A New Proposal for Power Sharing in LVDC Energy Community Microgrids

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***Abstract*—In recent years the development of LVDC distribution networks is under consideration. DC electrical distributions offer several advantages compared to AC ones in many applications, in particular in the presence of energy storage systems and distributed generation like high efficacy, flexibility and simple integration of renewables. The DC distribution allows to integrate in a more efficient "microgrid" different sources with DC/DC converters. The paper proposes an innovative model of microgrid configuration for aggregations of end-users able to share the power produced by common generators and energy services named by the authors Power Sharing Model (PSM) using a DC bus that connects in a one way approach, the common generators to the end-users. The paper investigates on the different suggested configurations of the PSM, with the converter characteristics and controls. A simplified case study is analyzed to test the performance of the sharing model and the stability of the control in different scenarios. The paper compares the PSM based on a LVDC grid with existing approaches of virtual aggregations, and it highlights the main differences between the currently existing methods and our new LVDC microgrid approach. The suggested PSM appears more efficient, convenient and flexible than the existing virtual models, because users physically self-consume and share the energy locally generated.**

Keywords— building automation, DC system, distributed generation, power sharing model, electrical vehicles, energy efficiency, renewable energy sources, smart grids.

I. INTRODUCTION

It is well known that the 40% of the European energy consumption corresponds to buildings of residential, commercial and tertiary use [1]. Multi Units Residential Buildings (MURBs) in downtown zones and Dwelling Units (DUs) in peripheral zones determine a large sector of users in terms of power and energy, characterized by a very high fragmentation of power systems. The recent energy policies encourage the Nearly Zero Energy Building (NZEB) approach as the reference model for new constructions and the target to reach for the renovation of existing buildings [2]. The presence of renewable generations plays a fundamental goal in the NZEB model considering that the greater part of the load demand must be furnished by renewable energy. In the next year, the number of electrical vehicles (EV) will increase, and it is important to investigate their integration in the energy system [3]. In a framework of fragmented users each with the owned micro power system and each connected with an independent connection point, the application of aggregated grids approach with the optimized integration of renewable generation, storage, and other services appears very difficult. The aggregation of the users in energy communities seems to be the best way to promote the realization of smart microgrids with an optimized integration of energy sources. The European Directive 2018/2001 [4] introduced as final users also forms of aggregations between users living in the same building (jointly acting self-consumers) or multiple buildings (renewable energy communities). The new Directive opens the way for smart microgrids serving several users, maximizing the renewable energy exploitation, decreasing costs, and increasing the benefits of the participants. Studies have shown that limitations to new energy concepts are present in the current energy market regulations [5], both at national and at European level [6]. The integration of buildings into smart grids has therefore been studied, e.g. for residential buildings [7], and deserves further investigation. In Italy, the state of the art refers to admissible aggregation configurations based on a virtual model for sharing the generated renewable energy among the end-users. This model is proposed by the national regulatory authority for energy ARERA and it is called Modello Regolatorio Virtuale (MRV) [8]. It requires that the renewable energy produced by the members of the community, is virtually shared, so the generated power must flow into the public AC grid before to supply the end-users. Therefore, even if this solution does not need a new grid because it exploits the public AC existing one, the power exchange could overload the AC grid or introduce voltage regulation problems preventing to connect other end-users and/or limiting the amount of exchanged power. The paper presents an innovative configuration of smart microgrid for the aggregation of residential users based on the adoption of a Low Voltage DC (LVDC) distribution and the realization of a smart control able to manage in a shared way the energy generated by common renewable sources. The proposed configuration called *power sharing model* (PSM) [9] and [10] is represented in Fig. 1.

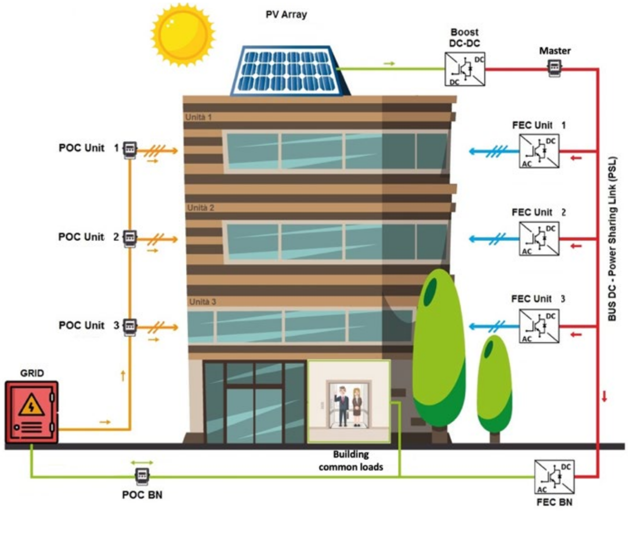

Fig. 1. Power Sharing Model (PSM) for energy communities

In the PSM the energy is not shared virtually, as in MRV, but it is shared physically using a LVDC bus, inside the building, which connects all the end-users. A previous paper highlighted that PSM is more efficient, convenient and flexible than the existing virtual models, because users

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physically self-consume and share the energy locally generated [11] .The management doesn't require any kind of calculation and incentives as the MRV because the users share the energy instantaneously by predefined rules. This proposed model, even if it is not yet considered by the regulatory authorities, technically can be considered appropriate in all national regulatory frameworks because it is based on the principle that the shared energy is the only one that is generated by common generation plants, therefore it is absolutely not shared energy taken from the distribution network. The smart microgrid proposed in this paper integrates a DC network in the residential context where one goal is to increase the Power Quality (PQ), as the exploitation level of renewable sources is increasing. So, to face problems of LV network voltage supply quality, an electronic power system called Open Unified Power Quality Conditioner (Open UPQC) is used [11]-[15].

The paper is an extended version of previous work [15] and is organized in the following way. An introduction about EU directives on residential smart microgrids and a comparison between the State of Art in Italy and the proposed model. Then a brief description of a topology of possible LV distribution system is given in Section II. A microgrid model suggested for power sharing study case is introduced in Section III. The converter configurations used in the proposed microgrid model are given in Section IV. A detailed description of each housing unit is presented in Section V. In Section VI an experimental simulation of the proposed model is elaborated, on a simplified network, to show the power flows from PV to the users and the algorithm able to sharing that power while Section VII concludes the work.

II. PERSPECTIVE OF LVDC DISTRIBUTION SYSTEMS

Discovering that major part of our consumption loads in the residential sector are becoming more and more DC, e.g., laptops, cellphones, LED lights, displays, etc., an LVDC distribution system could be a good alternative to AC conventional distribution system since they are more performing in terms of efficiency, scalability and stability [17],[18]. Even if the electric grid is conceived in AC since the grid has been designed to support conventional loads, basically induction motors and other AC appliances, the increasing introduction of DC loads let us think that there will be change. Besides, generation also changed from big synchronous generators in power plants to small solar panels, fuel cells, or batteries, which are essentially DC sources. Therefore, the increase of the DC sources promotes their spread due to the fact that it is easier and more efficient to connect them to a DC distribution system directly, or through a controlled DC/DC converter.

Moreover, considering modern electrical systems it is often necessary to improve the PQ of the LV AC electrical network by introducing electronic interface devices between the network and loads. One of these devices is the Shunt Unit of the Open UPQC described in [11] and [13], then the multi-wire power layout of the device in a three-phase, four-wire distribution network is illustrated by Fig. 2.

The Open UPQC device is obtained by one series unit installed in the MV/LV substation and several shunt units installed close to the end-users (in Fig. 2 only one shunt unit has been shown). In Fig. 2, the Open UPQC device is represented in the three-phase configuration, but obviously, it can be realized in the single-phase configuration also.

The Open UPQC Series Unit consists of a coupling transformer (TR), with the primary circuit connected in series with the mains line and a secondary one supplying the reversible AC/DC power converter. The output stage of the Pulse Width Modulation (PWM) voltage controlled converter contains passive RC shunt filters, to compensate for the harmonic currents at switching and multiple frequencies. Neglecting the active power to compensate the converter losses, the series unit is controlled to act as a purely reactive inductor injecting a voltage V_x (perpendicular to the line current I_s) when the supply voltage V_s is within its operation limits ($0.9\cdot V_n \leq V_s \leq 1.1\cdot V_n$) to maintain the voltage at the point of common coupling V_{PCC} at the reference value, following Equation (1).

$$\overline{V}_{PCC} = \overline{V}_s - \overline{V}_x \tag{1}$$

This fact is of fundamental importance because in this range the loads must be supplied by the mains more than 95% of the time, as established by the IEEE Std 1159 "IEEE Recommended Practice for Monitoring Electric Power Quality" and European EN50160; therefore, the storage system must not discharge itself. Outside of this range, active power can be used to compensate disturbances, in the same way as the usual series compensation devices when a storage system is present. To go more in detail about the working principle of the series unit it is possible to analyze [11].

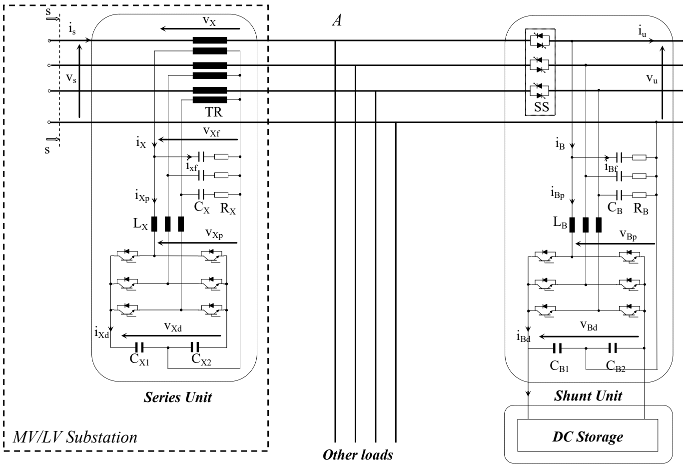

Fig. 2. Multiwire power diagram of the Open UPQC

The Open UPQC Shunt Units consist of an AC/DC power converter, similar to the one used in the series unit, connected to an energy storage system and a set of static switches (SS). Depending on the state of the network voltage, it can supply either the entire load or a part of it.

There are two different operation modes of this device:

- compensator: when the load supply voltage is within its operation limits, the SS are closed, the series unit works as a three-phase voltage generator and each shunt unit works as current generator;
- back-up: when the load supply voltage is outside of its operation limits, the SS are opened, decoupling the network and the load-compensator system. Each sensitive load is supplied by its shunt unit, which acts as a sinusoidal voltage generator, using, as energy source, the energy stored in the storage system.

By coupling a unidirectional DC/DC converter to this device, the Open UPQC Shunt Unit becomes ready for PSM implementation to further improve its PQ level when connected to a DC microgrid. Indeed, microgrids can increase buildings' reliability, PQ, safety and efficiency, and also employ renewable energy resources as the main local power generation. Moreover, they are becoming more and more popular because they are a promising alternative to enable the proliferation of net zero energy buildings.

Furthermore, electric vehicles will play a key role in this network evolution. In fact, the sudden increase in charging stations and the speed of DC charging will lead to further development and integration of DC systems. Moreover, the control of harmonic injections into the AC side through the main converters would be reduced thanks to the connection of all DC loads to the DC side of this new hybrid grid, thus guaranteeing high-quality AC in the utility grid [19].

Finally, the DC grid could solve negative and zero sequence current problems caused by unbalanced loads in AC distribution systems, and the neutral wire in sub transmission might be eliminated and the related transmission losses reduced.

III. SMART MICROGRID MODEL FOR POWER SHARING

The suggested model of microgrid consists of the realization of a DC common power system connected to the single end-users by special converters for power sharing.

Fig. 3 shows the general full scheme of the proposed Power Sharing Model serving a residential building with five different units. Into the suggested model the DC common power system is a bipolar with neutral line, operated at the voltage of 500VDC with a 3-wires system at +250V, -250V respect to the neutral point 0 that is grounded.

On the roof of the building there is a common photovoltaic (PV) array connected to the main DC common power system (red line) through a DC/DC converter named DC_PV in the model. The function of the DC_PV converter is to adapt the output voltage of the common PV array to the voltage of the main DC common power system and allow the maximum power of the PV array (MPPT) to be tracked through an incremental conductance algorithm. The power and energy generated by the PV system are measured by the C_{PV} meter.

To ensure the continuity of service even during the night a common storage system (BESS_G), connected through a DC/DC converter called DC_Batt, is adopted. It is important to observe that BESS_G can be charged only by the energy produced by the PV array.

The balance node represents one of the main elements of this model, as it consists of the bidirectional DC/AC converter, named FEC_BN (Front End Converter_Balance Node). It has the task of feeding into the AC grid the excess power produced by the common PV array. By excess, it is intended the surplus power that is neither withdrawn from the end-users, nor stored in the BESS_G accumulator, nor withdrawn by common DC service (such as public DC lights, EV etc.).

In more general way, common services are defined as those services present in a building and made available to users. In this model are considered significant as common services:

- plant for lifting people (elevator), AC load;
- charging system for electric or plug-in hybrid cars, DC load;
- plant of heating or cooling through heat pump, AC load.

The common services power and energy withdraw, and the excess power and energy produced by the common PV array injected into the AC grid are measured by the POC_BN meter. This point of connection (POC) is, therefore, of the active type because it must be able to measure, in the same way, the provide power to common services when the common PV array does not generate enough power, or to measure the excess power produced by the PV that is not used by common service, end-users and stored in the BESS_G.

In the DC common power system, the Diode_C is introduced to force the power flow in the right direction; indeed, the use of this device allows the proper PSM operation even in a case of failure of the power electronic converters connected to the DC common power system.

The Diode_C is used to divide the DC common power system in two parts:

- unidirectional DC Grid (U-DC), red line in the Fig.3;
- bidirectional DC Grid (B-DC), pink line in the Fig.3.

In particular, only loads that could get a contribution of power from the AC grid will be connected to the B-DC. Therefore, in this B-DC grid EV are connected, and the power flow can come from both the AC grid and/or the U-DC one. This DC connection from power converter and EV does not have a defined voltage range, as it depends on the charging mode (fast or low charging), and in this work is not considered.

Each end-user in the building can be connected to the U-DC only:

- for units from 1 to 4 by an unidirectional DC/DC converter named C_PS (Converter_Power Sharing);
- for unit 5 by a unidirectional AC/DC inverter named FEC_PS (Front End Converter_Power Sharing).

To guarantee the unidirectionality of the energy and power a diode could be used to connect each end-user to the U-DC, in this way it is possible, also in case of fault, to draw power from the U-DC grid but never input it.

According to the customer needs, several configurations can be realized starting from the simplest one, that is Unit 5 in Fig. 3, reaching a possible evolution with the Open UPQC Shunt Unit configuration, before described, and reported in Fig. 4.

In the configuration of Fig. 4, a unidirectional C_PS converter is connected to the user-owned DC bus (green line) inside the Open UPQC Shunt Unit. In this way, the U-DC can support the end-user's AC loads.

It is important to highlight that each end-user can decide his best configuration for his needs. In the example in Fig. 3 all end-uses has an own POC to measure the energy and power exchanged with the AC network. Considering POCs, it is important to observe that normally end-users are passive, so their POC can measure only unidirectional power because they cannot exchange active power with the mains. Only active end-users have a connection point with the distributor that can be active and passive, so they can exchange active power with the mains, but in this case, it is fundamental that when the load becomes active this active power can come only by its PV power plant and not from the U-DC grid.

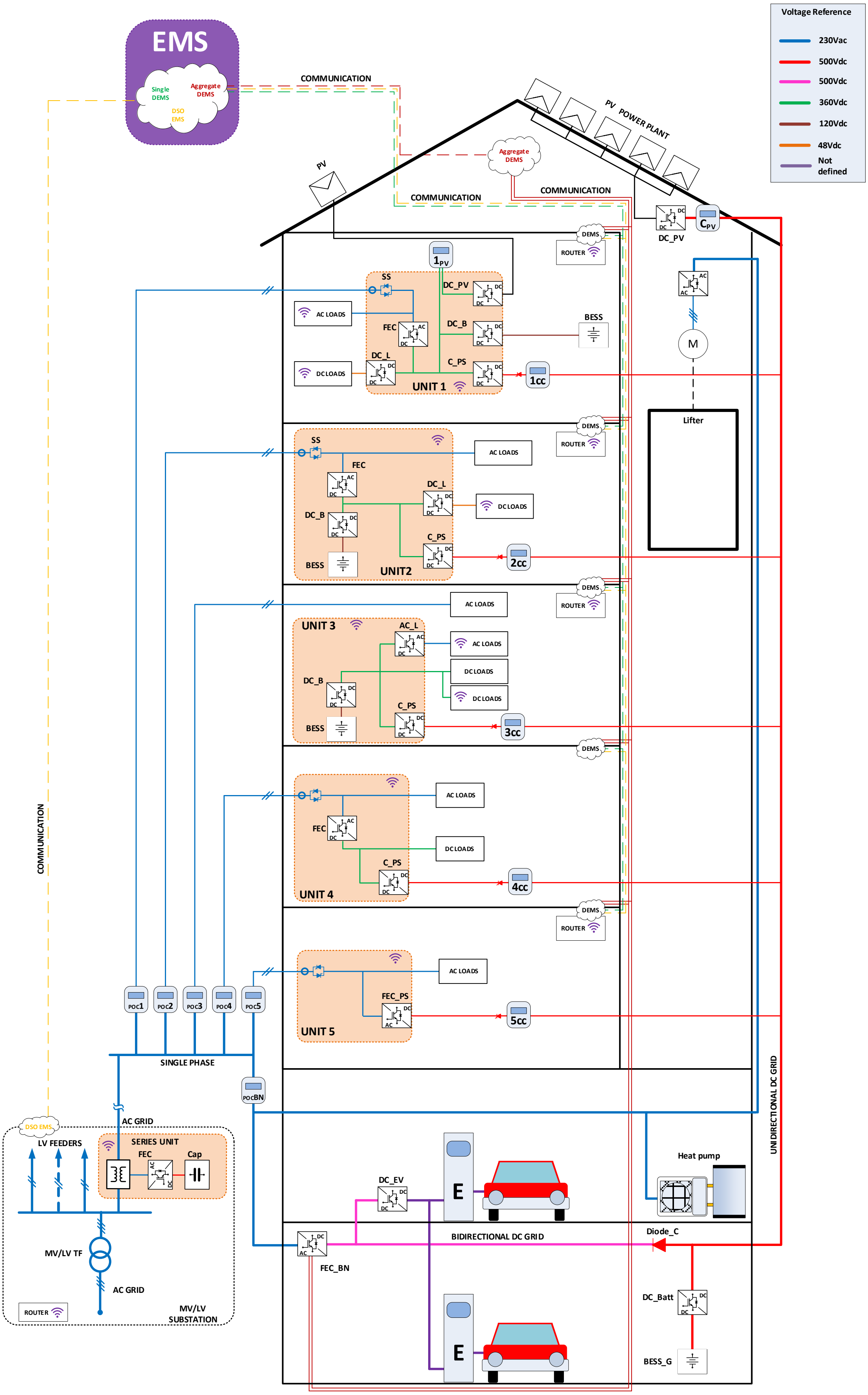

Fig. 3. Model of complete smart microgrid for power sharing in a building

In conclusion, each end-user is connected to the public AC network and, in addition and at the same time, to the U-DC grid to exploit the electricity produced by the common PV array. The main focus of the operation control is to reduce the power demand from the AC distribution network. The control avoids power injections from the end-user to the U-DC grid and from the end-user to the public AC network. The end-user is a passive "sponge" node. This power sharing could occur in a democratic way, by using the measure of energy and power of #CC meter, as described in [20].

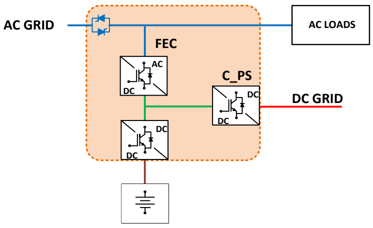

Fig. 4. Shunt Unit of Open UPQC for Power sharing

The interesting aspect of the proposed model consists in the fact that the power sharing is not virtual but physical using a shared DC common power system. Moreover, this solution could be seen as a smart multi-vector energy grid. Indeed, the peculiarity of this solution could be the integration of different energy networks, concerning power (P), gas (G), heat (H), and electric vehicles (V), supported by a communication network (I), into an "I-PGHV" novel management model. Thus, the resulting smart grid operates three energy vectors (power, gas, and heat) and an ICT channel. The nodes of this network are:

- users (smart buildings):
- prosumers (smart buildings with local generation);
- distributed generators;
- storage systems;
- cogenerators;
- electric vehicles.

IV. CONVERTER CONFIGURATIONS

Now, before analyzing in detail, starting from the most complex, all the units present inside the building, some common considerations on the converters will be introduced.

One of the main problems to develop this system is fixing all the converter configurations. In the proposed solution there are several converters that are responsible for the conversion of the electric power between an AC section to a DC one and other conversions that are responsible for the conversion of the electric power between two different DC sections normally at different voltage levels.

These converters can be unidirectional, bidirectional and can be configured to control independently the output or the input voltage within certain working ranges. Moreover, they can implement special functions such as MPPT (maximum power point tracking) adopted for PV converters or constant current power supply adopted to supply LED lamps, etc.….

Considering the front-end converter (FEC), as the FEC_BN in Fig. 3, it can be shaped in different configurations depending on the DC network requirements. When the DC network needs stable and fixed polarities (3 wires), several solutions are possible but, from an economical point of view, it could be profitable to work with the fourth balancing leg. When this requirement is not requested the classical solution within three legs is normally adopted. With these assumptions, two main categories of FEC can be defined:

- Non-isolated FEC. This solution presents metallic continuity between the AC and DC sides and hence presents an easier structure with respect to the following case, as the one shown in Fig. 5;

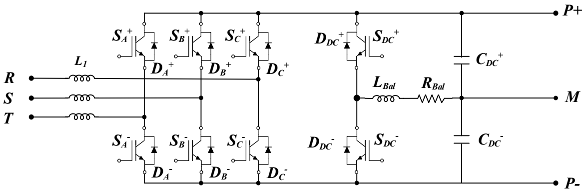

Fig. 5. Three-phase not isolated FEC with balancing leg

- Isolated FEC. This solution does not present metallic continuity between AC and DC sides. To form this condition, it is necessary to exploit a decoupling transformer. Two separate structures take place depending on the working frequency of the transformer, so an isolated FEC can be realized with a transformer supplied at mains frequency or with a transformer supplied at high frequency (HF – usually in the order of kHz). The second solution has the characteristic that the HF transformer has considerably lower dimensions with respect to the traditional one, moreover, the filter sizes are minimized due to high frequency operation.

Considering the DC/DC converters, in Fig. 6 a simplified classification of them is presented. They are categorized, once again, into non-isolated and isolated converters. Also in this case, in isolated converters the input and output stages are electrically separated, this is achieved by HF transformer and coupled inductors.

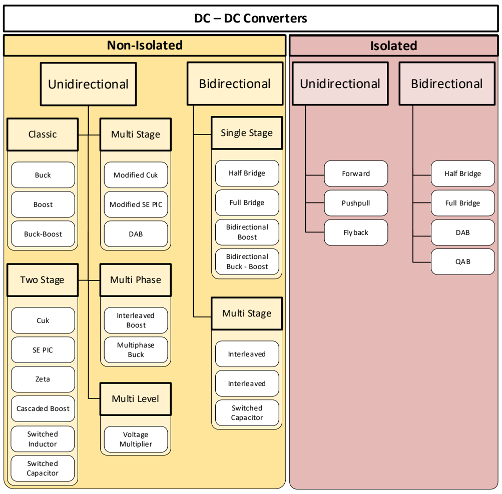

Fig. 6. Classification of DC/DC Converters

The HF transformer, among other functions, is always necessary to achieve a high step-up or step-down ratio of voltage conversion. Therefore, in these cases, only isolated converters can be adopted. On the drawback side, they are less efficient than the non-isolated converter because more switches and components are used increasing the conversion losses. Depending on the direction of power flow, the isolated and non-isolated converters can be further classified into two sub-categories which are unidirectional and bidirectional converters, respectively. In unidirectional converters, the power flows from input to output stage. In bidirectional converters, the power can flow in both directions.

Given the numerous topologies available in the literature, which have their own requirements, characteristics, and features, it is quite complex to further categorize DC/DC converters. Hence in this work, the fundamental topologies proposed are presented in the next paragraph.

V. SHUNT UNIT CONFIGURATION OF OPEN UPQC SHUNT UNIT FOR POWER SHARING MODEL

The proposed residential building, as shown in Fig. 3, can represent an energy community that adopts the Power Sharing model. All the five different housing units present inside the building will be here described.

A. Unit 1

The housing Unit 1, shown in Fig. 7, has a private PV array, a storage system and both DC and AC loads.

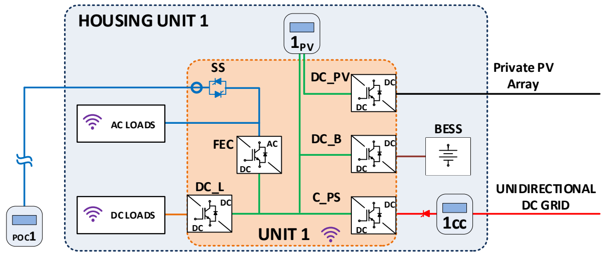

Fig. 7. Housing Unit 1

It is based on the Open UPQC Shunt Unit configuration and contains within it a user-owned DC bus (green line) that allows five converters to be connected together.

The C_PS, shown in Fig. 8, is an isolated unidirectional DC/DC full bridge converter. Thanks to the HF transformer it allows to adapt the voltage of the DC network (red line – V_{input}) to that of the user-owned DC bus (green line – V_{output}) which could be at a lower or higher voltage. It has the function of taking power from the U-DC network only. The power that this converter can transfer it is assigned to each C_PS, it can be only a portion of the power produced by the common PV system.

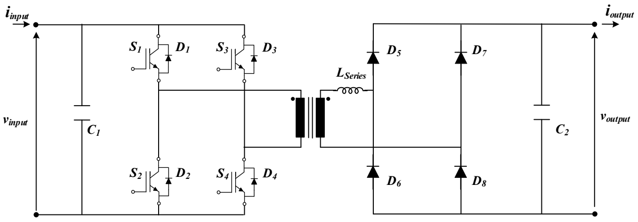

Fig. 8. Scheme of the unidirectional isolated DC/DC full bridge converter

The DC_L (which for safety reasons can be similar to the one shown in Fig. 8) can be realized as a unidirectional DC/DC buck converter, as shown in Fig. 9. It allows DC loads to be powered at a suitable voltage (V_{output} normally lower than V_{input}), connecting the input of the converter to the user-owned DC bus (green line - V_{input}).

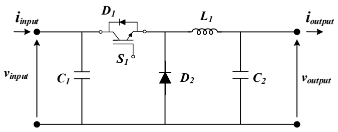

Fig. 9. Scheme of the unidirectional DC/DC buck converter

The DC_PV, which is similar to the one shown in Fig. 9, is a DC/DC converter that allows to interconnect the private PV system, at the higher voltage value V_{input}, to the user-owned DC bus (green line - V_{output}). Inside this converter, an MPPT control technique is adopted.

The DC_B, shown in Fig. 10, is a bidirectional not isolated DC/DC buck-boost converter that interconnects the Battery Energy Storage System (BESS) to the user-owned DC bus.

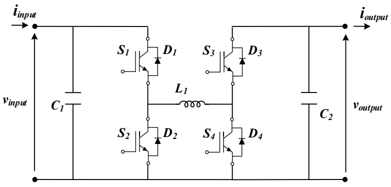

Fig. 10. Scheme of the bidirectional DC/DC buck-boost converter

Independently of the connection, it allows the BESS to be charged or discharged by drawing or feeding power from the user-owned DC bus (green line). When the BESS is unloaded and there is a surplus of unused power on the user-owned DC bus, this converter draws power from it to charge the batteries. On the other hand, when the BESS is loaded and the user-owned DC bus requires more power than the sharing provides, this converter can feed power to the user-owned DC bus by discharging the batteries. Inside this converter, at least a constant charging current control technique is adopted.

The FEC (Front End Converter), shown in Fig. 11, is an AC/DC single-phase converter that allows to connect the user-owned DC bus to the point of connection with the AC grid and to the AC loads.

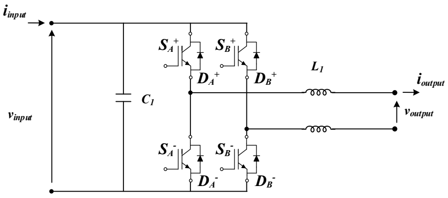

Fig. 11. Scheme of the bidirectional not-isolated AC/DC FEC

This converter is bidirectional, so it can either take power from the user-owned DC bus (green line – V_{input}) and feed it to the AC bus (blue line – V_{output}), or feed power to the DC bus by taking it from the AC grid.

Due to the presence of a private PV system, the connection point of unit 1 (POC 1) must be of the active type. The FEC works by maintaining the user-owned DC bus voltage at the desired reference value, using a control circuit. The voltage present on the user-owned DC bus is compared with a reference voltage, the error that is generated by the comparison represents the input of the entire control system. The error signal is used to manage the ON/OFF control of the electronic switches inside the FEC to drive power from the AC bus to the user-owned DC bus. When the user-owned DC bus is lower than the reference value, this means a power deficit from FEC, C_PS and DC_PV, the DC_B converter tries to restore the user-owned DC bus voltage to the nominal value by discharging the BESS. Instead, when the voltage on the user-owned DC bus is higher than the nominal value, this means a power surplus from C_PS and DC_PV, the DC_B converter tries to restore the user-owned DC bus voltage to the nominal value by loading the BESS. If this is not enough or BESS is fully charged, the FEC converter feeds the surplus power onto the AC bus to restore the user-owned DC bus voltage to the nominal value. Depending on the power made available by the FEC on the AC side, the AC loads may or may not draw all the power made available by the FEC. This depends on two factors: the power that the AC loads are requesting, and the power made available by the FEC (through the DC_PV connected to the private PV array and the isolated unidirectional C_PS connected to the main DC network). In the case where the power made available by the FEC is not enough to meet the power required by the AC loads, the power is supplied by the grid through the POC. On the other hand, if the power required by the AC loads is less than that made available by the FEC, the remaining power should be fed into the network respecting the roles that this power cannot exceed the power generated by the private PV array (measured by the smart meter 1_{PV}).

B. *Unit 2*

The housing Unit 2, shown in Fig. 12, is very similar to the housing Unit 1. The only difference is that it doesn't have a private PV system, therefore, the meter in the connection point is of the passive type (POC 2).

In this case, the user-owned DC bus (green line) allows to interconnect four converters: C_PS, DC_L, DC_B and FEC.

The hardware and the software functions of these converters are very similar to what was described for housing Unit 1.

With the possibility to increase the ability to solve the power quality problem of the end-user that will adopt this solution, a private BESS has been adopted, obtaining, once again, a solution based on the Open UPQC Shunt Unit configuration.

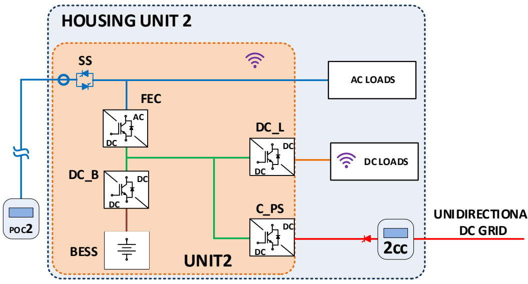

Fig. 12. Housing Unit 2

C. *Unit 3*

The housing Unit 3 is shown in Fig. 13. A portion of the AC loads are directly supplied from the grid through a passive type connection point to the distributor (POC 3). These AC loads are not affected by the power made available by the sharing, but all the power they require is supplied by the AC network.

Therefore, at the moment when there is a fault in the AC distribution network, these not privileged AC loads cannot be supplied, and the continuity of the power supply cannot be maintained. The other AC loads, the privileged ones, are powered along with the DC loads through the user-owned DC bus (green line). These AC loads are connected to the user-owned DC bus via a one-way DC/AC converter (AC_L) that has the same configuration presented in Fig. 11 for single-phase needs. This converts the power available from DC to AC and adapts the voltage to the needs of the AC loads.

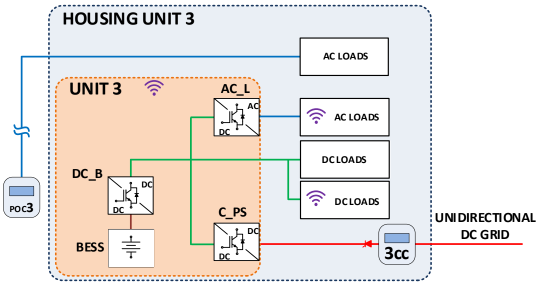

Fig. 13. Housing unit 3

This solution is based, once again, on the Open UPQC Shunt Unit configuration by simply opening the Static Switch (SS). Therefore, it can supply privileged AC loads by AC_L as the housing Unit 2 when the AC network is in a fault condition.

DC loads can be directly connected to the user-owned DC bus. Two converters are also interconnected to it: DC_B and DC_C, which have been already described. The privileged AC and DC loads connected to the user-owned DC bus are supplied by the sharing power and with the help of the battery. When the common PV system does not produce power (for example during the night), the sharing power is null, therefore the loads connected to the DC bus can only be supplied by the BESS, if loaded and for a short time. On the other hand, if the common PV system generates little power (cloudy day), the power sharing is reduced. Therefore, the loads connected to the user-owned DC bus, if they require more power than that supplied by the sharing, they can all be initially supplied only if the BESS is loaded. On the other hand, if the BESS is unloaded, a part of the loads can be powered by the power sharing, while the remaining part cannot be powered.

D. *Unit 4*

This housing Unit, shown in Fig. 14, is very simple, presenting both DC loads and AC loads. It contains within it a user-owned DC bus (green line) that allows two converters to be connected together: the FEC and the DC_C, which have been already analyzed. The connection point with the distributor POC4 concerning this housing unit is in any case a passive one. So even if the FEC is here bidirectional it is fundamental to control the FEC to avoid injecting power into the AC main grid.

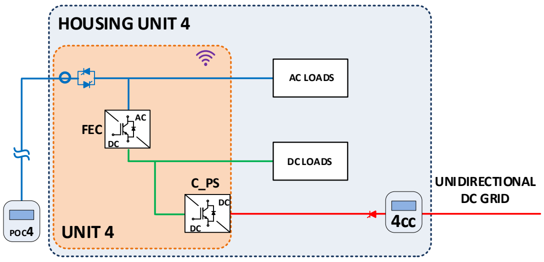

Fig. 14. Housing unit 4

In this configuration, a BESS in the housing is not present because in case of emergency it should be possible to supply the load using the BESS_G of the building.

This solution is based, once again, on the Open UPQC Shunt Unit configuration by simply removing the BESS and its power converter.

A variation of this solution could include a DC/DC converter, with a similar configuration to the one shown in Fig. 8 or in Fig. 9, to supply DC loads when a different level of voltage is required.

E. Unit 5

The housing Unit 5, shown in Fig. 15, is the simplest unit in the building.

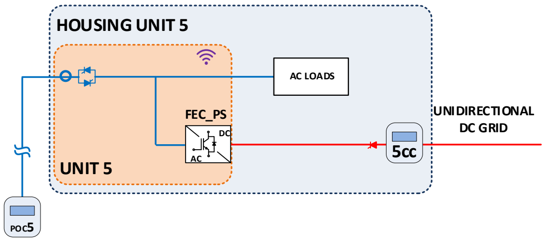

Fig. 15. Housing unit 5

In this configuration only AC loads are present, and it does not contain a user-owned DC bus. The FEC_PS is a DC/AC unidirectional converter that takes power from the U-DC grid and put it on the AC grid to supply AC loads only. Also in this case, the FEC_PS control logic must avoid injecting more power to the AC bus than the AC loads require (so the converter needs to maintain under control the absorbed current from the AC grid). This is because the connection point (POC 5) must be a passive "sponge" type, so it can only supply power to the end-user but not draw it. Therefore, the logic that handles this FEC_PS is different from that introduced for the housing Unit 1.

The housing units analyzed so far are normal passive load, only housing Unit 1 can be active, so it can be called prosumer. In practice, the prosumer is the one who has an energy production plant of which he consumes a part.

In the proposed model the condominium has a common PV generator, and its production is exchanged physically with all the housing units by a private U-DC grid. When an excess of power happens, the remaining energy can be accumulated and then returned to the consumption housing units at the most appropriate time, or even supplied into the AC network.

All these configurations' components, in practice, can be characterized by the data reported in Table I.

TABLE I
MAIN COMPONENTS CHARACTERISTICS

Name	Topology	Voltage	Power
FEC	AC/DC Bidirectional	230V/350V 230V/500V	3kW
DC_C	DC/DC Unidirectional	500V/350V	3kW
DC_B	DC/DC Bidirectional	350V/120V	3kW
DC_L	DC/DC Unidirectional	350V/48V	1kW
DC_PV	DC/DC Unidirectional	500V/350V	3kW
Private PV	/	500V	3kW
BESS	2kWh	120V	3kW

VI. CASE STUDY: POWER SHARING APPLIED IN A RESIDENTIAL SIMPLIFIED BUILDING

To evaluate the performance and stability of the model described in the previous Sections, a simplified residential building can be considered. The case study show in Fig. 16 is obtained from the fully described building in Fig. 3 considering 3 users (all as Unit 5) only.

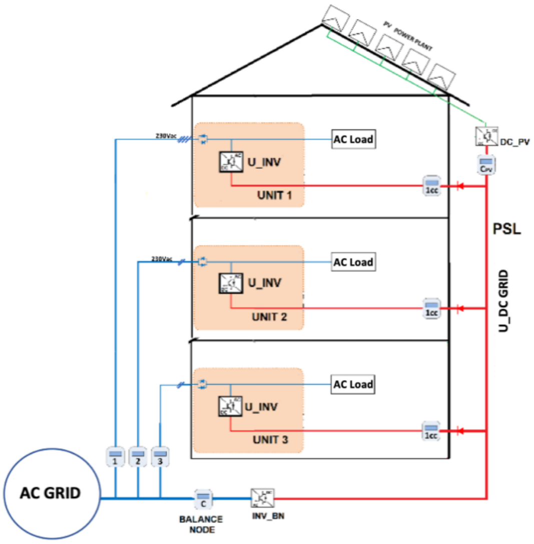

Fig. 16. Semplified residential microgrid with PSM

As shown in the Fig. 16, 3 types of converters are adopted in this case study.

A DC-DC converter (DC_PV) with a MPPT control is adopted between the PV system and the U-DC bus link. The nominal power of this converter is sized according to the nominal power of the PV generator.

A DC-AC inverter (FEC_BN) is adopted to connect the U-DC grid to the public AC grid. This inverter is controlled to be a *grid forming* for the DC side voltage. It works to maintain constant at 500V the DC voltage. In this way this inverter can be defined as balance node because it transfers active power from the AC grid to the DC one and vice versa. The nominal power of this converter is sized according to the nominal power of the PV generator because, if no-user requests power, it must be fed into the AC network.

A DC-AC user inverter (FEC_PS#) is adopted between the DC bus link and each end-user. The control of this inverter is an active power control managed by the master control of the system. It must work to avoid injecting active power in the public AC grid. The nominal power of this converter is sized according to the end-user contract demand.

In previous papers, several algorithms to share the energy produced by the common photovoltaic system among the users were investigated. The following main rules can be resumed:

- the power generated by the PV system is shared among the users according to the nominal power of the end-user FEC_PS# inverters;
- for each i-th user, the assigned power is compared with that required by the total load;
- for the i-th user, the power sharing strategy is stopped when the power shared by the inverter is equal to the total load demand (peak shaving);
- if the power allocated to the i-th user is greater than its power demand, the excess is shared among the other users;
- the excess power coming from fully satisfied loads is assigned to the users whose demand has not yet been satisfied, always according to the nominal power of the

inverters still participating in the power sharing strategy;
- the further excess power not assigned to the users at the end of the control loop is fed into the B-DC network and then, if not used, to the AC one through the balance node.

As case study, a 3 different residential end-users aggregated in a power sharing model were examined. User 1 is a 3-ph end-user with a load demand of 10kW, User 2 and User 3 are 1-ph end-users, with a load demand of 6 and 3 kW, respectively. The load profile is considered variable in the time. The PV system has a 30kW peak power. During the simulation, the power produced by the photovoltaic system is considered variable. The front end converter of the balance node FEC_BN has a nominal power of 30kW, 3-ph. The other FEC_PS# are sized for the nominal power of the corresponding user 10kW 3-ph, 6kW 1-ph, and 3kW 1-ph, respectively.

In the next, three scenarios have been considered. In all the scenario the load request of the PV power injected by the DC_PV is shown by a brown line, User 1, User 2 and User 3 are presented by a blue line, a red line and a green line respectively.

First scenario: in the first case we tested the dynamic response of the FEC_BN as the power generated by the PV system varies. For this reason (and only in this case) we consider flat and constant to the nominal power the load profiles. As demonstrated in the Fig. 17, during the simulation, the photovoltaic system varies its power output as solar irradiation changes. In particular, the irradiation is equal to 1000W/m^2 for the first 2s, presents a linear decrease from 2s to 4s arriving at 500W/m^2, and then remains constant for the remaining stretch. Consequently, the initial photovoltaic power is 29.5kW and then arrives at the end of the simulation at about 14.5kW.

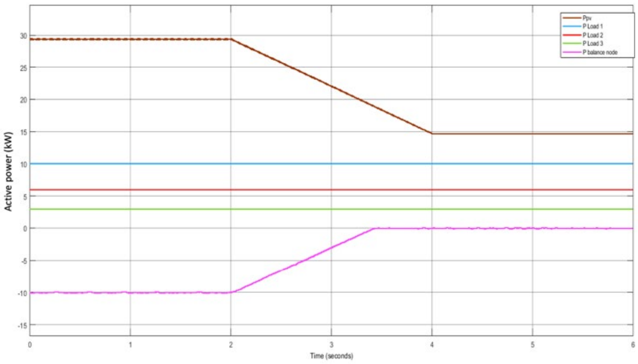

Fig. 17. Power balance of the first scenario

Fig. 17 clearly shows that as long as the power of the photovoltaic system is higher than the demand of the users, the FEC_BN feeds power into the network (pink line). In correspondence of a time equal to 3.5s, the power produced by PV is equal to the sum of the powers requested by the users, that is 19 kW, consequently, from this instant on, the power injected in the network by the balance node becomes null. Starting from 3.5s then, since the power coming from the sharing continues to decrease, the three users will make up for the lack of power through the POC that connects each user to the distributor.

Second scenario: In this case, the response of the system considering a load variation is analyzed. The User 1 and User 3 absorbed powers have been considered constant and equal to their nominal value, while the 1-ph User absorbs a variable power from a null load up to its rated power of 6 kW, as shown in Fig. 18.

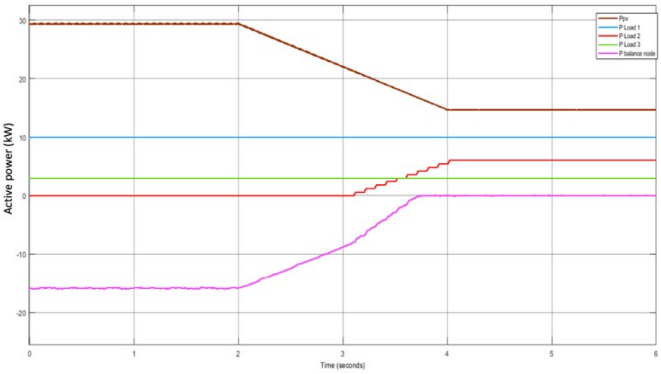

Fig. 18. Power balance of the second scenario

Fig. 18 shows that in the interval from 1s to 2s the PV system generates a constant power of 29.5kW while the three users require a total power of 13kW. The power fed into the grid by the balance node is therefore 16.5kW. Then, in the interval from 2s to 4s, the PV system reduces the generated power passing from 29.5kW to about 14kW. In this interval the User 2 required power increases from 0kW to 6kW. It is possible to verify how the power fed into the grid by the FEC_BN (pink line) is initially 16.5kW at 2s and then cancel itself exactly at 3.7s. From this instant onwards, the power required by the loads (19kW) exceeds the power made available by the PV system, consequently, as seen in the previous cases, the users make up for this power by taking it from the network through the POC that each user has with the distributor. The most critical time instant of this simulation is at 4s, since the PV system reduces the generated power and at the same time the users have a peak of absorption.

Third scenario: As a last scenario to consider a temporary fault, the detachment and reconnection of all the three users present in the architecture has been considered. As shown in Fig. 19, the PV system produces a constant power of 29.5kW. The three users, up to 1s, require power equal to their nominal value. In the interval from 1s to 4s, the three users are detached from the U_DC grid, so the power required by the three users is zero. Then, in the interval 4s-6 s, the three users are reconnected to the system, returning to absorb their nominal powers.

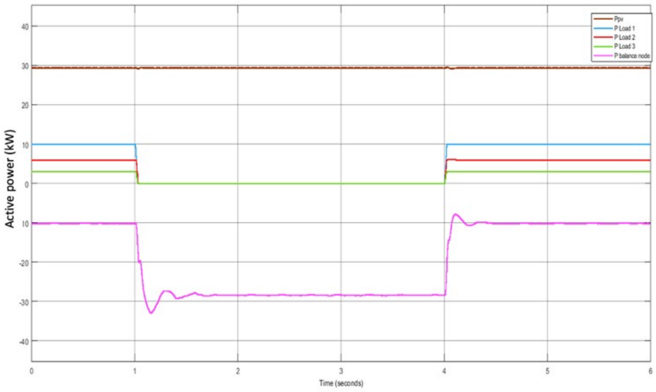

Fig. 19. Power balance of the third scenario

Fig. 19 shows that when all the three users are disconnected, all the power generated by the PV is fed into the AC grid through the 3-ph FEC_BN (pink line). When the users reconnect to the system, at 4s, the power sharing power goes back to the respective loads. As a result, the FEC_BN (pink line) now feeds a power surplus of about 10kW into the AC grid. This simulation confirms how the proposed model can work stably even in the presence of faults on the users.

VII. CONCLUSIONS

The peculiar aspects that constitute the objectives of the realization of the smart grid model suggested in the paper are:

- use of DC systems managed by Open UPQC Shunt Unit in order to increase buildings reliability, power quality, safety [21] and efficiency;
- transition towards the use of the electric vector to exploit on-site aggregate generation from renewable sources and intelligent storage systems;
- creation of an energy community in order to optimize the use of energy resources in a shared way;
- ability to integrate electric vehicle charging systems, providing for a massive diffusion of electric cars in the short to medium term;
- create a robust and resilient energy infrastructure capable of dealing with emergency situations;
- prepare the system to integrate a common heat/electricity generation system ready for the use of high technology and low enthalpy solutions foreseeable in the short term with the redevelopment of buildings and create an energy system based on electricity and therefore with reduced emissions.

A case study of a simplified residential DC microgrid model consisting of a PV system and three users (two 1-ph and one 3-ph) was modelled and analyzed. The case study revealed that the DC microgrid remains stable for the entire duration of the simulations, showing no unexpected situation or critical values. The next step will be to integrate in the simulation the other types of user units described in the previous Sections and verify the stability of the system.

Future studies on the coordination of protections will be also implemented in order to propose a model-improving self-healing schemes when the overall supervisory system falls [22]-[28].

In the end, although the regulatory framework is not yet available for PSM, a DC microgrid, such as the one proposed in this paper, may have some important advantages: such as increasing the energy efficiency of loads by reducing electronic energy conversion, and thanks to the physical exchange of energy the possibility of avoiding AC grid overload and voltage regulation problems that could preclude the connection of other end-users and/or limit the amount of energy exchanged by the AC network.

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