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EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm

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ABSTRACT

In the last years, electric vehicles (EVs) are getting significant consideration as an environmental-sustainable and cost-effective alternative over conventional vehicles with internal combustion engines (ICEs), for the mitigation of the dependence from fossil fuels and for reduction of Green-House Gasses (GHGs) emission. However, many challenges are still ongoing to their large scale implementation. Among them, the negative impact on the electrical grid operation in case of an uncoordinated contemporary charging of a huge number of EVs. In the recent literature different solutions are proposed for handling the peak demand of EVs and the related problems. One answer is offered by the implementation of EV charging strategies, through aggregation agents, for containing the impact on the grid, guaranteeing the quality of the service. The implementation of a real charging strategy is strictly related to a deployment of smart-grid technologies, such as smart meters, Information and Communication Technologies (ICTs) and energy storage systems (ESSs). In particular ESSs are playing a fundamental role in the general smart grid paradigm, and can become fundamental for the integration in the new power systems of EV fast charging stations of the last generation: in this case the storage can have peak shaving and power quality functions and also to make the charge time shorter. In the present paper, an overview on the different types of EVs charging stations, in reference to the present international European standards, and on the storage technologies for the integration of EV charging stations in smart grid is reported. Then a real implementation of EVs fast charging station equipped with an ESS is deeply described. The system is a prototype, designed, implemented and now available at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) labs. A wide experimental activity has been performed on the prototype system in order to test its functionalities in the integration in a smart grid available at the same ENEA lab, including a smart metering system. The integration has been possible thanks to the use of a customized communication protocol, developed by the researchers and here described. The results of the experimental tests show that the system has a good performance in the implementation of peak shaving functions, in respect of the main distribution grid, making the prototype like a network nearly zero-impact system.

1. Introduction

Electric vehicles (EVs) have received significant attention in the last years as an eco-friendly and cost-effective alternative over conventional vehicles (CVs), driven by internal combustion engines (ICEs). In the transport sector they are considered as the solution for decreasing the current dependence from fossil fuels and for reducing the pollutant emissions [1]. However, many challenges still exist to their large scale implementation. First of all, although EVs operating costs are inferior to the CVs ones, they are still more expensive to buy than CVs. Secondly, the access to the charging stations are still limited and large capital investment is required for developing a public charging infrastructure. Furthermore, EVs require to the grid during their charging a power as higher as the recharge time want to be short. Therefore, an uncoordinated charging of a huge number of EVs can have a negative impact on the electrical grid operation, in terms of power outages, voltage fluctuations, harmonics pollution and so on [2,3].

In the recent literature different solutions are proposed for handling the peak demand of EVs and the related problems:

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- to rise up the power generation, especially at the distribution level with renewable energy sources (RES) power plants spread, to increase the transport capacity of the distribution lines, and to coordinate EVs charging stations with intermittent power generation from RES, so making the electric power usage efficient. This solution involves a consistent up-grading of the infrastructures and then has a significant cost;
- to schedule the charging/discharging profiles of different EVs, by aggregating different sets of EVs with different start times and durations, such that grid constraints are maintained. The temporal availability of EVs along with their location information is important parameters to consider, while aggregating EVs for possible grid congestion planning and management. Moreover, the evaluation of charging strategies needs to take into account the electric energy price and the habits of the EVs owners. Thus, determining the appropriate EVs charge and discharge strategy, that does not violate grid constraints, though maintaining acceptable degrees of users' satisfaction, is still a challenging problem.

The implementation of an EVs charging strategy, coordinated with RES power plants, through an aggregation agent, is strictly related to a deployment of smart-grid technologies, such as smart meters, ICT and energy storage systems (ESSs) [4–12]. The ESSs are playing a fundamental role in the smart grid paradigm, and can become fundamental for the integration in smart grids of EV fast charging stations of the last generation: in this case the storage can have peak shaving and power quality functions and also to make the charge time shorter [13–16].

In the present paper, Section 2 reports an overview on the different types of EVs charging stations, in reference to the present European standards, and on the storage technologies for the integration in the EVs charging stations. In Section 3, a real implementation of a EVs fast charging station equipped with ESS is deeply described. The system is a prototype, designed, implemented and now available at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) labs [17–19]. Section 4 summarizes some results of a wide experimental activity performed in the last year on the prototype system, in order to test its functionalities in the integration in a smart grid available at the same ENEA labs, including smart metering system. The integration has been possible thanks to the use of a customized communication protocol, whose details of implementation are discussed. Finally Section 5 reports the conclusions.

2. EVs charging systems and storage technologies integration

Different standards for EVs charging systems have been explored by several organizations around the world. For defining the standards, organizations consider the safety, the reliability, the durability, the rated power, and the cost of the different charging methods. At the same time the charging equipment for EVs plays a critical role in their development, grid integration and daily use: the configuration of the charging station can vary from Country to Country depending on frequency, voltage, electrical grid connection and standards. In any case, charging time must match with EV's battery characteristics in order to guarantee an optimal charging and a long lifetime of EV's battery. Then a charger should be efficient and reliable, with high power density, low cost and low volume and weight. From the grid side an EV charger has also to ensure a low harmonic distortion, so that minimizing power quality impact, and a high power factor to maximize the real power available from a utility outlet. Generally conventional EVs battery chargers contain a boost converter for power factor correction (PFC) for this purpose. From battery side, high frequency PWM converter has been proposed to reduce inductor size used as current filter to decrease the battery current ripple. Various topologies and schemes are available on the market with these aims.

Essential tasks for EVs charging equipment are the ability to quickly charge the EVs battery, to detect the state of charge (SOC) of the battery and to adapt to various battery types and car models. Additional functions can be required, for instance to modulate the charging curve in function of the electricity price in the time of day, automatically bill for the electricity delivered, etc. The charger power level is the main parameter that has an influence on charging time, cost, equipment and effect on the grid. For these reasons the international standards in Europe are referred to this parameter for the EVs charging equipment classification.

Besides, the EVs charging systems can be categorized in off-board and on-board types with unidirectional or bidirectional power flow:

- an unidirectional charging limits hardware requirements and simplifies interconnection issues;
- a bidirectional charging supports battery energy injection back to the grid.

A charger located inside the vehicle allows owners to charge their vehicles everywhere a suitable power source is available. Nonetheless on-board chargers usually have limited power due to their weight, space need and costs. They can be integrated with the electric drive for avoiding these problems. The availability of a charging infrastructure reduces on-board energy storage requirements and costs. An off-board charger can be designed for high charging rates and is less constrained by size and weight.

2.1. European standards for EVs charging stations

European electricity companies, particularly distribution system operators (DSOs), are investing in the necessary infrastructure to build a single European market for EVs. European standards are indispensable to safeguard that drivers enjoy convenient EU-wide charging solutions that avoid a multiplicity of cables and adaptors and so retrofit costs. In June 2000, the European Commission issued a mandate to the European standardization bodies CEN, CENELEC and ETSI (M/468) concerning the charging of EVs. The mandate stressed the need for interoperable plugs and charger systems to promote the internal market for EVs and to discourage the imposition of market barriers. The Focus Group setup to respond to M/468 delivered a comprehensive and valuable report [20–22]. However, given that the mandate objective was to achieve interoperability, not the adoption of a single connector, no recommendation has been made with regards to the choice of the AC mains connector. As a consequence, two types of connectors have been assessed as appropriate for the European situation. The choice between them is left to the market and will depend on the different national regulatory frameworks [23].

Today the only standards available at European level, dealing with the charging system, plugs and sockets, are contained in the IEC 61851 [24]. It provide a first classification of the type of charger in function of its rated power and so of the time of recharge, defining three categories here listed and shown in Fig. 1.

- Normal power or slow charging, with a rated power inferior to 3.7 kW, used for domestic application or for long-time EVs parking.
- Medium power or quick charging, with a rated power from 3.7 to 22 kW, used for private and public location.

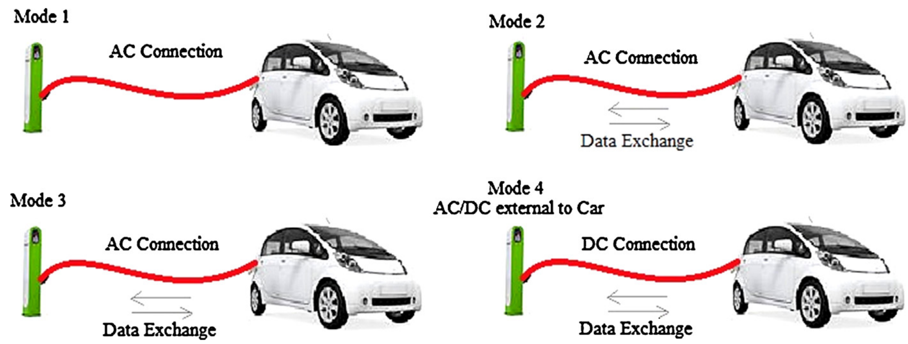

Fig. 1. IEC 61851-1 charging modes.

- High power or fast charging with a rated power superior to 22 kW, used for public location.

In function of the amount of power, different mains connections are possible and they are summarized in terms of electrical ratings in Table 1.

The IEC 61851-1 Committee on "Electric vehicle conductive charging system" has then defined 4 modes of charging, concerning:

- the type of power received by the EV (DC, single-phase or three-phase AC),
- the level of voltage (for AC in range between single-phase 110 V and three-phase 480 V),
- the presence or absence of grounding and of control lines to allow an one- or two-way dialogue between the charging station and EV, and
- the presence and location of a device protection.

The four modes are briefly described below and shown also in Fig. 1:

- Mode 1: slow charging from a household-type socket-outlet in AC.
- Mode 2: slow charging from a household-type socket-outlet with an in-cable protection device in AC.
- Mode 3: slow or fast charging using a specific EV socket-outlet with control and protection function installed in AC.
- Mode 4: fast charging using an external charger in DC.

For the Mode 4 (fast charging) in DC two sub-modes of operation are then considered:

- DC level 1 (voltage inferior to 500 V, current inferior to 80 A, power at 40 kW).
- DC level 2 (voltage inferior to 500 V, current inferior to 200 A, power at 100 kW).

The same committee has defined three types of socket-outlets:

1. IEC 62196-2 Type 1: single phase vehicle coupler (reflecting the SAE J1772/2009 automotive plug specifications, Yazaki).
2. IEC 62196-2 Type 2: single and three phase vehicle coupler (reflecting the VDE-AR-E 2623-2-2 plug specifications, Mennekes).
3. IEC 62196-2 Type 3: single and three phase vehicle coupler with shutters (reflecting the EV Plug Alliance proposal, SCAME).

Actually, the only country in Europe using the Type 3 connector is France.

In the last years, the Society of Automotive Engineers (SAE) has recognized another type of connector for EV: the Combo Connector J1772 (or Combo 2) [25]. It is able to combine the fast charge Mode 4 in DC (levels 1 and 2) with the slow/fast charge Mode 3 in AC in a single unit.

The actual situation in Europe in terms of application of charging mode and type of plug is summarized in Table 2.

Recognising that there is a need to offer customers a high-power charging possibility that allows them to recharge the EV battery within a limited timeframe, only the high power connection would satisfy this aim. Two technologies are at hand for high-power charging: DC off-board charging or AC on-board charging.

DC off-board charging is more common today, due to the introduction of the first generation of Japanese electric cars on the European automotive market. Nevertheless, European automotive manufacturers have expressed their intention to promote EV with an on-board charger, which would be compatible with a high-power range AC supply arrangement. For the DC connection, a Japanese socket (CHAdeMO protocol), with a maximum power level of 50 kW, is currently the only available product on the market and is thus being rolled out in several European countries although it is not internationally standardised yet [26].

The European Automotive Industry is however promoting the combined charging system with the Combo connector, which features a single inlet for AC and DC charging on the side of the EV and can potentially deliver high-power charging of up to 100 kW in future. The Combo connector is currently under development and going through the IEC standardisation process.

2.2. Storage technologies for EVs integration in smart grid

One of the major challenges for EVs charging stations, especially the public ones, is to reduce charging time. As seen, this aim can be addressed by increasing the rate of power transfer: the fast

Table 1
Electrical ratings of different charge methods in Europe.

Charge method	Mains connection	Power (kW)	Max current (A)	Location
Normal power	1-Phase AC connection	3.7	10–16	Domestic
Medium power	1- or 3-phase AC connection	3.7–22	16–32	Semi-public
High power	3-Phase AC connection	>22	>32	Public
High power	DC connection	>22	>3.225	Public

Table 2
Actual mode and type of plugs for EV charger in Europe.

	Private domestic socket	Private dedicated E-mobility socket	Semi-Public AC	Public AC	Public DC
Power connection	≤3.0 kW/ ≤3.7 kW 1-phase AC	Up to 22 kW	Up to 22 kW	Up to 22 kW	50 kW (CHAdeMO)
Plug (infrastructure side)	Domestic	Type 2/Type 3	Type 2/Type 3	Type 2/Type 3	Yazaki (CHAdeMO)
Charging mode	Mode 2	Mode 2 Mode 3	Mode 2 Mode 3	Mode 2 Mode 3	Mode 4

charge method corresponds in the European Standards to the maximum value of power (50–100 kW). When a large number of EVs are charged simultaneously, problems may arise from a substantial increase in peak power demand to the grid. The integration of an ESS in the EV charging station can not only reduce the charging time, but also reduces the stress on the grid.

A suitable comparison among the various energy storage technologies applicable for this scope is among electrochemical storages (batteries), electromechanical storages (flywheels) and electrostatic storages (ultra-capacitors).

The batteries are electrochemical storages that alternate charge–discharge phases allowing storing or delivering electric energy. The main advantage of such a storage system is the high energy density, the main inconvenience is their performance and lifetime degrade after a limited number of charging and discharging cycles. This affects the lifetime for all applications.

The flywheels are electromechanical energy storage devices, where energy is stored in mechanical form, thanks to the rotor spinning on its axis. The amount of stored energy is proportional to the flywheel moment of inertia and to the square of its rotational speed. The life of flywheels is greater than the batteries and the frequent charging and discharging does not adversely affect their lifetime. Additionally, flywheels have a power density that is typically a factor of 5–10 greater than batteries. A drawback of the flywheel technology is the time of reply to fast variations of required power: it is also proportional to the inertia of the system, so the gradient of the power in time is generally low.

The ultra-capacitors are electrostatic storage systems, characterized by a very high power density, but with a lower energy density than batteries and flywheel. Ultra-caps have also the benefits of charging and discharging much faster than batteries, a longer service life and a higher efficiency than batteries.

Typical values of energy density, power density and energy efficiency of the three energy storage technologies (batteries, flywheels and super-caps) are summarized in Fig. 2 [27,28].

Another important issue in this comparison deals with the cost: the installation, maintenance and replacement costs of the batteries make them not as attractive as stationary energy storage system; the installation cost of a flywheel is usually greater than batteries, but its longer life and simpler maintenance results in a lower total cost.

Finally an important consideration is about the different physical size and weight of the three technologies: for the same amount of energy stored, batteries are lighter and smaller than ultra-capacitors and flywheels.

From this brief analysis, it is clear that a good ESS for the coupling fast EV charging station can be considered a system including batteries and ultra-capacitors: the first are suitable for their high energy densities and the second for their high power density. In the literature, different applications of ESSs based on use of batteries and super-caps for the integration with EV charging station are present [28–30]. Today, the storage technologies really available are summarized in Table 3. Comparing the different types of batteries shown in Table 3:

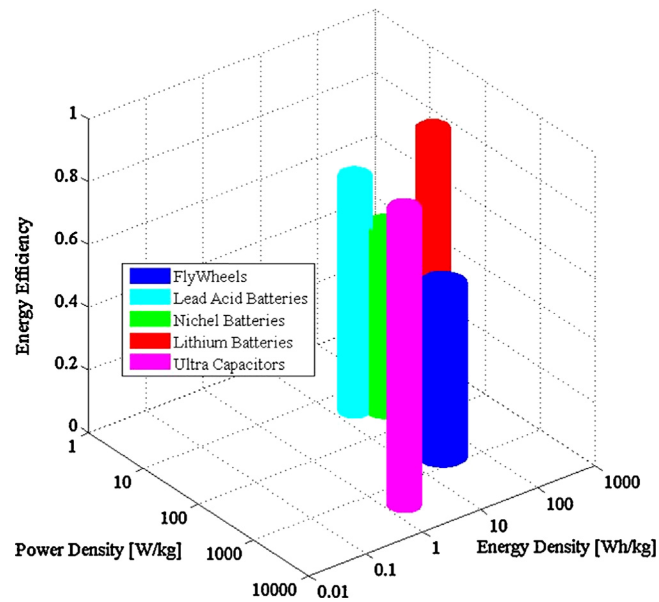

Fig. 2. Comparison of different energy storage technologies.

- Pb–acid batteries, with a lifetime of 200–300 cycles, have high capacity, low volume energy density, low capital cost, long lifetime, but on the other hand are characterized by low efficiency (70–80%) and a potential adverse environmental impacts.
- Ni–Cd batteries have low energy density (40–60 Wh/kg), low efficiency (60%) and suffer of memory effect.
- Ni–MH batteries, with a lifetime of 100–200 cycles, have a very high energy density.
- Li-ion batteries have a very high efficiency (85–95%), high energy density, and high number of life cycles (3.000–5.000).
- Li-poly batteries have lower energy density than Li-ion ones, but they are not flammable as Li-ion and so offer more safety.

At these technologies it is necessary to add the sodium-sulphur (Na-S) batteries that, with a lifetime of 2.000–3.000 cycles, have a very high energy and power capacity, high energy density, but they are characterized by high production cost and safety concerns, that make them not commercially sustainable at the moment.

Table 3
Energy storage technologies.

Type	Energy efficiency (%)	Energy density (Wh/kg)	Power density (W/kg)
Pb–acid batteries	70–80	20–35	25
Ni–Cd batteries	60	40–60	140
Ni–MH batteries	50–80	60–80	220
Li-ion batteries	85–95	100–200	300–2000
Li-polymer batteries	70	100–200	300–2000
Super-caps.	90+	25–75	5.000–20.000

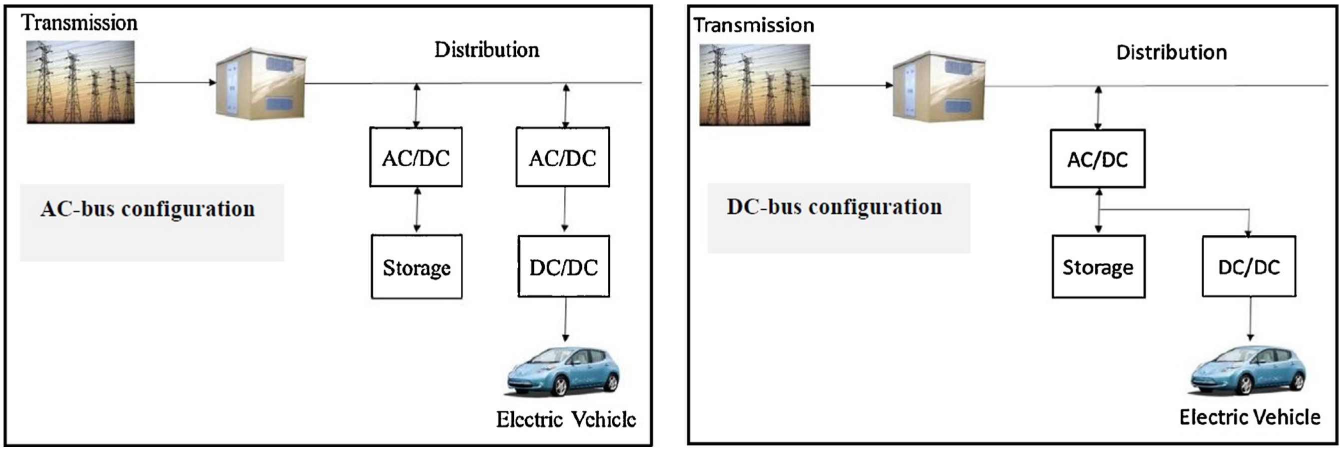

Fig. 3. Scheme for the integration of the ESS with the EV charging station.

The most common technology for batteries used for EV application is Li-ion battery, with energy capacities included between 5 kWh and 53 kWh.

Talking about the integration of ESSs in EVs charging station, another important issue is the way of integration in terms of electrical scheme. Two possibilities are investigated in the literature, based on an AC-bus configuration and DC-bus configuration, shown in Fig. 3 [27,29–32].

The AC-bus scheme is generally preferred, because the AC components have well defined standards, and AC technologies and products are already available in the market. However, DC-bus based system provides a more convenient way to integrate renewable energy sources and also higher energy efficiency thanks the inferior number of conversion stages.

The other advantage of the AC-bus configuration is that in this case the ESS can be used for more than one EVs charging station, in case of multiple points of charging on the same AC-bus, or for offering an active power service for other customers in case of presence of different loads on the AC-bus requiring this type of facility (i.e. essential loads, sensitive loads, etc.). In both the cases the sizing and siting of the ESS can make the difference, choosing between the possibility to have a distributed ESS (one for each EV charging station/load, as shown in Fig. 4) and to have a concentrated ESS (one for all the EV charging stations/loads, as shown in Fig. 5).

On this issue, no specific study is present in the literature and a general purpose methodology able to address the choice in function of number, power size and physical layout of the involved loads could be useful. In analogy to the problem of reactive power compensation, the architecture with distributed ESS has advantages on the performance of the grid, since the active power demand is compensated locally avoiding unnecessary power transits on the main grid. Moreover, the presence of a system of general supervision and remote control that monitors the general point of connection with the main grid, allows to manage the system with distributed ESS with a double objective: to reduce the transit of power on the local grid and to reduce the impact of the charging systems on the main grid.

3. A real implementation of fast charging station with energy storage

A prototype of real implementation of an EV fast charging station and a dedicated ESS has been designed, implemented and is now available at ENEA labs. The prototype includes a special EV fast charging station and an ESS equipped with Li-poly batteries inverter-controlled.

The system can be considered the nucleus of the layout in Fig. 5. To test its performance is the first step for implementing a methodology for the siting and sizing of a distributed ESS on

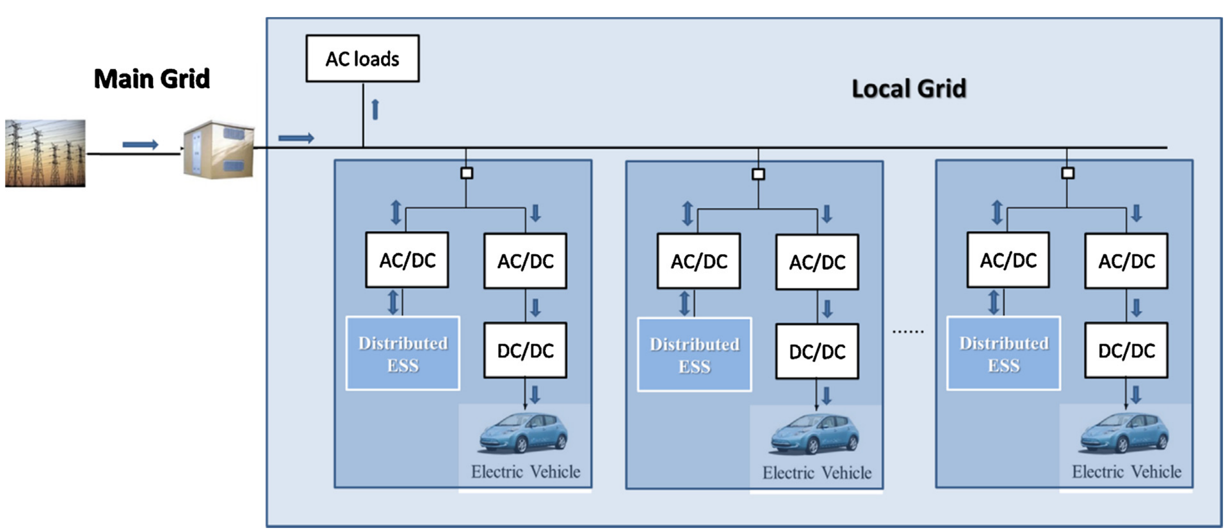

Fig. 4. Scheme for the integration of distributed ESSs with the multiple EV charging stations.

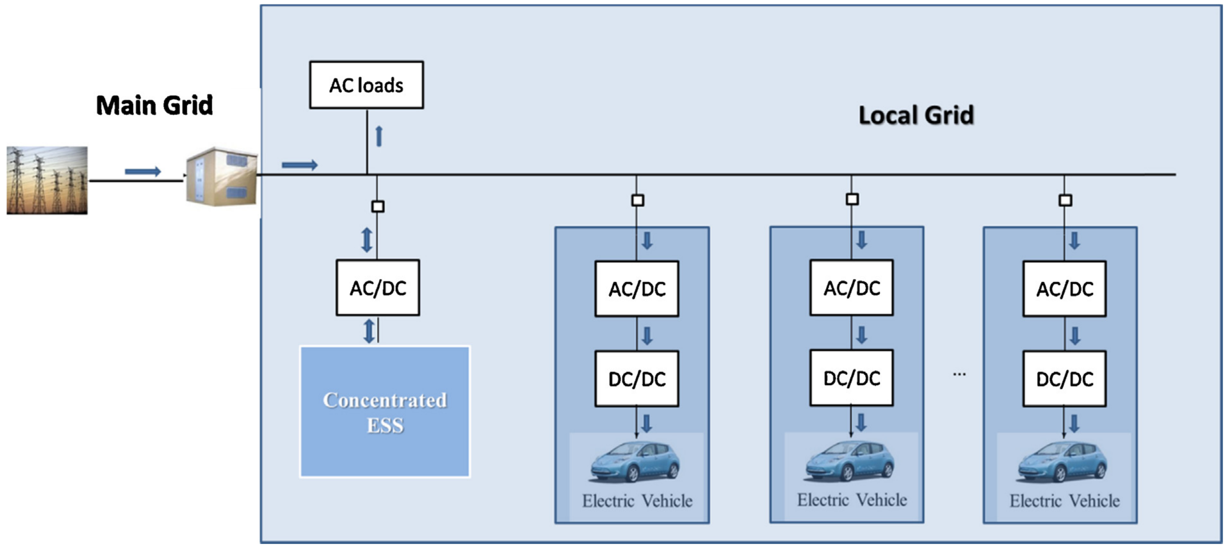

Fig. 5. Scheme for the integration of a concentrated ESS with the multiple EV charging stations.

an AC distribution network, including multiple EV charging stations and other loads requiring an active power service. In fact the present work aims to highlight the opportunity to link the EV charging station with a distributed ESS and with the metering system of the grid in order to implement the mentioned approach.

A picture of the real system in ENEA labs, during a test on a Nissan EV, is reported in Fig. 6.

The complete electrical scheme of the EV charging station and the ESS is reported in Fig. 7.

The suggested compensation approach operates by measuring the global active power P in the point of common coupling (PCC) with the AC main grid; it is possible to implement a logic control based on a peak threshold for the active power compensation C provided by the ESS. P is the sum of the charging station power demand V and the normal load L. A classic approach is to deliver simply the power C to compensate the power V.

3.1. EV charging station and ESS inverter-controlled

The EV charging station is a prototype, built by an industry on some specifications given by an Italian and Spanish Distribution System Operator (DSO) and ENEA, that implements two modes of EV fast charging in reference to the International Standard IEC 61851-1:

(1) Charging Mode 4 in DC, characterized by the use of off-board chargers (see Fig. 1), with an active power in output of 50 kW DC. The socket-outlet is an Yazaki Plug (CHAdeMO protocol).
(2) Charging Mode 3 in AC, characterized by the use of on-board chargers (see Fig. 1), with an active power in output of 22 kW AC. The socket-outlet is a Type 2 socket-outlet (Mennekes protocol).

Fig. 6. EV charging station and ESS inverter-controlled during a test on a Nissan EV.

The two types of plugs are shown in Fig. 8.

Table 4 summarizes the technical features of the whole EV charging station.

The ESS coupled with the charging station is based on lithium-polymer batteries and includes 6 modules with 12 cells series-connected. The main features of each cell are summarized in Table 5.

Table 4
Main features of EV charging station.

Input		
Input voltage	400 Vac 3P + N	
Nominal input power	77 kV A	
Input frequency	50/60 Hz	
Output		
	AC	DC
Maximum rated output current	32 A	125 A
Maximum rated output power	22 kW	50 kW
Maximum output DC voltage	400 Vdc	500 Vdc
Charge system	Mode 3	Mode 4

Table 5
Features of battery pack.

Feature	Value
Total energy	16 kWh
Maximum power output	20 kW
Maximum discharge current	90 A
Maximum charge current	70 A
Life in terms of cycles to 80% discharge	2.000
Maximum operating temperature	45 °C

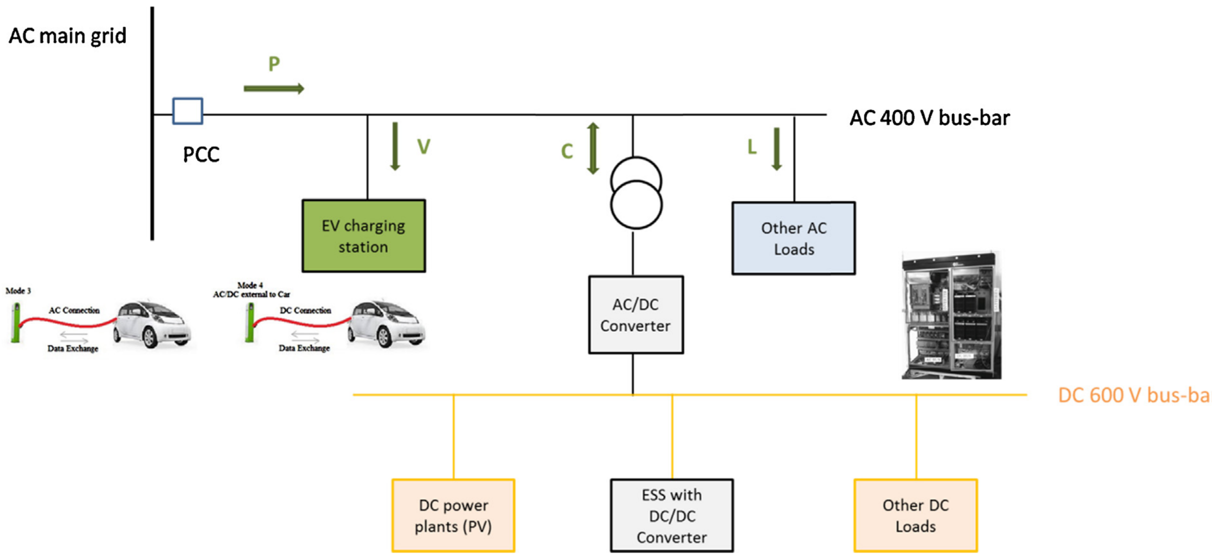

Fig. 7. EV charging station and ESS inverter-controlled scheme.

Fig. 8. Plugs in the prototype: DC CHAdeMO protocol and AC Type 2 Mennekes protocol socket-outlet.

The performance in terms of active power is limited by the characteristics of the batteries: they are able to give energy not more than 16 kWh in an hour and a power not more than 20 kW for at least 30 min. The battery cells datasheet charge and discharge curves are shown in Fig. 9.

As shown in figure, the battery complete charge is performed in two steps: the first step includes a charge at constant current, since the voltage cell is equal to the nominal voltage; once that the cell voltage reaches the nominal voltage, the charge is performed at constant voltage, since the battery cell current goes to zero. Usually the system works in the linear zone, from 15% to 85% of state of charge (SOC), to reduce as less as possible the impact on the lifetime of the batteries.

The ESS is linked to an AC low voltage grid at 400 V through an inverter, with a 30 kVA nominal power, and to a DC low voltage bus-bar at 600 V, through a DC link supplied by a DC/DC chopper and an electrochemical storage. The scheme of connection of the ESS to the grid is shown in Fig. 10.

The transformer is included with the main function to adapt the output voltage to AC low voltage grid and to realize the

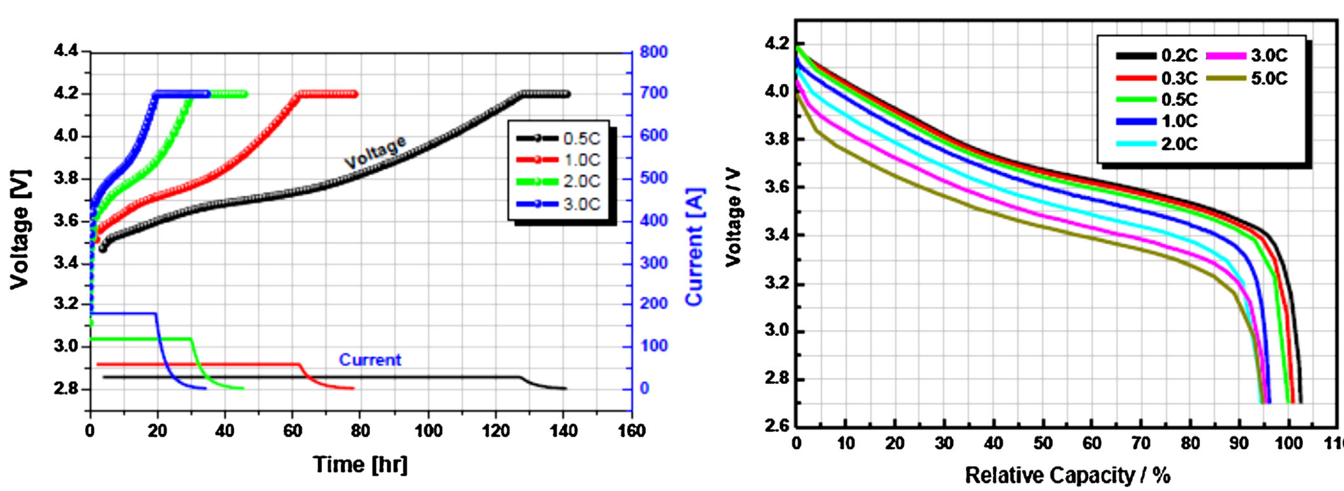

Fig. 9. Charging and discharging battery graph.

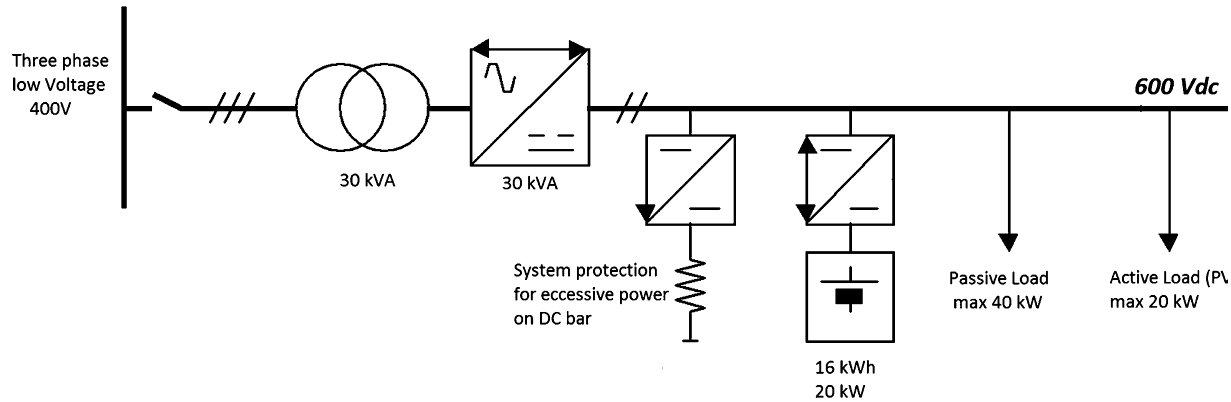

Fig. 10. Complete layout of the ESS.

electrical isolation between the sections in AC and DC and it is provided with appropriate input and output filters for suppressing disturbance, according to the directives 89/336/EEC and 92/31/EEC. Its main features are summarized in Table 6.

The power inverter includes solid state static components: it is equipped with IGBTs with blocking voltage suitable to work on the bus voltage necessary adjustments. The switching overvoltages at full power must not exceed 200 V. For this purpose special limiting circuits are included. The static converter is provided with appropriate input and output filters for suppressing disturbance, according to the directives 89/336/EEC and 92/31/EEC. The connection to the 400 V AC grid is complied with the requirements of Italian Standard CEI 0–21. The bus-bar at 600 V DC is sized to connect both a DC load with a maximum power of 20 kW and a production system with a maximum power of 30 kW.

A detection and protection system provides the information on the status of the components: power supply for the electronics out of range, communication error with DSP, voltage bar out of range, inverter over temperature, leakage currents to ground, gear time out, inverter overcurrent, protection IGBT modules, thermal protection inverter, line voltage out of range, low line voltage alarm.

The inverter is connected to a bidirectional DC/DC converter that can adjust the power exchange between the storage system and the bus-bar itself through a 600 V DC bus-bar. The objective of DC–DC converter control is, in first instance, maintaining the voltage at a constant level realizing the balance between the powers exchanged by other devices on bus-bar itself.

The main working functions are allowed thanks to the power electronics devices included in the system and controlled by a local controller. The internal local control system communicates also with an accurate battery management system (BMS), whose scheme is reported in Fig. 11.

The BMS acquires the signals of cells voltage and temperature and so knows the batteries state in every time instant. Through the current sensor, it also estimates the state of charge of the battery and gives information to the central system, through a Control Area Network (CAN) protocol communication, on the battery state. All functions that BMS provides are: charge/discharge current measurement; cell high voltage protection and alarm; cell low voltage protection and alarm; overcurrent protection and alarm; high temperature alarm and protection; automatic shutdown and wakeup; magnetic contactor ON/OFF control; SOC calculation; cell equalization and balancing; detection of ignition; closed loop charge/discharge control.

The ESS can be controlled in manual, automatic, and remote way. The manual control mode is generally applied just to check the system functionalities in test mode changing the powers by front panel. In automatic mode it is possible to have some working functions, generally defined for the specific application. The automatic control acts defining the magnitude and phase of the fundamental voltage of the inverter, produced on the basis of four controllers: frequency, voltage, power limit and current limit. The outputs are sent to the power converter for controlling the switch-on pulses of IGBT with a PWM method. The inverter output voltage is given by:

$$E(t) = V_{dc} \cdot m(t) \cdot \sin\theta(t) \tag{1}$$

where $\theta(t)$ angle is the integral of the pulsation $\omega(t)$ that is $2\pi f(t)$. The frequency f is related to the active power supplied by the inverter according to the characteristics shown in the lower left part of Fig. 12. The amplitude $V_{dc}{\cdot}m(t)$ is related to the reactive power supplied according to the characteristics shown in the lower right of see Fig. 12, and the control is done by the modulation index $m(t)$.

In this way with this system it is possible to perform a P–Q control according to a secondary control simply by acting on the

Table 6
Features of insulation transformer.

Feature	Value
Nominal power	30 kV A
Primary nominal voltage	400 V
Primary nominal current	43.3 A
Primary winds connection type	Z
Secondary nominal voltage	320 V
Secondary nominal current	54.1 A
Winds connection type	Y
Overvoltage class	B
Isolation class	F
Short-circuit voltage	4%
Group	Zy11
IP	23
Weight	225 kg

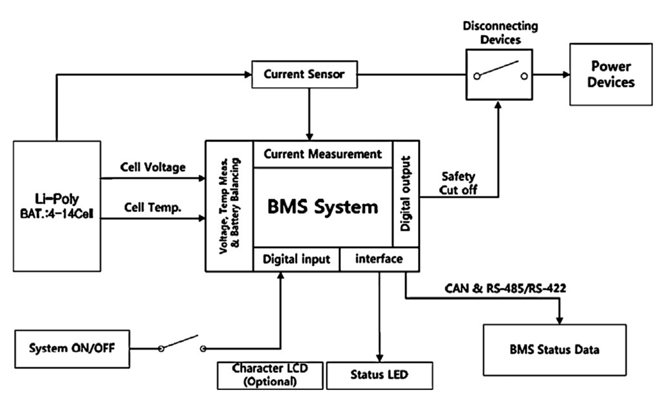

Fig. 11. Battery management system scheme.

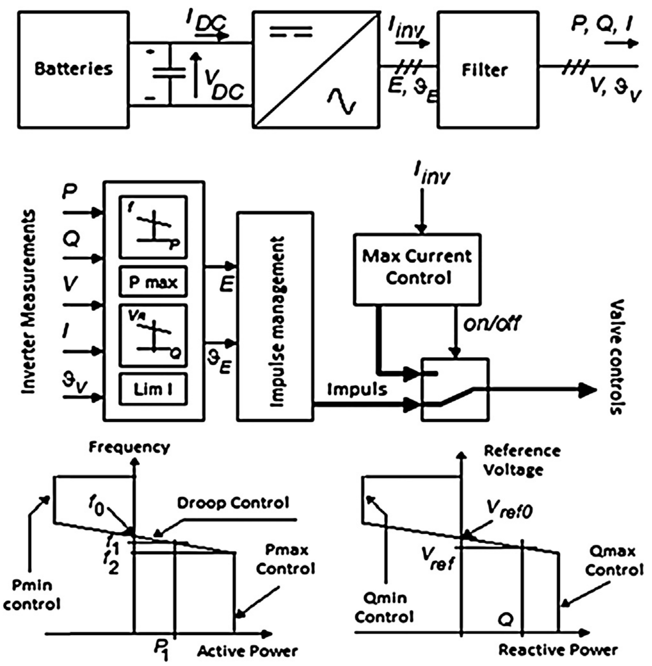

Fig. 12. Control scheme and curves.

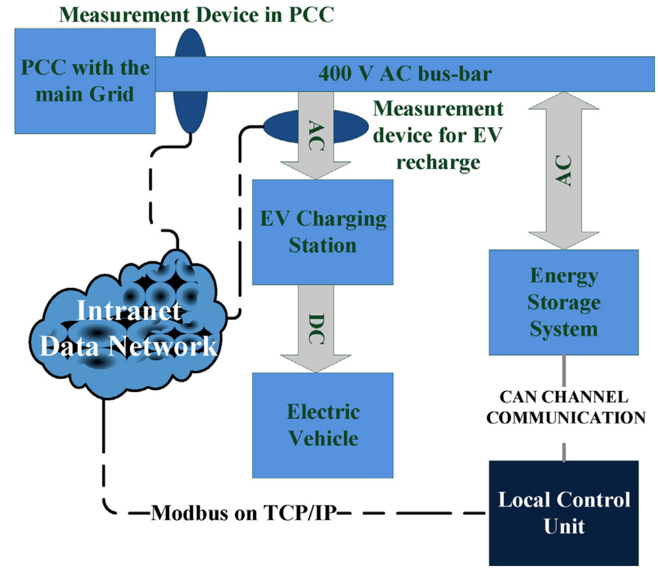

Fig. 13. Prototype of EV charging station with ESS included in a real smart micro-grid.

references of the curves f–P and V–Q given on the bottom part of Fig. 12.

In remote mode, the ESS can be managed by an external control system. In fact, the ESS is equipped with communication interface that allows to the equipment installed in the system, communicating data remotely to a supervision point. Communication can take place via CAN, via Modbus or via Serial connection.

4. ICT for experimental tests in a real smart micro-grid: implementation and results

The remote control mode of the ESS inverter makes possible the integration of the whole system, including the EVs charging station in a smart grid, and in particular in the smart micro-grid (MG) of the ENEA labs.

In fact, ENEA research centre is supplied with a HV line with a dedicated electrical sub-station at 150/8.4 kV. From the main sub-station, different lines in MV supply MV/LV sub-stations (8.4 kV/0.4 kV). The smart micro-grid (MG), where the EVs charging station and the ESS inverter-controlled are fed thanks to 2 MV/LV sub-stations, has a ring configuration with radial operation. Each MV/LV sub-station, feeding the MG, is supplied through a dedicated MV cable by the same HV/MV sub-station. The whole grid is equipped with a smart metering system.

A local control unit (LCU), composed by a microprocessor system (DSP), is available to send to the metering devices specific requests of data and acquires them using an available internal Modbus network on TCP/IP. As shown in Fig. 13 the TCP/IP communication channel is used for transmitting the measured data on the main grid, and in particular in the point of common coupling (PCC), and on the EV charging stations where the metering devices are located.

An additional ICT is needed for sending the commands to ESS inverter through the LCU. The choice of the right communication system and protocol is important. The final choice has been to use a CAN Protocol. To have a full integration of the system EV charging station + ESS in the micro-grid of ENEA labs and to apply the internal control of the ESS a LabView interface has been realized, able to communicate with:

(1) the smart metering system present on the MG and on the EV charging station, through Modbus on TCP/IP connection using the internal LAN (Local Area Network);
(2) the ESS converters through the CAN protocol.

Once that TCP connection has been established with the advanced metering devices, a Modbus request is sent encapsulating this request in internet protocol, indicating which values the devices must send back to the control system. When the smart meter device gives the answer, the control system can decode this data through the IEEE 754 Standard and decides which operation to send to the ESS to manage it. In fact the developed control system manages the ESS through the acquired data of measurements on grids and on ESS internal system state, defining how much active power the system has to provide or to take. In this way, the implemented control system can read the internal status and transmit the values of set points. These set points are for the active and reactive power. The bit rate of this communication has been fixed to 250 kbit/s, and the set data must be provided every 100 ms on a determinate identification message providing it the values of active and reactive power in every time instant. The ESS sends the information on the CAN bus every about 20 ms, instead of the smart metering device that has data available after about a second, because, using the Modbus protocol, the data must be requested by control system. Therefore, the Modbus request must be sent on TCP/IP and it arrives to TCP/IP – Modbus gateway. The gateway forwards this request on Modbus bus, so it arrives directly on the measurement device that needs about 60 ms to answer. After that, it comes back to the gateway and so to the control system. Therefore, the total response time of the device is about 500 ms. Fig. 14 shows the connection schema of smart devices and the total response time of the utilized devices to implement the system. The peaks show when the device is gone on timeouts. The control system requires the data from the smart metering system every second to avoid that the device goes in timeout. However, the control system manages the timeout using the previous acquired value.

Summarizing the control system implemented is able to manage more telecommunication protocols that have different bounds/rates and different management philosophy. It is able to synchronize the entire system.

The LabView control has also a customized graphical interface for the representation of the I/O data of the ESS. The front panel is

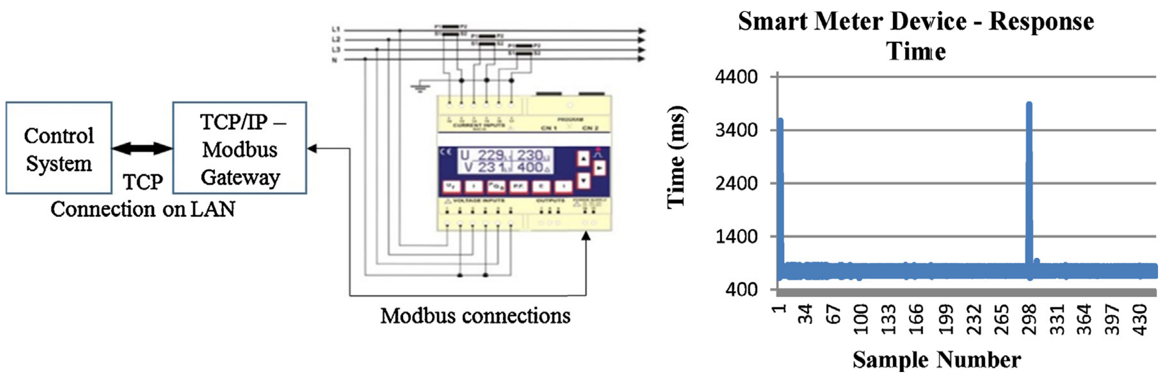

Fig. 14. Smart metering system and calculated values.

able to show different magnitudes, in particular, the CAN messages displayed are:

- Id 0 × 19F0CC59: every 100 ms the total battery voltage, the total battery current and the state of charge (SOC).
- Id 0 × 0200: every 10 ms the grid voltage and the current of single phases.
- Id 0 × 0201: every 10 ms active and reactive power, the frequency and the BUS DC voltage.
- Id 0 × 0180: every 50 ms the active and reactive power of the ESS.

Fig. 15 shows a screen shot of the front panel of the realized control system where there are:

- the power required by EV,
- the active power given by ESS,
- the battery pack voltage,
- the battery current,
- the ESS state of charge, and
- the total voltage and the current of the battery pack.

Thanks to the implementation of this customized monitoring and control system a wide experimental activity has been performed on the prototype, dealing with the use of the system for the charging of a specific EV: a Nissan Leaf car. It is an electric car manufactured by Nissan and it has autonomy of 200 km on the New European Driving Cycle. This EV is equipped with:

- a Li-ion battery pack with a nominal energy of 24 kWh and a nominal peak power of 90 kW;
- an 80 kW (110 HP) and 280 N m front-mounted synchronous electric motor;
- a charging system able to guarantee both the slow and the fast modes.

The power density of the Li-ion battery is 500 W/kg (discharge to 3 C, 2500 W/kg) and the battery energy density is of 140 Wh/kg. The charging time according to fast charge is about of 30 min with a recharge from 0% to 80%.

The experimentation has used the CHAdeMO protocol to supply the EV. The AC power has converted in the charging station to DC and the plug ensures that only a matching electric vehicle can be connected. Typical charging times of the Mode 4 are in a range from 20 to 30 min. In this case the charging time is limited by the permissible current of 125 A and voltage of 500 V on the CHAdeMO connector.

The procedure to delivers power after checking the connection with the EV and after approval of the user runs with radio frequency identification (RFID). An LCD screen, shown in Fig. 16, provides an

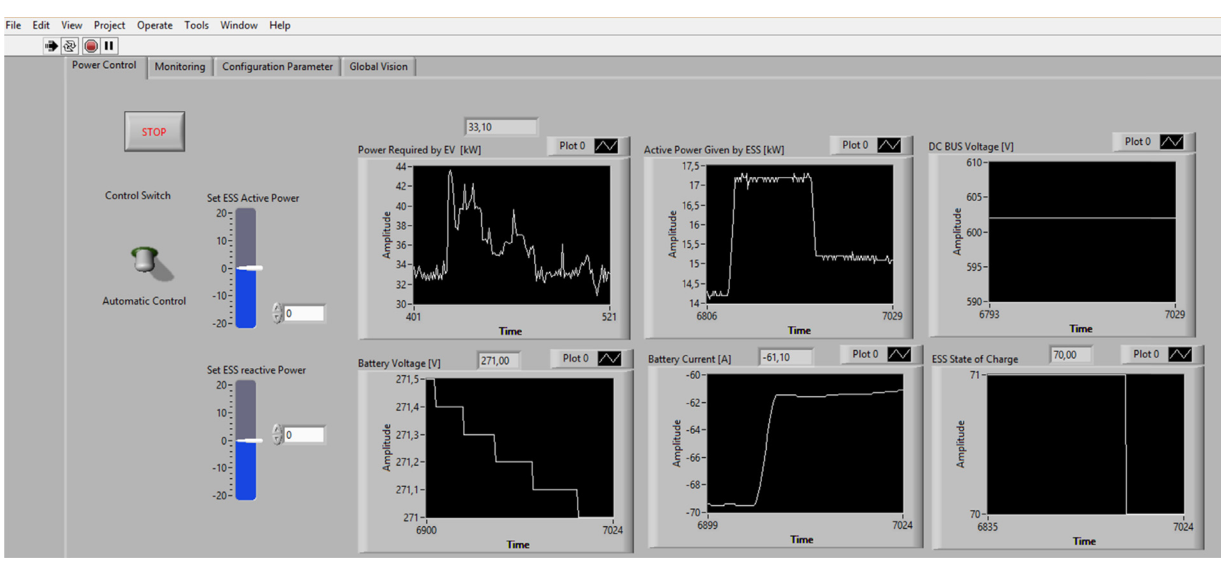

Fig. 15. Front panel of realized LabView control system.

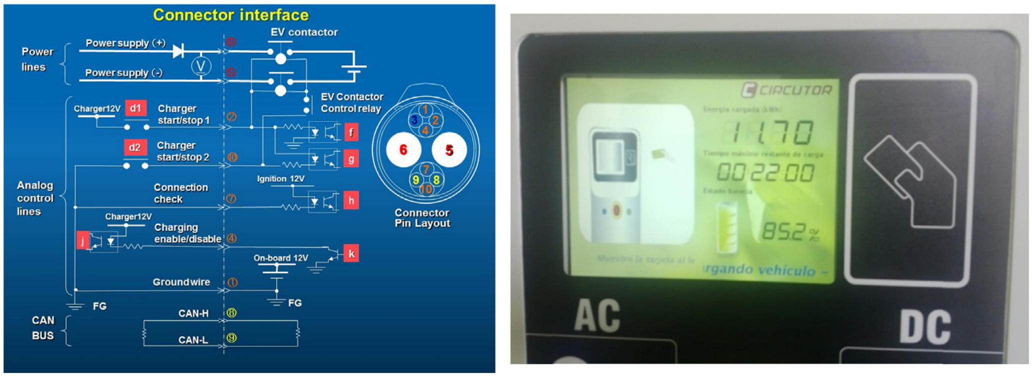

Fig. 16. Connector interface and LCD screen.

interface for the user that can know charging time, charging energy and SOC of the storage system of the EV.

Every second the system acquires by smart metering system the following values:

- the total power provided by the main grid, where the EV charging station is located;
- the power required by EV for the charge;
- the state of charge of the batteries in the ESS.

The experimented control logic system has tested implementing a peak shaving algorithm, whose flow chart is reported in Fig. 17. If the power absorbed by EV charging station is greater than a settled threshold and the ESS SOC is in the range 20–80%, the ESS provides the power given by the difference between the total power provided by the grid and the threshold. The result is limited to maximum power of ESS. In this way the grid can supply a lower and constant power value during the EV charge time.

Different tests have been performed to check the peak shaving logic. Here two results of them are reported as example.

A first test has been implemented starting from EV battery SOC of 65% and implementing a peak shaving function on the main grid, setting different thresholds on the maximum power required. This threshold has been set in the first 320 s, at 35 kW, and later at 15 kW. The LCU acquires the EV power request by smart metering system and it compares this value with the threshold. The real data acquisition for the first test is shown in Fig. 18 where:

- the red curve gives the profile of the power required by EV for the battery charging (left axis values);

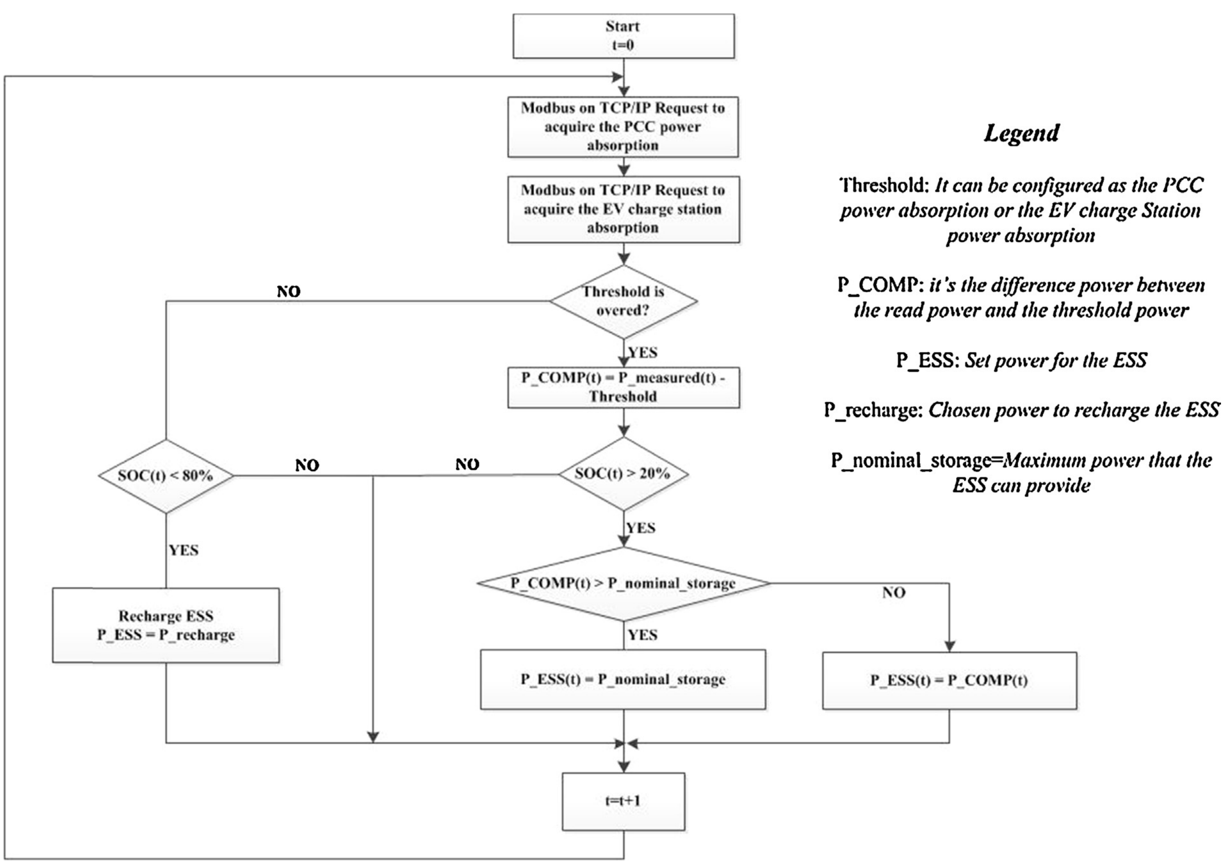

Fig. 17. Peak shaving logic with the LabView control system.

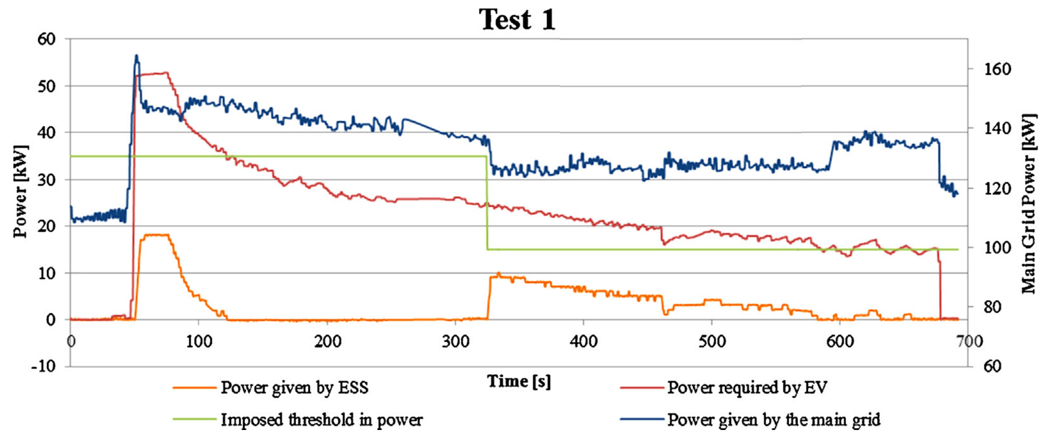

Fig. 18. First test results.

- the blue curve gives the profile of the power given by the main grid (right axis values);
- the orange curve gives the profile of the power given by ESS (left axis values);
- the green curve gives the imposed threshold in power, set by the LabView interface (left axis values).

In the first instants, going from the start observation time to 45 s, the system checks that the EV power request is lower than threshold (35 kW) and it commands the ESS to not deliver active power. When the procedure to start the EV recharge is ready, the EV power request grows and the value exceeds the threshold. The initial power is provided by the grid, but after few seconds the control system recognizes this status and orders to the ESS to deliver power of the same quantity that exceeds the threshold up to the maximum ESS power. The absorbed power to recharge the electric vehicle is not constant for all recharge time and so the control system commands to ESS to not deliver active power when this value goes down and becomes lower than threshold.

The second test has been implemented starting from EV battery SOC of 40%. The experiment is composed by two different charging phases: the first phase has the target to bring the SOC up to 85%; the second phase is another quick charge that brings the SOC up to 100%. The threshold has been changed in this experimentation also. In the first part, up to 500 s a threshold of 35 kW has been inserted. Then it has been changed in 15 kW for the rest of quick charge that has brought the SOC up to 85%. A threshold of 1 kW has been used for the second phase of charge that starts from about 1.470 s up to the end. The tests carried out have led to an overall trend of the powers shown in Fig. 19.

The initial value of the power required by the EV is about 55 kW in the first time of the test, so the energy storage provides its maximum power of 20 kW. After about 200 s, the absorbed power from the EV charging station changes and consequently the ESS starts to decrease the active power provided to zero. After 500 s, the threshold on the maximum power is changed from 35 to 15 kW, so the ESS provides active power another time.

The total energy supplied by the ESS in the experimental tests, carried out with the logic of peak-shaving, has been of 4.5 kWh and thus equal to 36% of the 12.4 kWh absorbed by the EV charging station.

The results of the experimental tests show that the system has a good performance in the implementation peak shaving function, in respect of the main distribution grid, making the prototype, including the EV charging station and the ESS inverter-controlled, like a potential network nearly zero-impact energy system.

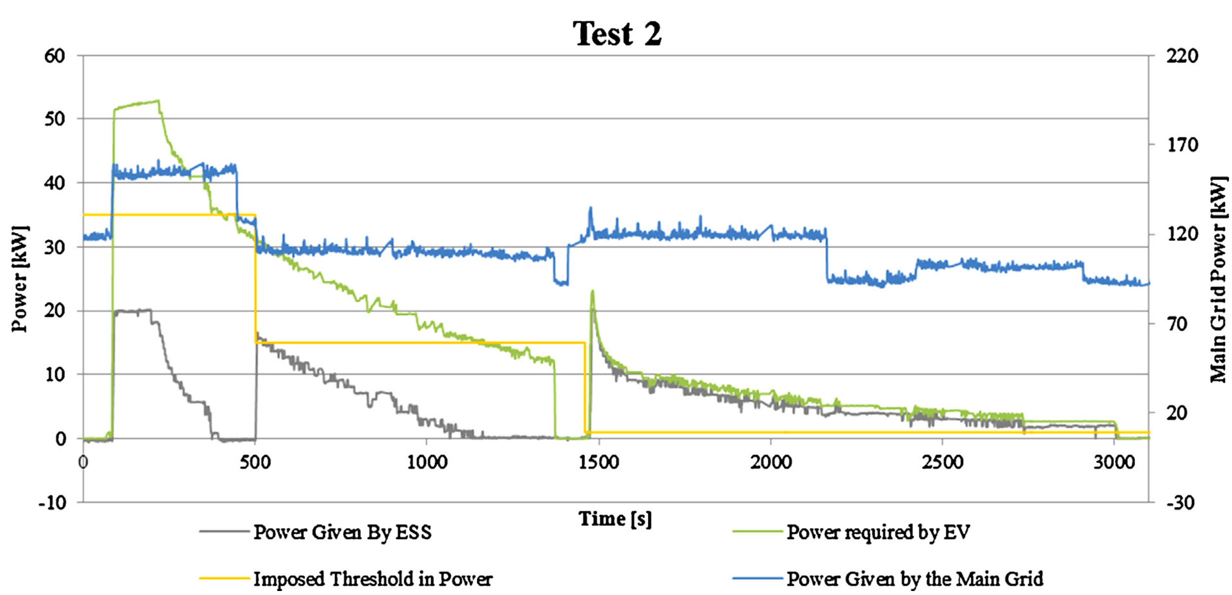

Fig. 19. Second test results.

5. Conclusions

A real implementation of electrical vehicles (EVs) fast charging station coupled with an energy storage system (ESS), including Li-polymer battery, has been deeply described. The system is a prototype designed, implemented and available at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) labs. A wide experimental activity has been performed on this system in order to test its functionalities in the integration in a real smart grid, available at the same ENEA labs, including a smart metering system. The integration has been possible thanks to the implementation of a customized communication system and a LabView control interface. The communication system implemented has been tested to be able to manage more telecommunication protocols with different bounds/rates and different management philosophy: it communicates with the smart metering system present on the MG and on the EV charging station, through Modbus on TCP/IP connection, using the internal LAN, and with the ESS converters, through the CAN protocol.

The results of the experimental tests have shown that the prototype, including the EV charging station and ESS, managed through the communication and control system, shows good performance in the implementation peak shaving function, in respect of the main distribution grid. It makes the prototype like a network nearly zero-impact system. Considering that the system can be considered the nucleus of a more complex power system, including more than one EV charging station, in an AC bus-bar configuration, with a distributed storage, to have tested the performance of a so-made system can be considered the first step for implementing a methodology for the siting and sizing of a distributed ESS on a AC distribution network, including multiple EV charging stations and other loads, requiring an active power service.

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