The Use of a Bidirectional Converter to Integrate Life PO_4 Batteries with Res-based Generators

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Abstract

This article describes a system for managing and tying together generators and electric storage devices that are powered by Renewable Energy Sources (RES) to the utility supply grid. The tool is a bidirectional converter that can be controlled to simplify the interface between low voltage grid and small generators coupled with Li-ion batteries, currently addressing the needs of the reference technical standards for users connection and providing various ancillary services. In the publication, the DEIM of the University of Palermo and ENEA detail the field and laboratory testing they did in 2013.

Keywords: Bidirectional converter; energy storage system; lithium-ion; laboratory and field test.

1 Introduction

According to the recent technical standards dealing with the connection of active and passive users to the Italian LowVoltage (LV) distribution grid [1], all the distributed generators must fulfil precise requirements.

Small electric generators must participate to the voltage regulation and to the frequency transients regulation. In particular they must be able to:

– reduce the generated power, if frequency exceeds amaximum value;

– gradually inject power into the grid after a stop;

– inject reactive power according to specific capability curves.

Being the most of these generators fed by not controllable Renewable Energy Sources (RES), they are not always able torespect the above-mentioned requirements. Due to the diffusion of RES generators, this issue becomes more and more important for the grid, thanks to the numerous financial support measures [2]-[10].

The coupling of RES generators to Electric Energy Storage (EES) systems can be a way to mitigate these problems, providing the required services [11]-[17].

Thanks to the above mentioned coupling, the efficiency of RES generators is increased, providing a higher management flexibility and power quality level. Doing so, voltage and

frequency deviations are kept within the limits, even in the presence of rapid perturbations.

To this end it is necessary to devise new interfaces and control systems able to operate following both remote and local control signals, creating a double interface to the grid and the telecommunication system. Measurement systems need also to be included in order to detect the electrical quantities of the conversion system [18].

The device was firstly presented in [19]. It was designed and realized by the DEIM (Department of Energy, Information Technology and Mathematics) of the University of Palermo in collaboration with ENEA, the Italian National Agency for new Technologies, Energy and Sustainable Economic Development, within the project “Advanced Energy Storage Systems”, financed by the Italian Minister for the Economic Development through the program RdS (Research on the Electric System). The device and the related control strategieshave been presented in [20].

The device consists of a bidirectional converter, composed by a DC/DC converter followed by a DC/AC converter. The power converter has a rated capacity of 20 kW and can interface both photovoltaic (PV) and wind generators.

During the functioning, the bidirectional converter provides several ancillary services and regulate the current flow inorder to minimize the customer electricity cost, followingspecific price signals from the utility grid.

The control system has been designed according to the CEI 0- 21 standard [1] (the Italian standard for the connection of active and passive users to the LV grid). It implements voltage and frequency monitoring, maximum and minimum voltage and frequency protection, Low Voltage Fault Ride- Through (LVFRT) function, limitation of the DC current injected into the grid, power quality control according to the technical standard EN 50160 [21], reactive power regulation, active power injection control.

During 2013, the device presented in [19] was modified in order to improve the exchange of data with the Li-ion Battery Management System (BMS), also including protections against electrostatic discharges (originally not present). The revising and finalizing design of the conversion device have been described in [22].

In the present paper the laboratory and test field activities are described. The tests have been carried out inside the factory of LAYER Electronics SRL, a company located in Erice, Italy. The company is connected to the distribution network through a three-phase 400V line. During the field test phase the device has been connected to the PV plant of the building.

2 List of the Tests

The conversion device has been tested connected to the LV grid of the factory:

- by varying the discharge speed, in order to check the battery performance;
- by varying the energy produced by the RES generator, in order to verify the efficacy of the control logic;
- in stand-alone mode, simulating a network failure, supplying the electric load of the factory plant;
- by varying the value of the grid voltage until the setup limits of the Interface Protection Relay (IPR) are reached.

The load has been realized using a 15 kW three-phase resistorand three single-phase resistors, as shown in Fig.1.

Three categories of tests have been carried out in order to:

- verify the proper operation of the device under different working conditions;
- check the compliance with the CEI 0-21 standard;
- verify the operation of the battery by varying the temperature in a climatic chamber.

3 Results of the Tests

3.1 Tests in different working conditions

The operation of the conversion device under different working conditions has been investigated by referring to the following operation modes:

- SUPPLY MODE: the EES is in stand-by mode and the device injects the whole power produced by the RES generator into the grid;
- LOAD MODE: the device absorbs energy from the grid in order to charge the EES, even if the RES generator is producing;
- STORAGE MODE: the device injects energy into the grid from the EES (or vice versa), while the RES generator is in stand-by mode;
- STAND-ALONE MODE: the device is disconnected by the grid due to the intervention of the IPR and supplies the privileged loads using the energy both from the EES and from the RES generator.

The tests have been done according to the following protocol:

- one of the four above-mentioned working conditions is manually selected;
- the device remains in the selected mode for a test time interval not shorter than 2 minutes;
- possible error messages are checked on the LCD displayof the device;
- output voltages and currents, generated/absorbed power and battery state-of-charge (SOC) are measured and their values are compared with the expected ones;
- all interventions of the IPR are registered, in all operating conditions (except for STAN-ALONE MODE);

In addition, the proper operation of the device has been checked, in switching from an initial working mode to another.

At the conclusion of the first series of tests, it has been provedthat the device works properly in all conditions and no errors or malfunctioning are detected.

Fig. 1. Three-phase and single-phase resistors.

3.2 Tests for checking the compliance with CEI 0-21 standard

The following tests have been carried out:

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- check for the parallel connection to the grid;
- check for the IPR switching time, under different frequency and voltage levels;
- check for the harmonic distortion according to the EN 61000-3-2 [23] and the EN 61000-3-12 [24] standards;
- check for the gradual active power injection;
- check for the reactive power injection;
- check for the active power limitation;
- measurement of the DC component appearing in the inverter output current;
- check for the LVFRT function.

Test conditions have been established according to [1] and arereported in Table 1.

Ambient temperature	20°C ± 2°C
Atmospheric pressure	96 ± 10 kPa
Relative humidity	65 %
Grid frequency	50 Hz
Reference voltage waveform	According to EN 50160

Table 1: Test conditions.

The second series of tests was carried out connecting the device to an artificial DC source and using a power analyzer connected between the device and the AC network. The test circuit is represented in Fig. 2. All tests were carried out in SUPPLY MODE.

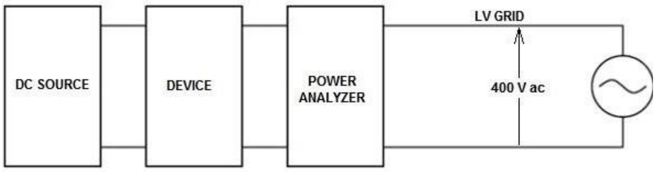

Fig. 2. Test circuit for the second series of tests.

3.2.1 Parallel connection to the grid

The purpose of this test is to verify that the device is able tobe connected to the grid only when the frequency and the AC voltage values are in the range permitted by the CEI 0-21 standard:

- voltage range: 0.85Un ÷ 1.10Un;
- frequency range: 49.90 Hz ÷ 50.10 Hz.

The test was carried out according to section B.1.1.1 of [1], and the result was positive.

3.2.2 IPR switching time for different frequency and voltage levels

The tests involved the following two kind of relays:

- frequency relays;
- voltage relays.

The IPR operation has been tested by measuring the switching times of the voltage and frequency relays according to the section 8.6.2.1, table 8 of [1]. The test results were positive.

Fig. 3 shows the measurement set-up used for the test. Test results are reported in Table 2.

3.2.3 Harmonic distortion

The test was carried out measuring the amplitude of the voltage harmonic components through the power analyzer.

The measured THD is equal to 4.68%, below the limit (8%)stated by [21].

Fig. 3. Measurement set-up for IPR testing.

Test	Measured switching time [s]	Maximum switching time [s]
Over frequency relay	0.040	0.1
Under frequency relay	0.093	0.1
Overvoltage relay	0.195	0.2
Under voltage relay	0.195	0.2

Table 2: IPR test results.

3.2.4 Gradual active power injection

The test was carried out switching from the no-load to the full-load condition, with a rising ramp of at least 300s.

The power analyser has been used in order to register the output active power, for the voltage and frequency ranges permitted by the CEI 0-21 standard.

The test results are assumed positive if the injected power is below the limit curve P = 0.333 % Pn/s (when the device supplies more than 5% of its rated power), accepting a deviation no higher than +2.5% Pn, as shown in Fig. 4. Alsoin this case the test was positive.

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3.2.5 Reactive power injection

Measure	Kind of load	P [kW]	Q [kVAR]	(Q/P)%	cosφ
1	i	8.10	3.97	49.01%	0.898
2	i	8.01	3.97	49.56%	0.896

Table 3. Test results for the reactive power injection test.

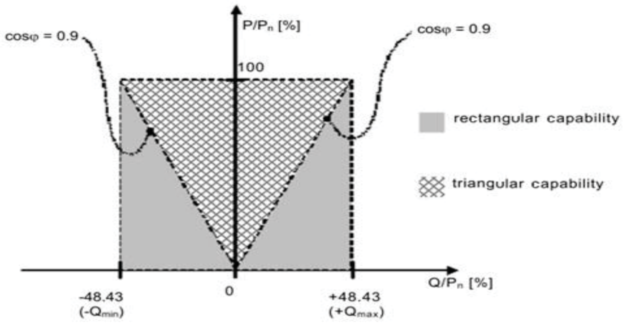


Fig. 5. Reactive power capability curves (CEI 0-21 standard).

The test was carried out with the purpose of checking the capability of the reactive power generated by the device, for different active power values, in order to guarantee the minimum requirements established by [1] (section 8.4.4.2), namely:

- an instantaneous power factor in the range between - 0.90 ÷ +0.9, according to the triangular capability curve shown in Fig. 5;
- an absorption or injection of reactive power within the 48.43% of the active rated power Pn, according to the rectangular capability curve shown in Fig. 5.

The test result is passed if the conditions expressed in section B.1.2.2.2 of [1] are verified, namely if the reactive power injected in or absorbed from the grid is no lower than 48.43% Pn.

The test result was positive. Table 3 reports the values of the measured reactive power for inductive (i) and capacitive (c) loads and the related cosφ values, as a function of the injectedreal power.

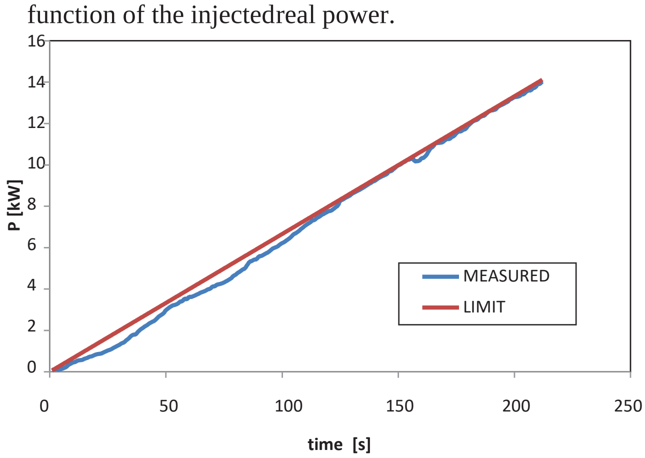


Fig. 4. Comparison between the measured injected power and the limit power during the gradual active power injection test.

3.2.6 Active power limitation

The test was carried out with the purpose of checking the automatic reduction of the active power generated by the device in case of over frequency conditions. The test was carried out according to section B.1.3.1.1 of [1].

The test result is positive if the following conditions are satisfied, for two series of measurements (at 100% Pn and at 50% Pn):

- for each of the first six measurements, the difference between the expected value of the real power (accordingto Annex F of CEI 0-21) and the measured value is not higher than ± 2.5% Pn;
- during the seventh measurement, carried out with frequency set to the nominal value, the device maintains the minimum level or real power of the previous measurement for not less than 5 minutes, and then it gradually restarts the injection of real power with a positive gradient not higher than 20% per minute of the power generated before the rise of the frequency.

The test result was positive. In Fig. 6 is reported the diagram of the P/Pn ratio during the test at 100% Pn. The maximum difference between the expected and the measured values was 2.27% Pn, therefore lower than the limit 2.5% Pn [1].

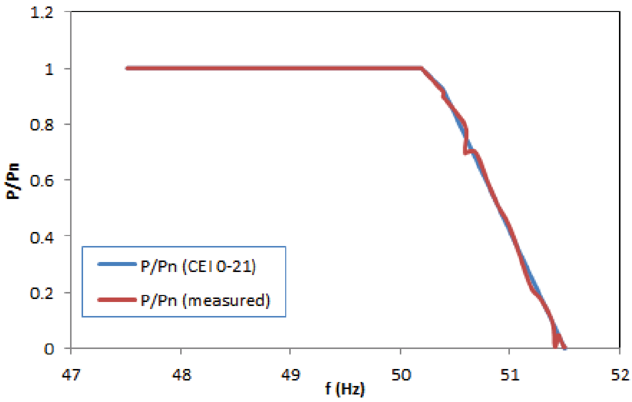


Fig. 6. Comparison between the measured and the limit values of the P/Pn ratio under the active power limitation test.

3.2.7 Measurement of the DC component of the outputcurrent

The test was carried out by measuring the amplitude of the DC component of the output current through the power analyzer, according to the section B.1.4.1 of the CEI 0-21 standard.

The results is positive if the measured DC component is lower than 0.5%, according to section 8.4.4.1 of CEI 0-21 standard. In the test, a DC component of 1.16% was detected, meaning that the device needs to be connected to the LV grid using an external isolating transformer.

3.2.8 LVFRT function

LVFRT is the capability of an electrical device to operate, during a time period, at lower grid voltages.

The device has been tested according to section B.1.5 of CEI 0-21 standard, with the purpose of verifying that:

- in the small net area of Fig. 7, the device remains connected to the grid;
- in the gray-colored area of Fig. 7, the device disconnectsfrom the grid;
- when the voltage restores within the range +10% Un ÷ – 15% Un, the device restarts the production of the active and reactive power values that he was producing before the fault in no more than 200 ms (a tolerance in the range of ± 10% Pn is admitted).

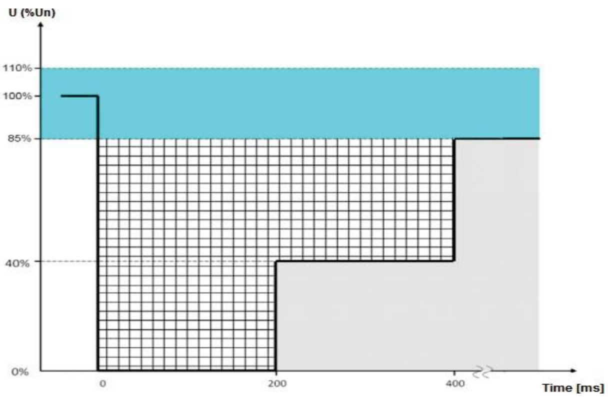


Fig. 7. LVFRT capability (CEI 0-21).

The test result was positive.

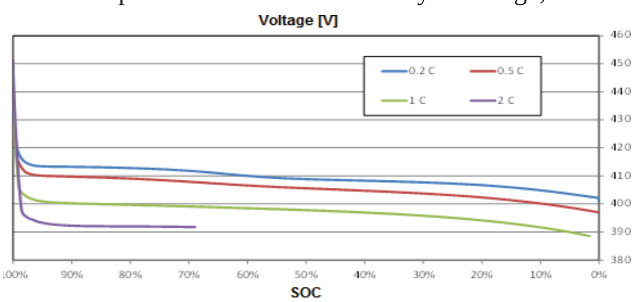
3.3 Operation of the battery by varying the temperaturein a climatic chamber

3.3.1 Discharge at constant temperature

The purpose of these tests is the experimental detection of thebattery terminal voltage as a function of the SOC, for different discharge current values. The test was carried out in STORAGE MODE.

The test consists in:

- a complete constant-current battery discharge;



- a standby period, during which the battery temperature takes the same value imposed in the climatic room;
- a complete battery recharge.

The test was carried out considering the same temperature value (+25 °C) and using four different values of the discharge current (0.2C, 0.5C, 1C, 2C). Test results are reported in Fig. 8.

Fig. 8. Voltage as a function of SOC for different values of the discharge current.

3.3.2 Discharge at variable temperature

The test was carried out in STORAGE MODE, by measuring the battery terminal voltage as a function of the SOC, for different temperature values (imposed by the climatic room). The discharging rate is assumed constant in all tests and equalto 0.5C.

Since the measured values are very similar in the temperature range of 25°C ÷ 60°C, Fig. 9 shows the results only fortemperatures between 15°C ÷ 30°C.

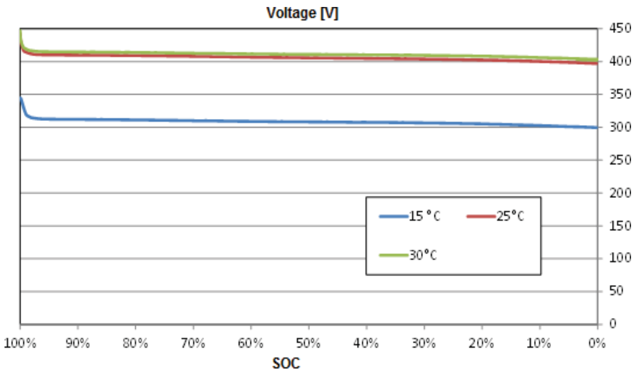


Fig. 9. Voltage as a function of SOC for different values of the temperature.

4. Conclusion

The paper has presented the laboratory and field tests activities of a conversion device providing an interface between the LV grid and a PV generator combined with a Li–ion battery.

The device presented in this work can also operate exploiting a load shifting strategy, in order to maximize the arbitrage benefit for the end–user, by shifting the energy consumption from on–peak to off–peak hours.

In a future work the implemented load shifting algorithm will be presented.

Acknowledgment

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