Protection Scheme for Energy Storage Systems Operating in Island or Grid Connected Modes

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ABSTRACT

The integration and proliferation of Energy Storage Systems (ESS) in the power grid has been a current hot topic among the electrical community. In 2015 EDP Distribuição (EDPD) decided to install a Storage system in its distribution grid that would be prepared to operate connected to the grid offering flexibility and services to the grid but also in island mode with a Client which was EDP's partner in this project.

Storage systems have the possibility to either inject or consume power from the network in addition to islanding operation. This causes new challenges to the power system protection. Therefore, EDPD, Siemens and INESC ID focused on the analysis of the response the ESS to faults either connected to the network or isolated from it. To ensure the safe operation in both modes new protection schemes were studied and a solution that fulfils the requirements was proposed and adopted.

To validate all calculations and simulations made during the research phase, EDPD performed several on site tests which included real short-circuit experiments. EDPD verified that some of the results obtained in these on site tests were different from the simulations and theoretical calculations. Based on the studies and real tests, EDPD protections and automation department developed a two group setting to be applied to the ESS, one group to be used when in parallel with the grid and another to be used when in island mode. Changing between these modes is automatic. This proposed scheme insures the safe operation of this new type of asset.

INTRODUCTION

In 2015 EDP Distribuição (EDPD) decided to install in the Évora District a Lithium powered Energy Storage System (ESS) and connect it to the 15kV Medium Voltage (MV) distribution Grid near an EDPD Client which is a partner in the project.

The System was design to support the Client's load for at least 30 minutes if a power outage occurs, to provide energy services to the grid and flexibility to the electrical system. Therefore, the ESS installed by EDPD should be able to work both in parallel with the grid, allowing for an active and reactive power control, and in islanding mode with the Client installation, automatic voltage and frequency control.

EDP DISTRIBUIÇÃO ENERGY STORAGE SYSTEM DESCRITION

EDPD, after consulting the market, chose an ESS from Siemens, which partnered with EDPD in the project, offering EDPD the possibility to acquire further knowledge in Storage solutions and Siemens to get enhanced information to further develop the system.

The system proposed by Siemens to EDPD was modular and was installed in a moveable container, which is equipped with a dry type transformer, SF6 insulated medium voltage switchgear, racks of lithium batteries, inverters and all the necessary communications and energy management systems.

The general system characteristics are summarized in Table 1.

An ESS connected to the distribution grid which allows for both parallel and island mode operation modes raises new challenges on how to guarantee the required safety for people, including live works on the power grid, and equipment's.

In order to determine the best protection scheme to allow the safe usage of the system, EDPD protection and automation department, with the participation of Siemens and an academic partner (INESC ID), conducted extensive analysis, researched for similar works on the topic [1], conducted simulations and proposed a series of tests to be performed on site to fully characterize the behaviour of the ESS when feeding a short circuit in the grid. The information gathered supported the proposed protection scheme.

Table 1 - EDPD Energy Storage System main characteristics

Power Transformer	
Rated Power	500 kVA
Connection	Star / Delta
Voltage	30/15kV – 0,4kV
Inverter	
Number of Inverters installed	4
Voltage Level	400 V
Current (each Inverter)	170 A
Rated Power (each Inverter)	118 kVA
Battery	
Storage Capacity	360 kWh

SHORT CIRCUIT CALCULATIONS AND SIMULATIONS

One of EDPD's major priorities is ensuring the safe operation of its grid. In order to decide on the best protection Scheme for this new asset, EDPD had to fully understand the behaviour of the system, in particular when a fault occurs in islanding mode.
An issue that needs to be taken into account is the fact that the protection relays of the Storage System are installed in the MV and these relays have to detect faults in the MV side but also in the Low Voltage (LV) Client side. The short-circuit power of the ESS is much lower than the one provided by the grid leading to lower fault currents that may lead to an increase difficulty in faults detectability. It is also important to refer that the distribution transformer installed in Client side, due to its group connections, filters out the zero sequence currents from the LV side to the MV increasing the difficulty to detect earth faults in LV side with protection relays only on the MV side.

Simulations performed by ESS manufacture

EDPD asked for Siemens support in performing some computer simulations of the storage system to determine its response to several types of LV fault on Client site. The electric circuit that was modelled and simulated by Siemens is presented in Figure 1.
The following types of faults were simulated:

- Zero impedance Phase – to – Earth;
- Zero impedance Phase – to – Phase;
- 3-phase;
- 10 Ω phase – to – Earth.

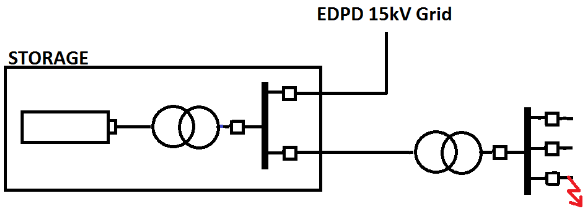

Figure 1 - Depiction of the electric model used in the Simulations

The results of the simulations are presented in Figure 2 and Table 2.

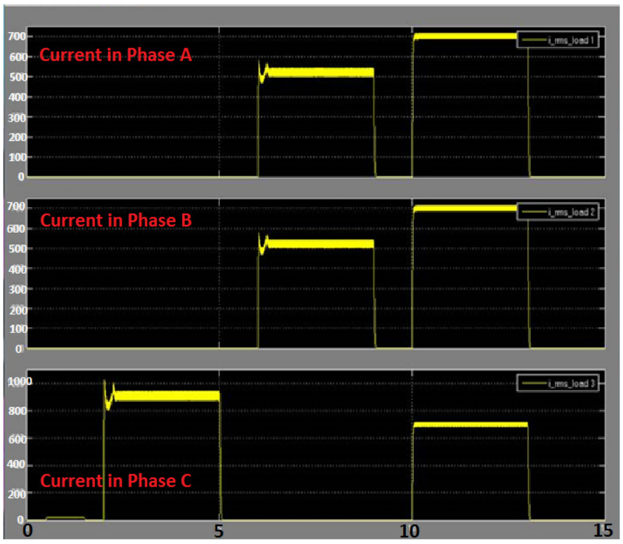

Figure 2 - EDPD ESS simulation results of the response to various fault types at the LV side.

Table 2 - Results of the LV short-circuit simulations presented by Siemens to EDPD of its ESS

Time Interval	Fault Type	Fault Current in LV Busbar
0,5s - 1,5s	Phase - to - Ground (10Ω)	≈ 0 A
3s - 5s	Phase - to - Ground (0Ω)	≈ 900 A
6s - 9s	Phase - to - Phase (0 Ω)	≈ 500 A
10s - 13s	Three-Phase (0 Ω)	≈ 700 A

As can be seen in Table 2, the simulations pointed the system to be able to inject fault current from 500A to 900A, depending on the type of short-circuit.
The rated current of EDPD ESS on the LV side is 681A which means that 900A, the maximum short-circuit current, corresponds to $1.32I_N$.

Short Circuit Calculations by EDPD

The department of Protection and Automation in EDPD analysed the simulation results and, using these results, EDPD team calculated the positive sequence, negative sequence and zero sequence currents and voltages for the MV side to determine which protection functions to use and the values to set. Calculations were performed for the best case scenario (highest fault current which in this case is a Phase – Ground fault) and for the worst case scenario (lowest fault current which in this case is a Phase – Phase fault).

Phase – To – Ground Fault

The calculations were made using phase-to-ground fault equivalent circuits, found in most power system faults literature, as in [2], [3].

Using the correct equations and the values provided obtained through simulation (Table 2) is it possible to obtain the following currents and voltages when a phase-to-ground with zero impedance fault occurs:

$$I_{ABC_{MV}} = \begin{bmatrix} 16\text{ A} \\ 8\text{ A} \\ 8\text{ A} \end{bmatrix} \quad I_{012_{MV}} = \begin{bmatrix} 8\text{ A} \\ 8\text{ A} \\ 0 \end{bmatrix}$$

$$V_{ABC_{MV}} = \begin{bmatrix} 0\text{ V} \\ -7369\text{ V} \\ 7369\text{ V} \end{bmatrix} \quad V_{012_{MV}} = \begin{bmatrix} 4313\text{ V} \\ 4313\text{ V} \\ 0\text{ V} \end{bmatrix}$$

The previous values were obtained considering the following initial conditions:

$$I_{ABC_{LV}} = \begin{bmatrix} 700\text{ A} \\ 0\text{ A} \\ 0\text{ A} \end{bmatrix} V_{ABC_{LV}} = \begin{bmatrix} 0\text{ V} \\ -199\text{ V} \\ 199\text{ V} \end{bmatrix}$$

Phase – To – Ground Fault Short Circuit Calculations

For phase – to - phase faults the values of currents and voltages obtained on the MV side were:

$$I_{ABC_{MV}} = \begin{bmatrix} 0 \\ 13{,}51\ A \\ 13{,}51\ A \end{bmatrix} \qquad I_{012_{MV}} = \begin{bmatrix} 7{,}8\ A \\ 7{,}8\ A \\ 0 \end{bmatrix}$$

$$V_{ABC_{MV}} = \begin{bmatrix} 8625\ V \\ 4312\ V \\ 4312\ V \end{bmatrix} \qquad V_{012_{MV}} = \begin{bmatrix} 4312\ V \\ 4312\ V \\ 0\ V \end{bmatrix}$$

The values were obtained considering these initial conditions:

$$I_{ABC_{LV}} = \begin{bmatrix} 0\ A \\ 500\ A \\ -500\ A \end{bmatrix}$$

The previous results for both phase to ground and phase to phase represents the theoretical response of the system and provided EDPD an estimate of the system behaviour when subjected to the fault event. The results also serve as a baseline guidance on protection system design and setting for an ESS with the characteristics of EDPD Storage.

SYSTEM RESPONSE DURING ON SITE TESTS

To fully understand the behaviour of ESS, EDPD endeavoured to reproduce the faults already simulated in computer in the real world. So, EDPD created a test circuit that could fulfil the objectives while insuring all technical and safety aspects. EDPD relied on the ESS protection relays to record current and voltage waves that resulted from each test and then compared the results with the ones obtained in simulations and theoretical calculations.

The experiments included creating the following faults at the LV side:

- Phase – Neutral 25Ω impedance;
- Phase – Phase with 25Ω impedance;
- Phase – Phase with zero impedance;
- Phase – Neutral with zero impedance;

To execute the referred experiments, the LV cables connecting the power transformer to the LV busbar were disconnected and then connected to an auxiliary circuit breaker (see Figure 3), which also included an extra protection relay with two levels of overcurrent protection function for added safety during the test execution. The terminals of this circuit breaker were then connected to LV cables in a way that depends on the desired short circuit to be tested.

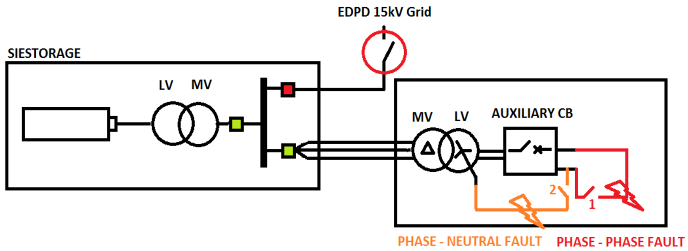

Figure 3 – Simplified electrical circuit of the onsite tests

The methodology used during the tests was:

1. Ensure all circuit breakers (CB) of the test circuit are opened;
2. Perform a blackstart on the ESS imposing a 15kV to the MV busbar installed inside the Storage container.
3. Close the MV circuit-breaker of EDPD Client installation feeder, powering the distribution transformer.
4. Close the LV auxiliary circuit breaker to create the short circuit. At this point, the protection functions would trip opening the auxiliary circuit breaker and/or the MV circuit breakers inside Storage container.

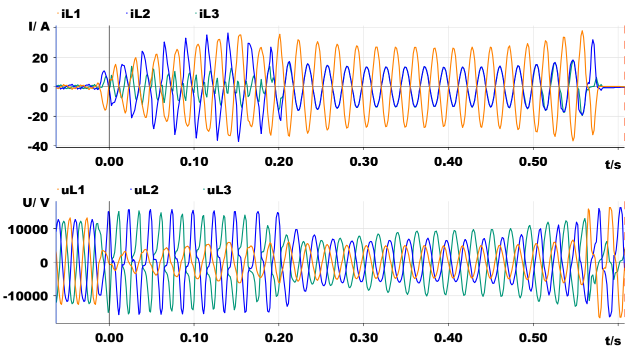

Figure 4 – LV Phase - Neutral fault with 25Ω Impedance Test Results

Table 3 – LV Phase – Neutral Fault with 25Ω Impedance Test values

I_A	26 A
I_B	13,9 A
I_C	12,2 A
U_A	4,83 kV
U_B	7,05 kV
U_C	9,27 kV
I_2	12,17 A

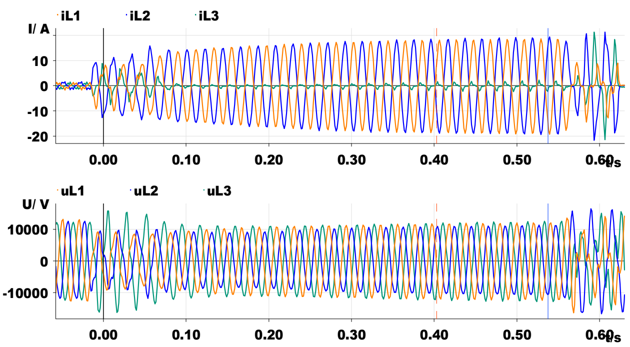

Figure 5 – LV Phase A – Phase C fault with 25Ω Impedance Test Results

Table 4 – LV Phase A – Phase C fault with 25Ω Impedance Test values

I_A	13 A
I_B	13,6 A
I_C	0,78 A
U_A	8,7 kV
U_B	8 kV
U_C	8,63 kV
I_2	7,5 A

As can be seen from Figure 4 to Figure 7 and Table 3 to Table 6, the results obtained with the onsite testing were higher than the ones obtained through simulation, especially if considered the higher impedance faults in which the simulations presented low fault currents and the real world tests proved the injected current in these cases was nearly the current for a zero impedance fault. The differences can be justified with the difficulty of correctly modulate the behaviour of the system inverters and the storage system controller in computer models. To know the real behaviour of the system and its controller is very important for the design of the protection system as the ability to inject higher fault currents facilitates the detection of a fault event and also helps in assuring the necessary selectivity with Client own protection relays.

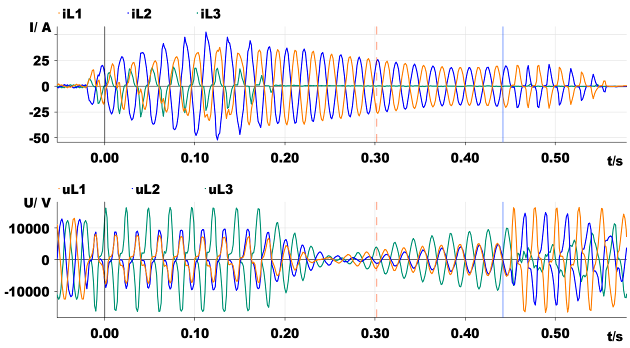

Figure 6 – LV Phase A – Phase C fault with zero Impedance Test Results

Table 5 – LV Phase A – Phase C fault with zero Impedance Test Values

I_A	14 A
I_B	13,8 A
I_C	0,1 A
U_A	3,7 kV
U_B	3,3 kV
U_C	6,8 kV
I_2	8 A

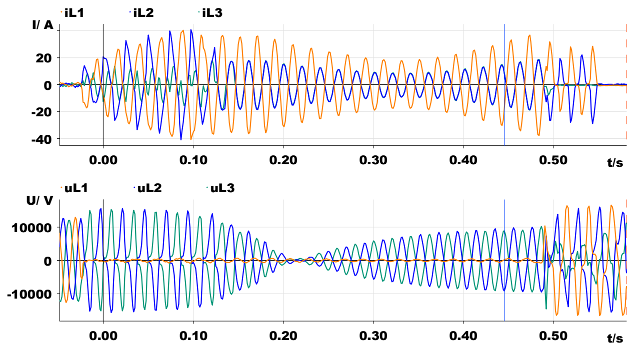

Figure 7 - Phase-Neutral with zero Impedance Test Results

Table 6 - Phase-Neutral with zero Impedance Test values

I_A	25.1 A
I_B	12,5 A
I_C	12,6 A
U_A	0,43 kV
U_B	6.54 kV
U_C	6.33 kV
I_2	12,45 A

PROPOSED PROTECTION SCHEME AND PARAMETERS

After all the studies and on site tests performed EDPD establish a protection scheme to the ESS which could

ensure the safe operation of the system. Two groups setting scheme was developed, one for the operation in parallel with the grid and the other to be used with the system in islanding operation.
The transition between the two groups is automatic and based on the state of the interconnection circuit breaker so the ESS can recognize if it is grid connect or is operating in island mode.

Table 7 - Proposed Settings for both Grid Connected and Island Operation modes.

	Parallel	**Island**
I>	25 A	25 A
t(I>)	0,1s	0,5s
Io>	20 A	20 A
t(Io>)	0,1s	0,1s
U<	12750 V	12750 V
t(U<)	0,5s	4,8s
U<<	7500 V	Off
t(U<<)	0,3s	Off
U>	17250V	17250 V
t(U>)	0,5s	0,1s
Uo>	866 V	866V
t(Uo>)	0,3s	0,1s
f<	49,5Hz	49,5Hz
t(f<)	1s	1s
f>	50,5Hz	50,5Hz
t(f(>)	1s	1s
F2<	47,5Hz	47,5Hz
t(F2<)	0,3s	0,05s
F2>	51,5Hz	52,5Hz
t(F2>)	0,3s	0,05s
Umin (F< Block)	3000V	3000V
I2>	Off	2,5 A
TM	Off	0,75
Curve	Off	Normally Inverse

Regarding the settings proposed in both groups, EDPD team asked for an overcurrent and earth current function to detect MV, LV and even internal ESS faults. The Zero Sequence Voltage Displacement also allows for detection of earth faults, especially the faults with very low earth fault current.
Both over/under voltages and frequency functions are activated to ensure the quality of service to the client, granting that the power supplied fulfils the necessary requirements, to allow for the disconnection of distributed energy resources when a fault occurs in the distribution grid or to detect situations in which the balance between energy storage provided and the loads is not achieved.
A negative sequence overcurrent function was set up using inverse-time current to enhance unsymmetrical system fault detection capability while achieving optimized selectivity with the Client's LV protections.

<u>Behaviour during a real short-circuit in the 15kV grid</u>

With EDP ESS fully operational and parametrized with the proposed setting from Table *7*, a fault occurred in the 15kV line that feeds the system which caused the ESS to automatically enter in Island Mode with EDPD Client with success.
In Figure 8 it is possible to observe the response of the system to this grid event.

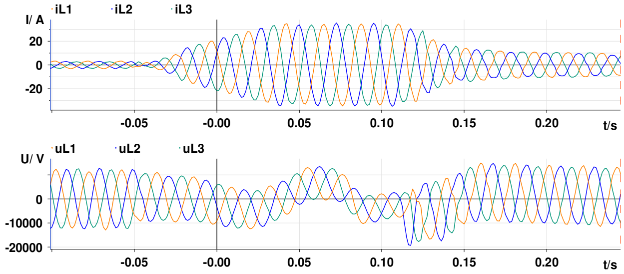

Figure 8 - ESS response entering island mode after a fault occurs in distribution grid.

As it can be seen in Figure 8 when the Short-Circuit is established the ESS starts contributing to the fault causing a rise in its current. When the ESS interconnection circuit breaker with 15kV grid opens and the system controller detects this change, the ESS starts to impose a 15kV and 50 Hz to the Client's, successfully forming an island. The protection system detected the fault in the 15kV grid, isolated the system and allowed the necessary time to the system stabilize while maintaining island stability.

CONCLUSIONS

The actions undertaken by EDPD, Siemens and INESC ID were essential to deepen the knowledge of ESS behaviour in network fault conditions. The live short-circuit tests performed on the ESS were essential and proved the necessity to conduct real tests in addition to simulation in order to achieve an adequate protection for the ESS and the network.
This allowed for the development of protection guidelines for ESS. EDPD ESS uses a two group of settings: one group to use in grid connection mode; and the other to use in islanding mode.

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