PERFORMANCES COMPARISON INSIDE THE ELECTRIC ENERGY STORAGE SYSTEMS OF ENEL DISTRIBUZIONE

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ABSTRACT

The Enel vision of Smart Grid include the Electric Energy Storage Systems as a fundamental component of the future distribution networks.
Four Electric Energy Storage Systems (1 ÷ 2 MVA – 1 ÷ 2 MWh) were recently build and connected on the MV Italian distribution network by Enel Distribuzione in cooperation with technology supplier; these four installations follow the first Enel Distribuzione Electric Energy Storage Systems connected on an MV Italian distribution network (1 MVA – 0.5 MWh) on 2012.
This paper presents a comparison of the results of the main site acceptance tests performed on these systems, detailing the adopted procedures.

INTRODUCTION

Four Electric Energy Storage Systems (EESSs) were recently connected on the medium voltage (MV) Italian distribution network by Enel Distribuzione (ED), particularly:

a. S_S = 2 MVA – E_S = 2 MWh, provided by NEC with NEC Li-ion batteries (Lithium Nickel Manganese Cobalt Oxide) installed in the MV busbar inside HV/MV substation “Chiaravalle” (Calabria region);
b. S_S = 2 MVA – E_S = 1 MWh, provided by ABB with FAAM Li-ion batteries (Lithium iron phosphate) installed in the MV busbar inside HV/MV substation “Dirillo” (Sicilia region);
c. S_S = 2 MVA – E_S = 1 MWh, provided by SAET with SAFT Li-ion batteries (Lithium transition metal oxidate) installed in the MV busbar inside HV/MV substation “Campi Salentina” (Puglia region);
d. S_S = 1 MVA – E_S = 1 MWh, provided by Loccioni with Samsung Li-ion (Lithium Nickel Manganese Cobalt Oxide) batteries installed in the MV busbar inside a MV/LV substation (Emilia Romagna region).

Where S_S is the nominal apparent power and E_S the nominal energy capacity.

These four installations follow the first ED EESS connected on an MV Italian distribution network: 1 MVA – 0.5 MWh provided by Siemens with Sanyo Li-ion batteries installed in the MV busbar inside a MV/LV substation (Molise region) [1].

Table I shows other main EESS nominal characteristics. With reference to the regulation way, the EESS can be monophase if it accept the settings (P and Q or V) for each single phase or threephase if it accept the settings (P and Q or V) just for the entire threephase system.

The EESS was assigned in 2 different tenders, a, b and c in tender 1 and d in tender 2. The installations, started on October 2012 (a, b and c) and on June 2013 (d), they have been completed on 2014 (a, c and d) and in the first quarter of 2015 (b). A complete set of Site Acceptance Tests (SAT) has been performed at the final stage of each installation.
As well known, the International Standard Committee (IEC) has not published any standard about testing methods and procedures to verify the system capability and performance on EESS; however this aspect is crucial to assure the correct development of the EESS market. For these reasons, ED has developed an internal commissioning procedure that was applied during the SAT of the above mentioned EESS installations.

Table I
Main EESS nominal characteristics

EESS	Number of cycle	System efficiency	Installation area	Regulation way
a. Chiaravalle	4000	80.71%	400 m^2	monophase
b. Dirillo	3000	83.2%	200 m^2	threephase
c. Campi Salentina	2000	80.4%	200 m^2	monophase
d. Emilia Romagna	5200	82.48%	120 m^2	monophase

This procedure contains a rich set of tests, capable to verify the most important EESS features, such as:

- system efficiency;
- consumption of the auxiliary services;
- active/reactive power capability;
- frequency regulation capability;
- voltage regulation capability;
- black start capability;
- islanding support capability;
- harmonic compensation capability;
- voltage dip compensation capability;
- remote control capability;
- system modularity;
- system response time;
- accuracy of the system output;
- accuracy of the system measures;
- EMC compliances.

This paper will present a comparison of the results of the main tests on the EESSs; these results will be deeply analyzed and commented.

MAIN TESTS DESCRIPTION

The commissioning procedure for the main SAT will be described in this section.

System efficiency

In ED point of view, the system efficiency must be measured after a single full charge/discharge cycle (energy charged and discharged must be $\geq E_S$) at the nominal active power ($P_S = S_S$).
The consumption of the auxiliary services are not taken into account, because the ED specifications require that they must be fed from a different point of connection in low voltage (LV). The EESS has 2 point of connections: the first in MV (MVCP) for the energy exchange services with the network and the second in LV (LVCP), this second one is just for the auxiliary services (passive loads).

So the following formula is applied:

$$\eta = \frac{E_d}{E_c} \quad (1)$$

Where E_c is the energy flowing in the EESS in all test duration, measured on the MV point of connection and E_d is the energy flowing from the EESS in all test duration, measured on the MV point of connection.
The ED specification impose that the system efficiency must be $\geq 80\%$.

Consumption of the auxiliary services

The consumption of the auxiliary services is continuously measured thanks to an electronic meter installed on the LVCP.
ED require that in the first operational year the consumption average of the worst ten days do not overcome 1600 kWh daily (a), 800 kWh daily (b and c) and 500 kWh daily (d).
One year of operation is necessary in order to take in consideration all the possible seasonal meteorological impacts; because of the high dependence between the auxiliary services (air conditioning in particular) and meteorological conditions.

Accuracy of the system output

The accuracy of the system output is the quality which characterizes the ability of the EESS to provide in the MVCP an output value (P, Q, V, f etc.) close to an input value imposed to its control system.
The ED requirements ask an accuracy < 1%; the requirement is not applied for inputs below the 4% of the capability.
So that means:

$$I_v \cdot \left(1 - \frac{0.01}{\sqrt{3}}\right) \leq O_v \leq I_v \cdot \left(1 + \frac{0.01}{\sqrt{3}}\right) \quad (2)$$

Where I_v is the input value and O_v is the output value.
With reference to the unbalance factor, a long discussion with candidates was made during the tender, in order to find a formulation for this parameter, finally the following requirements was adopted:

$$U_F = \frac{3 \cdot \left(\max_{i \in (1,2,3)} S_i - \min_{i \in (1,2,3)} S_i\right)}{S_S} \quad (3)$$

Where S_i is the apparent power for the phase i.
The accuracy (2) of the system output must be assured for $U_F \leq 20\%$.

Active/reactive power capability

ED require a circular threephase power capability in the MVCP (figure 1), with network voltage around the rated voltage (V_n), more precisely $0.9V_n \leq V \leq 1.1V_n$; in case of $V > V_n$ a degraded reactive capability can be accepted (active power capability cannot be degraded), but just in the capacitive sectors (figure 1).
The ED test is to impose 24 at least P/Q settings crossing the expected capability chart; for each P/Q point the accuracy of the output will be evaluated. The test should be repeated at different network voltage, according with the real voltage variations on field.
The EESS must respect this settings with no more of 1% of accuracy (2).

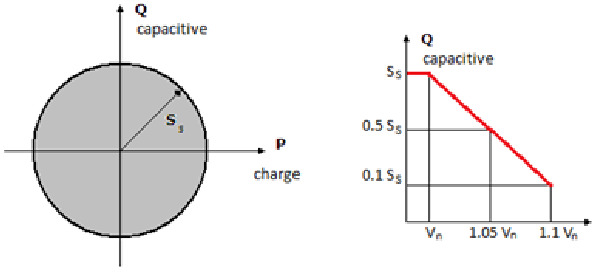

Figure 1: ED requirement for active/reactive power capability

Frequency regulation capability

The ED requirements ask active power compensation for frequency deviations at MVCP in accordance with the following regulation rule:

$$P_R = a \cdot f + c \quad (4)$$

Where P_R [kW] is the active power compensation, a [kW/Hz] and c [kW] are coefficients of active power calculation parameter and b [Hz] is the dead zone of frequency regulation. Practically, when frequency fluctuates beyond the range of dead zone b, the function is invoked and EESS will supply or absorb active power to compensate for the frequency deviation.
The EESS must respect this settings with no more of 1% of accuracy evaluated on P_R (2).
The tests was performed using a dummy frequency signal as input for the EESS regulation system.

Remote control capability

Generally speaking, the way in which ED manages all the network components installed on its network (such as circuit breakers, motorized switches, protection relays and others) is through remote terminal units (RTUs), mainly located in the transformation substations. These devices are able to deliver commands to the field and to gather information (measurements and signals) from the field. All the information collected by the RTUs are sent to the Network Control Centres (NCC) thanks to point-to-point (SCADA-RTUs) IP connection and/or GSM dial-up connections.

EESSs have to be compliant with this paradigm. For each EESS installation, there is an ED's RTU connected to the main EESS controller through different means and technologies:

- wired connections for installations close to a transformation substation (a, b, c);
- wireless connections for installations along MV feeders (d).

For wired connections (b and c installations), optical fiber cable has been chosen because of the distance between EESSs main controller and the ED RTU was greater than 100 meters, while a copper Ethernet cable has been adopted in a.
For d installation, a 4G LTE technology has been selected because of the EESS is 10 km far from the ED RTU.

Concerning the interface between the EESSs main controllers and the ED's RTUs, the IEC 61850 standard model has been adopted as it was for the very first installation in Molise region. At the time in which the communication interface had to be defined, there was no officially issued IEC 61850 standard related to the EESS information modelling. For this reason, the first and foremost effort was dedicated to develop a state machine diagram for each EESS and then to build a IEC 61850 profile choosing standard Logical Nodes as much as possible. The unavoidable different features of each EESS, due to above mentioned lack of standard reference, have been managed by ED RTUs and they are not seen at NCC level.

PERFORMANCES COMPARISON

A performances comparison from the tests described in the last section will be offered in this section.
For the installations b the comparison is not possible because the tests was completed after the final acceptance of this paper.

System efficiency

Table II shows the results of the system efficiency tests compared with the nominal values declared during the tender.
As a premise, ED adopted a prize/penalty mechanism for this parameter; so, during the tender the candidates received a prize (in term of virtual price reduction) based on the declared value (limit value 80%) and some weight factors; but if the declaration is not verified in the SAT, a penalty (stronger than the prize) is applied.

Table II
EESS system efficiency comparison

EESS	Nominal system efficiency	Verified system efficiency
a. Chiaravalle	80.71%	81.36%
c. Campi Salentina	80.4%	86.29%
d. Emilia Romagna	82.48%	85.44%

The effect of this mechanism is variegated. The first candidate declared very close to the minimum (so low prize on the tender) and was able to respect that without overdimensioning. The second candidate declared very close to the minimum (so low prize on the tender), but performed strongly better; in this case the fear of penalty generated a precautionary declarations and a good overdimensioning. The third candidate toke a good prize in tender phase and protect himself with a good over-dimensioning. Generally the mechanism worked well preserving ED interest, probably just a little adjustment of the weight factors will be applied in the next tenders.

Consumption of the auxiliary services

Table III shows the results of the auxiliary services consumption registered during the tests compared with the nominal values declared during the tender.
They are just preliminary values (1 year of operation is necessary to know the final ones), but some consideration are possible about them.
As a premise, ED adopted a prize/penalty mechanism also for this parameter; with same approach of system efficiency.
Seems clear that all the vendor are able to perform strongly better than the limits. So, the mechanism worked well preserving ED interest, but a strong reduction of the limit value is necessary. That was clear also during the design process of the first EESSs (a, b and c), for that reason the limit value for the second tender was reduced (from 800 kWh to 500 kWh).

Table III
EESS consumption of the auxiliary services comparison

EESS	Nominal daily consumption	Verified daily consumption (preliminary)
a. Chiaravalle	1598.7 kWh	787.75 kWh
c. Campi Salentina	792 kWh	356 kWh
d. Emilia Romagna	247 kWh	99.72 kWh

Accuracy of the system output

Tables IV, V and VI shows some results of the accuracy of the system output, for monophase power inputs.
Generally the requirement (2) was not easy to be respected particularly with very unbalanced inputs, for example in Table IV Test 4 a huge U_F was reached (around 67%), but with accuracy over 5%.

Table IV
Accuracy of the active/reactive power [kW/kVAr] outputs (for each phase) in the EESS a. Chiaravalle

	Test 1	Test 2	Test 3	Test 4	Test 5
I_{P1}	259	-163	-12	127	666
I_{P2}	184	-245	103	-300	666
I_{P3}	315	-204	2	-361	666
O_{P1}	260.92	-166.7	-13.38	130.55	671.56
O_{P2}	194.04	-240.46	111.21	-301.78	657.71
O_{P3}	321.19	-204.66	2.1	-345.54	665.34
I_{Q1}	236	311	421	457	-270
I_{Q2}	343	315	367	146	-275
I_{Q3}	356	389	296	691	-272
O_{Q1}	237.5	316.17	423.41	461.34	-275.56
O_{Q2}	338.83	322.48	368.13	155.1	-292.83
O_{Q3}	352.98	394.98	299.51	690	-280.78

Table V
Accuracy of the active/reactive power [kW/kVAr] outputs (for each phase) in the EESS c. Campi Salentina

	Test 1	Test 2	Test 3	Test 4	Test 5
I_{P1}	175	-229	5	-533	355
I_{P2}	353	-174	-56	-550	287
I_{P3}	175	-286	61	-449	419
O_{P1}	174.47	-230.4	2.7	-534.4	357.3
O_{P2}	351.5	-175.7	-58.3	-552.5	287.9
O_{P3}	172.4	-287.6	58.9	-451.4	425.2
I_{Q1}	197	202	398	486	-484
I_{Q2}	298	302	301	386	-603
I_{Q3}	397	298	297	426	-601
O_{Q1}	198	201.6	398.2	484.7	-482.1
O_{Q2}	300.22	301.1	300.7	381.2	-601.5
O_{Q3}	398.46	297.5	297.7	420.6	-598

Table VI
Accuracy of the active/reactive power [kW/kVAr] outputs (for each phase) in the EESS d. Emilia Romagna

	Test 1	Test 2	Test 3	Test 4	Test 5
I_{P1}	129	-81	-6	168	334
I_{P2}	92	-123	52	128	331
I_{P3}	158	-102	1	134	332
O_{P1}	127.62	-80.1	-6.17	166.83	331.63
O_{P2}	91.75	-122.7	49.59	130.1	333.26
O_{P3}	157.13	-101.4	0	135.09	333.44
I_{Q1}	118	156	210	-231	-135
I_{Q2}	172	157	183	-248	-138
I_{Q3}	178	194	148	-208	-136
O_{Q1}	118.61	155.7	209.12	-230	-27
O_{Q2}	173.56	156.6	183.41	-247.84	-26.98
O_{Q3}	178	194.3	148	-208.87	-30.1

Active/reactive power capability

Generally the requirements was respected in all the installations (figure 2, 3 and 4). Just an EESS applied the degraded reactive capability (figure 4), the others are able to provide circular capability in the full range $0.9V_n \leq V \leq 1.1V_n$.

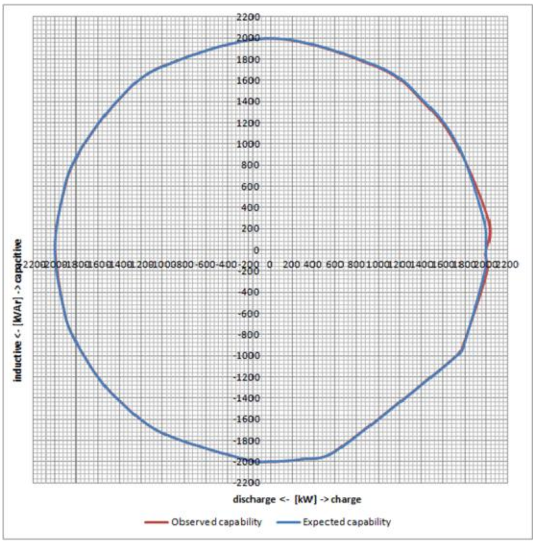

Figure 2: Active/reactive power capability in c

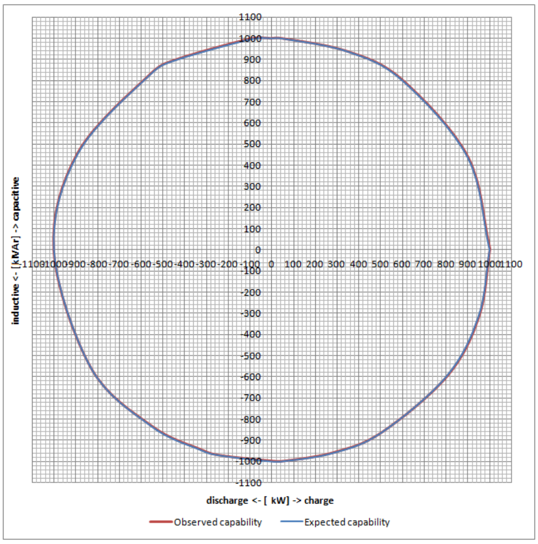

Figure 3: Active/reactive power capability in d

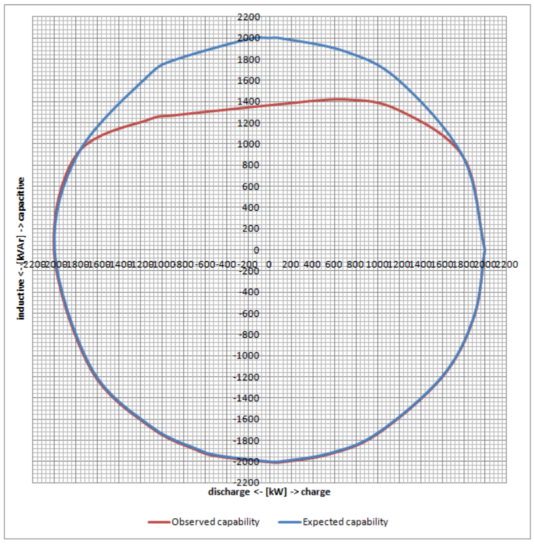

Figure 4: Active/reactive power capability in a with $V \approx 1.045V_n$

Frequency regulation capability

Generally the requirements were respected in all the installations (figure 5, 6 and 7). A different treatment for the overcharging is applied in c and d (figures 5 and 6); in c the EESS try to follow the regulation rule with the overdimensioning margin available, in d the output is cutted at the nominal capability.

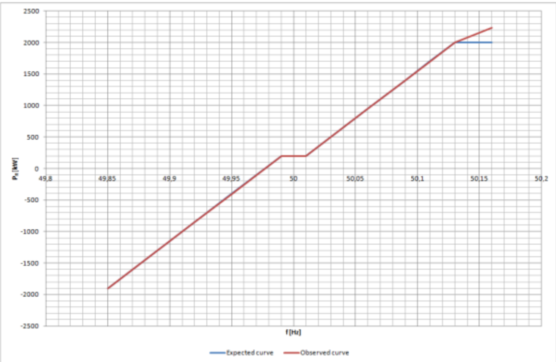

Figure 5: Frequency regulation curve in c

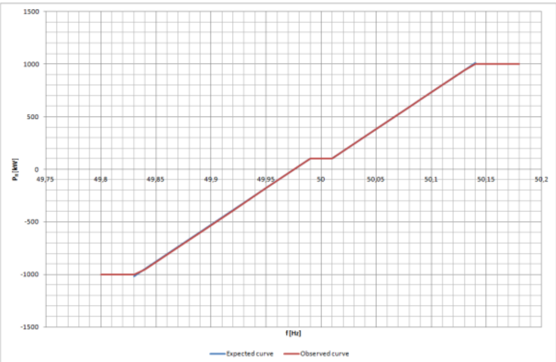

Figure 6: Frequency regulation curve in d

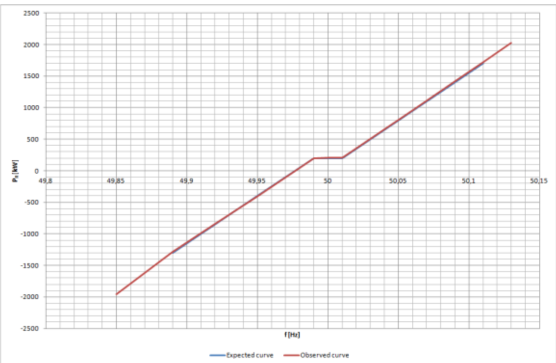

Figure 7: Frequency regulation curve in a

Remote control capability

The SAT on remote control capability is related to the communication from the EESS main controller to the ED's RTU. Generally the requirements were respected in all the installations. As above mentioned, the communication was developed adopting IEC 61850 modelling. The main results are summarised as follows:

- the percentage of standard logical nodes adopted in a, b and c were lower than d;
- installation a was the first put in operation with an automated, remotely monitored function that assigns active and reactive set points (figure 8);
- installation b was the second put in operation with the same function;
- installation d was the third successfully commissioned performing also a remotely controlled blackstart.

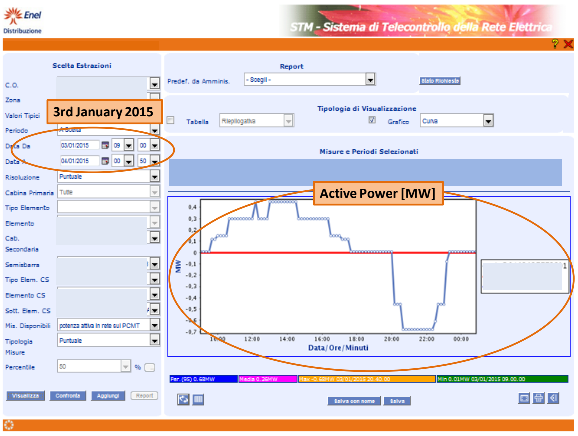

Figure 8: Measures at MVCP recorded on ED corporate web application

During the commissioning and the first months of operation, the experience have demonstrate that there are a lot of issues related to ICT (such as enough communication bandwidth for information gathering, remote connection with the EESS controllers) having a serious impact on the EESS management.

CONCLUSIONS

A comparison of the results of the main site acceptance tests performed on the EESS of ED was presented in this paper.

Generally the results was positive, demonstrating that the EESS technology has reached a good development level.

ED adopted a prize/penalty mechanism for some parameters; so, during the tender the candidates received a prize (in term of virtual prize reduction) based on the declared value and some weight factors; but if the declaration is not verified in the commissioning, a penalty (stronger than the prize) is applied. Generally the mechanism worked well preserving ED interest, but the FAT results are suggesting an adjustment of the weight factors in the next tenders.

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[1] L. Consiglio, G. Di Lembo, P. Eckert, C. Noce, A. Rasic, A. Schuette, 2013, " Performances of the first electric storage system of Enel Distribuzione", *Proceedings CIRED International Conference 2013, June 10-13, 2013, Stockholm, Sweden*