelec are presented.

For that purpose, a secondary substation low voltage (LV) grid was built, with the grid embedded storage devices connected to a LV busbar, which provide energy to a set of adjustable loads (three-phase heating fans). The studies were performed for all foreseeable configurations (parallel and island) to ensure clearing of faulted conditions, and with different load scenarios.

INTRODUCTION

Short-circuit phenomena in microgrids are mainly characterized by low short-circuit current magnitudes supplied by the converter type *DER*s and other current sources distributed along the microgrid. To ensure the protection selectivity and sensitivity, the inverter protection relay shall adjust the protection settings according to the grid operation mode (grid-connected or islanding) and the characteristics of *DER*s, or the inverter should have the capacity to achieve and maintain the short-circuit current necessary to trip the appropriate protection devices. This will be the case for this paper.

However, currently grid codes specify that 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.

Under the scope of *SENSIBLE* project, *EDP* Labelec tested for the Portuguese demonstrator of Évora one use case dedicated to the islanding operation of *LV* grids, where a part of a *LV* secondary substation is disconnected from the main *LV* grid, but remains energized and ensures continuity-of-service. This islanding operation can be either the result of a grid constraint, such as a trip due to a fault or the result of a deliberate action (intentional islanding). For that purpose, several developments were made both at high level energy management tools and at equipment level:

- Three grid battery energy storage systems (*BESS*), the first one (50 kVA) directly connected to a feeder in the secondary substation and the other two connected (30 kVA and 10 kVA) along the *LV* feeders;
- Residential *BESS* (2.3 kW), *PV* panels (1.5 kW), smart meters and controllable loads in each participating household.

To ensure the correct operation and the interaction between the referred devices, it was decided to test the whole system beforehand, in laboratory conditions. The results for the short-circuit tests, which are crucial to the correct parametrization of the DSO protection devices, are presented in this paper for islanding operation.

LABORATORY INFRASTRUCTURE

In this section, the laboratory conditions that allowed the correct implementation of the short-circuit tests are described.

The *SS* single line diagram used for the Laboratory tests is represented on Figure 1.

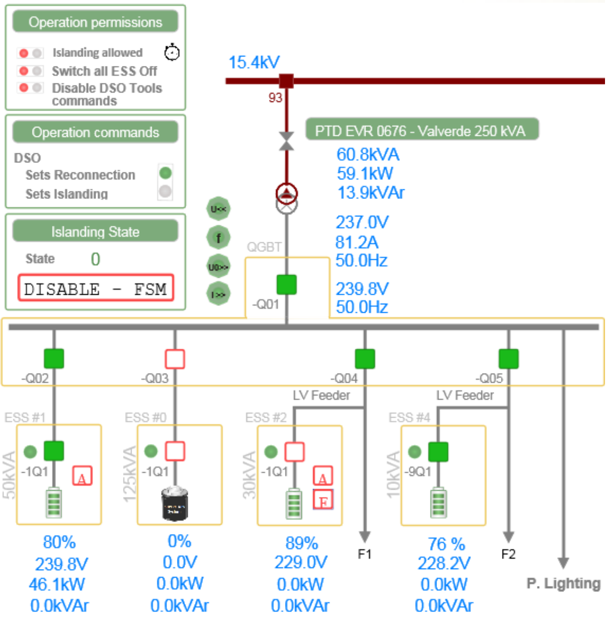


Figure 1 - System Architecture

This laboratory test bed was built with the same equipment that was installed on the field, a *LV SS* with several feeders, connected to the grid *BESS* and a set of adjustable loads that allow to simulate the real grid load diagram along the day.

The fault conditions were achieved through a circuit breaker which allows several configurations to simulate real fault conditions.

Control Systems

Concerning to the protection and automation equipment, the *SS* have installed the following equipment:

- *DTC* (Distribution Transformer Controller) - controller for the distribution network that integrate the LV network control and manage the whole operation since the transition to islanding, the islanding operation and the grid connection.

  It is also the equipment that ensures the communication with the high-level management tools;
- Islanding Manager – the main purpose of this device is to control the microgrid droop characteristic. It is connected to several IO signals, to the protection relay and interacts with the DTC to successfully achieve the transition between grid-connected operation and islanding.

Protection Devices

As it is possible to see on Figure 1 the protection of the whole system is assured by the following devices:

- Multifunction protection relay that controls the Island circuit breaker;
- Multifunction protection relay, for each of the three storage devices that operates each grid connection circuit breaker;
- Motorized circuit breaker, with a rated current $I_N = 200A$ protected by an embedded overcurrent protection device with adjustable time-current settings, for each of the two main LV grid feeders.

Besides the overcurrent protection the storage devices also have many different protection functions (over/under voltage, overcurrent, neutral voltage displacement).

The focus of this study was on the short-circuit currents that appeared on the grid in the result of a fault, and the storage devices capacity to provide the needed current to trip the protections on those situations.

Battery Storage Units

Electro-chemical storage (Li-Ion batteries) that provide the required flexibility for islanding operation, both at *SS* level and at feeder level. At *SS* level, the *BESS* 50kVA (ESS1) was operated in V/f control and at feeder level the BESS 30kVA (ESS2) in P/Q control. Droop control strategies were implemented at ESS level.

ESS batteries were sized so that an islanding could be possible in 80% of outages/failures on the main *LV* grid. In terms of energy capacity, based on historical data, 30 min would cover also 95% of the outages. This, results in a required power of 80kW and a required capacity of at least 40 kWh.

LABORATORY TESTS

Laboratory equipment

- Energy Storage Systems;
- *FLUKE* 1760 Power Quality Analyzer;
- PC with Siemens DIGSI software;
- Electrical feeder for the ESS;
- 1x (one) Short Circuit connector;
- Adjustable loads: fans and thermal resistors.

General considerations

1. In islanding operation the no-load tests could not be performed in the master generator (ESS1) due to the V/f control. There is always some load present in the master generator because the system is trying to maintain the grid parameters (voltage and frequency) inside the allowed limits.
2. The short-circuits duration were longer than 500 ms in order to confirm that all the inverters withstand the values stated by the manufacturer of 1.2xIn for 500 ms.

Protection relay settings

The relay protection functions and the settings used in the laboratory tests are described in Table 1.

Table 1 - Protection functions and settings

Protection Function	ANSI CODE	ESS1	ESS2
Instantaneous/ Time-delay Overcurrent	50/51	92 (2 s)	54 A (1 s)
Instantaneous/ Time-delay Neutral Overcurrent	50N/51	40 A (1 s) 92 (0.5 s)	15A (1 s) 38 (0 s)
Directional Overcurrent	67	X	X
Underfrequency	81U	49 Hz (1 s)	49 Hz (1 s)
Overfrequency	81O	51 Hz (1 s)	51 Hz (1 s)
Undervoltage (line-to-ground)	27	200 V (1 s)	200 V (1 s)
Overvoltage (line-to-ground)	59	300 V (1 s)	300 V (1 s)

Islanded operation protection tests and results

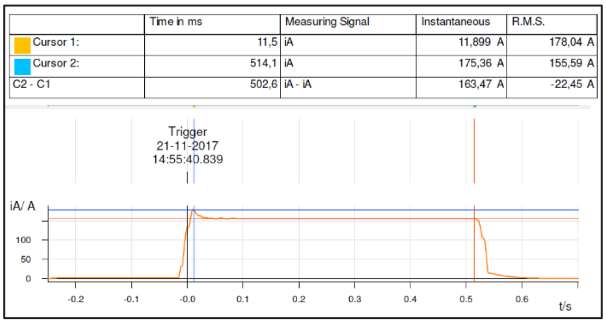
ESS1 is a 50 kW storage device with an In of 72 A. The aim of these tests was to compare the 1.2xIn (~ 87 A) short-circuit current stated by the manufacturer with the results under real conditions. As specified by the Portuguese DSO (EDP Distribuição) the storage systems have to maintain the 1.2xIn for at least 500 ms in order to trip the LV overcurrent protection devices efficiently and so the microgrid can be successfully maintained.

The short-circuit tests were performed for the ESS1 with different fault conditions (line-to-ground, line-line and three phase) considering solid and impedance conditions (Z ~ 0.156 Ω) with load (59 kW) and no-load. The storage devices were connected in parallel mode to the grid. The load conditions were enabled and the transition to the islanding mode was performed. After the transient and with all the grid parameters stable, the short-circuit test were performed for the specified fault configuration. The results obtained can be observed on Table 2 and are described by the fault duration (ms) and the current values (A_{rms}) for each phase. Being in P/Q mode the short-circuit current for the ESS2 is limited to the pre-fault specified setpoint, so the results are not relevant for this analysis. The storage device tripped due to undervoltage protection function after the trip of ESS1. Besides the results shown on Table 2, Figure 2 to Figure 5 represent some examples of the fault records obtained through the DIGSI Software (SIEMENS) during the short-circuit tests.

As it is possible to conclude by the results obtained, the load conditions have little influence on the storage devices short-circuit capacity. In opposition, the impedance fault has influence in the results, which is possible to see for the case of a line-to-ground fault, with a difference of about ~ 20A. In all the referred short-circuit tests the current values obtained were higher than the specified value of 1.2xIn, reaching values greater than 1.5xIn.

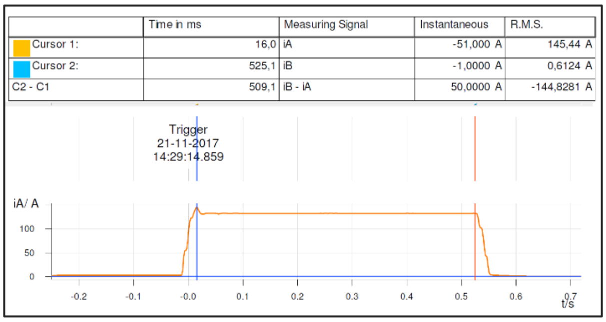
Table 2 - ESS1 short-circuit results

Type of Short-circuit	Duration **(ms)**	Current Values **(A)**
Solid three-phase (Z~0) (with load in the grid)	1100	IL1 = ~ 112 A (rms) IL2 = ~ 112 A (rms) IL3 = ~ 112 A (rms)
Solid three-phase (Z~0) (no-load in the grid)	1200	IL1 = ~ 111.8 A (rms) IL2 = ~ 111.8 A (rms) IL3 = ~ 111.8 A (rms)
Three-phase impedance (Z ~ 0.156 Ω) fault (no-load in the grid)	1030	IL1 = 110.75 A (rms) IL2 = 93.84 A (rms) IL3 = 110.53 A (rms)
Solid line-to-line (Z~0) fault (no-load in the grid)	513.7	IL1 = 163.9 A (rms) IL2 = 140.2 A (rms) IL3 = 3.7 A (rms)
Line-to-line impedance (Z ~ 0.156 Ω) fault (no-load in the grid)	516.12	IL1 = 133.5 A (rms) IL2 = 126.9 A (rms) IL3 = 2.5 A (rms)
Line-to-ground impedance (Z ~ 0.156Ω) fault (no-load in the grid)	509.1	IL1 = 145.4 A (rms) IL2 = ~2.5 A (rms) IL3 = ~2.5 A (rms)
Solid line-to-ground (Z ~ 0 Ω) fault (no-load in the grid)	502,6	IL1 = 155.6 A (rms) IL2 = ~2.7 A (rms) IL3 = ~2.7 A (rms)



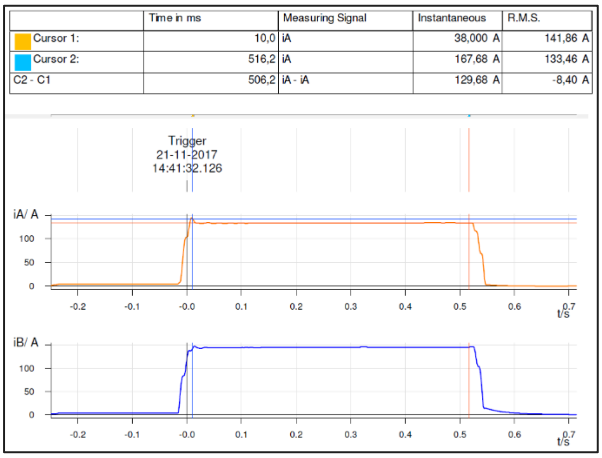
	Time in ms	Measuring Signal	Instantaneous	R.M.S.
🟧 Cursor 1:	11,5	iA	11,899 A	178,04 A
🟦 Cursor 2:	514,1	iA	175,36 A	155,59 A
C2 - C1	502,6	iA - iA	163,47 A	-22,45 A

Figure 2 – Solid Line-to-Ground (Z~0) fault, no-load



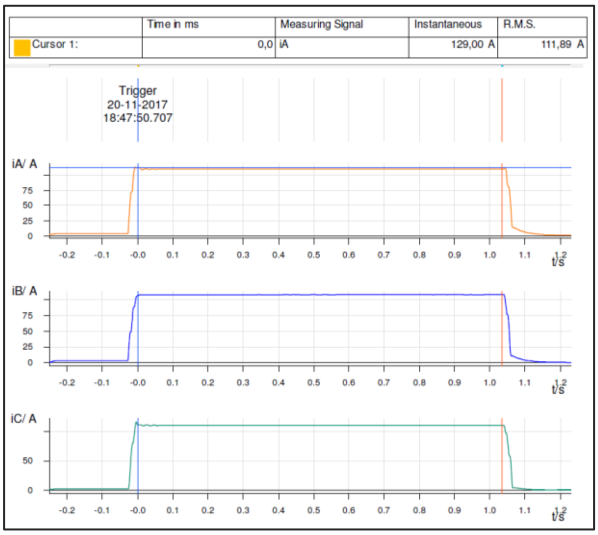
	Time in ms	Measuring Signal	Instantaneous	R.M.S.
🟧 Cursor 1:	16,0	iA	-51,000 A	145,44 A
🟦 Cursor 2:	525,1	iB	-1,0000 A	0,6124 A
C2 - C1	509,1	iB - iA	50,0000 A	-144,8281 A

Figure 3 - Line-to-Ground impedance (Z ~ 0.156Ω) fault, no-load



	Time in ms	Measuring Signal	Instantaneous	R.M.S.
🟧 Cursor 1:	10,0	iA	38,000 A	141,86 A
🟦 Cursor 2:	516,2	iA	167,68 A	133,46 A
C2 - C1	506,2	iA - iA	129,68 A	-8,40 A

Figure 4 - Line-to-line impedance (Z ~ 0.156Ω) fault, no-load



	Time in ms	Measuring Signal	Instantaneous	R.M.S.
🟧 Cursor 1:	0,0	iA	129,00 A	111,89 A

Figure 5 - Three-Phase ideal (Z~0) fault, no-load

DISCUSSION OF RESULTS/CONCLUSIONS

The test requirements and procedures described in this paper aimed to evaluate the behaviour of the several grid ESS under different fault conditions and load scenarios in order to confirm the manufacture specifications related with the capacity to maintain a short-circuit current higher than 1.2xIn for at least 500 ms (as required by the Portuguese DSO, EDP Distribuição).

The results obtained allowed to conclude that:

- The inverter in P/Q control mode (ESS2) could provide fault current, but that value was limited by the last P/Q set-point sent to the inverter (current source inverter);
- For the main storage device (ESS1), with V/f control mode (voltage source inverter), was verified that the short-circuit current values were lower with an impedance fault in comparison with a solid fault. Although the impedance small value, it was enough to influence the fault current value;
- The presence of load in the grid was not relevant for the fault current analysis;
- The microgrid operation time during a fault is dependent on the correct coordination between the internal protection settings of the inverter and the protection relay installed in the grid connection of the inverter control cabinet.

For the tests performed it was achieved a current level of more than 1.5xIn and a time duration superior than the 500ms specified, which fulfils the DSO requirements.

The results shown in this paper were then used by EDP Distribuição, the Portuguese DSO, to perform the parametrization of the digital protection relays settings for the Évora Demonstrator.
The computed protection functions settings were based on the presented results and intended to enable the successfully islanding transitions and microgrid operation without any protection tripping and at the same time maintain the coordination with the existing LV network fuses when the grid is connected. In the microgrid, (island operation) the grid protection is mainly based on voltage and frequency protection functions.

The study presented in this paper is just a small part of a much more complete work performed. One of the main accomplishments of the results presented in this paper was to provide to the DSO a preliminary guideline for future LV protection schemes implementation in the LV grid with islanding operation capabilities and in compliant with the current grid code requirements and quality of supply standards.

FUTURE WORK

All the SENSIBLE equipment (storage devices, logical devices and communications) are being tested in the field by EDP Labelec. 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
[3] – Miguel C. Marques, Luís Rocha, Pedro Castro, Alexandre Neto, SENSIBLE Tests Protocol – LV Grid Infrastructure, Edition A, Review 3, 2018