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Power architectures for the integration of photovoltaic generation systems in DC-microgrids

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Abstract

This paper describes a preliminary analysis on the integration of renewable energy systems in smart microgrids. The initial theoretical evaluations are referred to the case study of a laboratory DC microgrid interconnecting: electric mobility, stationary storage systems and renewable energy sources in a smart grid scenario. Specific power architectures for the integration of a 7kWp solar generation system with the considered microgrid are analysed and compared, in terms of efficiency and costs, in order to support the choice and the design of optimal solutions. Modeling and simulations of the related components are carried out in Matlab-Simulink environment in order to evaluate the performance of different embedded maximum power point tracking techniques, working in balanced and unbalanced irradiance conditions for the considered PV generation system. The promising results and the considerations reported in this paper highlight the importance of using the proposed smart power architectures and the related control techniques to support the optimal use of sustainable energy generation systems.

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Keywords: smart grids; renewable energy sources; electric vehicles; energy storage systems

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1. Introduction

The depletion of oil resources, the air pollution and climate changes related to transport and energy generation sectors are becoming key issues to be dealt with in the next future. In particular, despite the various EURO emission standards for thermal engine have recently caused a relevant reduction in pollutant emissions related to traditional

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road vehicles, further technological improvements are still required in order to meet the short and long-term decarbonization goals set by European Union directives [1]. In this context, the smart grid concept plays an important role as it is expected to support the electrification of transport sector with the efficient integration of stationary energy storage systems and renewable energy sources.

In particular, smart grid scenario has been widely investigated in the literature as a mean to enhance power generation and distribution networks, by obtaining more flexibility, efficiency, reliability and security, through the proper integration of power electronics and advanced ICT devices [2]. This scenario would make it possible to charge electric and plug-in hybrid vehicles (both also known with the acronym PEVs) with a relevant contribution of clean electric energy coming from renewable sources, avoiding the increase in fossil fuel consumptions for PEV charging operations through traditional power plants. In addition, vehicle battery packs connected to the smart grid could be used as auxiliary storage systems, supporting the natural fluctuations of the electric power produced by renewable sources, such as wind and solar. In this regard, [3] and [4] analyze and describe the advantages of using a large number of vehicles, grouped on the basis of different aggregative schemes and controlled through multi-agent logics, to support the main grid with ancillary services by means of the well-known vehicle to grid (V2G) and Grid to Vehicle (G2V) services. It is clear that the management of such a complex scenario represents an engaging technical challenge, as it will involve simultaneous control of a great number of demand-response services and low power unpredictable distributed generating units, which can be dislocated in a wide geographical area.

Starting from the above considerations, various papers reported in the scientific literature have mainly focused the attention on the optimal integration of renewable energy sources and sustainable mobility in a smart grid scenario. In particular, a first set of papers analyses and proposes power architectures to be used for the optimal design of smart PEV charging stations and renewable energy sources integration. In this regard, a performance comparisons between AC and DC microgrid is reported in [5] in terms of costs and efficiency, with particular reference to the proper integration of distributed energy sources. In authors [6] a review of power architectures for grid integration of renewable energy systems are analysed, with specific focus on modular multilevel converters. Another set of papers mainly refers to the evaluation and analysis of energy management strategies to be used in a smart grid context. In this regard, in [7], authors propose smart vehicle-to-grid and grid-to-vehicle strategies for a large population of PEVs, based on total daily PEV charging costs and Peak-to Average power Ratio (PAR). Energy management strategies for the dynamic control of PV generation systems are proposed and validated in [8], with particular reference to the use hybrid storage systems composed of high power and high energy units to support the integration of renewable sources.

The above-analyzed papers are mainly based on technical evaluations based on simulation activities and validated through small scale prototypes. For this reason, the main contribution of this paper is to present theoretical considerations for the optimal integration of renewable energy sources with a DC-microgrid, representative of an innovative smart urban district. Those considerations are carried out with reference to the case study of a real laboratory DC-microgrid, which integrates electric mobility, stationary storage systems and solar generation systems. In this regard, the considered case study is presented and described in section 2, with details on the main components. Then, Section 3 analyses and compares possible power architectures for the efficient integration of solar generation systems with the DC microgrid. Modelling and simulation results are described in Section 4.

In conclusion, the considerations reported in this paper and the obtained results represent a first step towards their validation through experimental activities related to the smart and efficient integration of a PV generation system with the considered DC microgrid.

2. Background and Case Study

As introduced in the previous paragraph, smart grids are characterized by specific requirements to be satisfied through proper energy management strategies, supported by the integration of advanced metering and control systems based on ICT devices. In this context, the adoption of microgrid architectures represents an interesting solution, which is characterized by lower cost and higher efficiency, in comparison with corrective interventions on the existing conventional AC grids. In fact, by means of multi-agent control schemes, microgrids can be managed by the DSO as a single high power dispatchable unit, which can work either as a load or as a generator (virtual power plant), providing ancillary services for the main grid. In addition, the integration of low power unpredictable energy sources, such as solar and wind energy, can be efficiently managed within the microgrid, by means of local control systems [9]. Finally, on the basis of the required operative conditions, microgrids have the possibility to work either in grid-connected mode, with continuous power exchange between the microgrid and the electric network, or in islanding mode, with the electric power supplied only by the distributed generation units included in the microgrid. This last operative mode is particularly suitable for restricted rural areas, where the connection with the main electric network is not convenient from the economical point of view [5].

A microgrid architecture is generally based on either AC or DC common bus, which allows the electric power exchange among the main microgrid components. In this regard, AC microgrid systems present different advantages in terms of cost and complexity as their operations are based on the existing AC standards related to power quality, frequency/voltage levels and protections. As a consequence, AC microgrids can be conveniently used for traditional applications related to industrial loads and AC distributed generation systems (e.g. wind turbines and micro-cogeneration systems). On the other hand, the expected large scale diffusion for the next years of plug-in electric vehicles, stationary storage units and solar generation systems justifies the growing interest of the scientific literature towards the use of DC microgrids. In fact, the above components could be easily integrated with the DC bus of the microgrid by means of high efficiency DC/DC converters, avoiding the use of DC/AC conversion stages. In this regard, the performance of DC microgrids, in applications related to power supply for critical loads in commercial buildings, electronics factories and hospitals have been investigated in [10] and [11] with good results in terms of power quality and reliability.

On the basis of the above considerations, this paper refers to the case study of a laboratory DC-microgrid, representative of a smart urban district, which integrates the electric mobility with stationary storage systems and DC loads. A functional scheme of the considered microgrid is reported in Fig. 1.

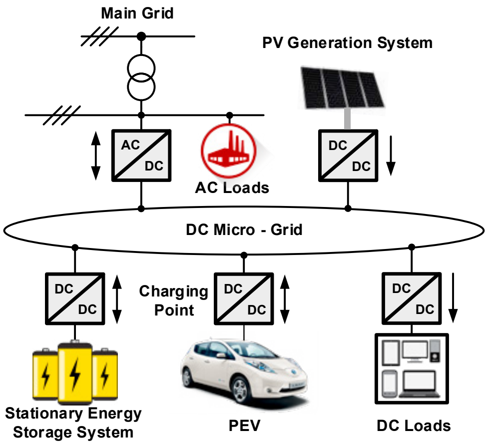

Fig. 1. Functional scheme of the considered DC microgrid.

In particular, the proposed architecture is based on a DC bus, which is obtained by means of a bidirectional AC/DC converter connected to the low voltage three-phase AC grid. This converter, also known as grid tied converter (or Active Front End), allows the power exchange between the microgrid and the main grid, performing at the same time active and reactive power control based on synchronous *dq-reference* frame control scheme. The use of bidirectional DC/DC converters allows charging/discharging operations of stationary energy storage systems and the smart management of PEVs, which can be charged, by using the energy coming from the microgrid, and discharged to implement V2G services. In this case, it is clear that also industrial loads, reported on the AC side of the grid tied converter, can take advantage of the power exchange with the considered DC microgrid. In addition, a PV field is installed near the microgrid with the aim of increasing the power contribution coming from clean renewable energy sources, during the main operative conditions of the microgrid. The PV field is composed of 32 PV modules, realizing 4 strings connected in parallel, with an overall maximum power of about 6.2 kWp. The PV modules are based on Heterojunction with Intrinsic Thin layer (HIT) technology which allows reaching cell conversion efficiency values up to 19% under standard test conditions [12].

More details and characteristics of the above described microgrid can be found in [13], where the authors, starting from the same architecture, have focused the attention on energy management strategies to support fast charging operations of PEV by reducing power requirement for the main grids through the use of the electric power coming from energy storage buffers. The optimal integration of PEVs has been analyzed by the authors in [14], with a comparison and review of a variety of power converter architectures for the smart management of vehicle charging/discharging operations.

For the above architecture, the optimal integration of solar generation systems through DC/DC conversion stages is still considered an open issue. In fact, the recent diffusion of PV fields has been supported by power architectures based on the use of one single DC/AC converter, able to optimize the electric power produced by solar systems through MPPT algorithms. On the other hand, the recent development of DC microgrids and modular power converters open the way for new smart distributed solutions, which require a specific analysis and comparison in order to carry out a proper choice on the basis of the considered application.

3. Power Architectures for the Integration of PV fields

Grid-tied converter topologies for photovoltaic systems are generally classified as a function of the grid voltage level, the plant peak power and the working principle. In this paper, the attention is focused on the most common topologies adopted for low voltage and low power systems (under 50 kW) [15]. In particular, as reported in Table 1, power architectures for integration of PV fields can be categorized in four main groups on the basis of galvanic insulation and maximum power point tracking (MPPT) working principle [16].

Table 1. Main classification for low power and low voltage PV architectures.

	CENTRALIZED MPPT	DISTRIBUTED MPPT
NOT ISOLATED	• 1 stage • 2 stage	• series PV connection – 2 stage • parallel PV connection – 2 stage • direct DC/AC conversion – 1 stage
ISOLATED	• LF isolation – 1 stage • LF/HF isolation – 2 stage	• LF/HF isolation – series PV connection – 2 stage • LF/HF isolation– parallel PV connection – 2 stage • HF isolation (PV module level) – direct DC/AC conversion – 1 stage

The galvanic isolation is required for grounded systems and is generally obtained with low frequency (LF) transformer connected to the PCC or inside the DC/DC converter with high frequency (HF) transformer. The HF transformer is generally more convenient than to the LF transformer due to the reduced costs, volume and weight. The conversion stage numbers impact over costs, converter efficiency and modularity. The single stage converter is characterized by the highest efficiency and reduced costs, which is related to the low number of components. On the other hand this configuration presents relevant drawbacks in terms of minimum input voltage and harmonic impact [18]-[20]. The multistage architectures are based on an internal regulated DC bus and have the advantage to allow the system to work also with small irradiance values.

As reported in Table 1, MPPT control can be executed with centralized or distributed power architectures. Those architectures are schematically reported in Fig. 2. In particular, with centralized MPPT (CMPPT), all photovoltaic modules (PV) are connected in series/parallel and the MPPT control is obtained with the use of only one single/double stage DC/AC converter (Fig. 2.a). With the distributed MPPT (DMPPT) architecture the MPPT control is performed at string level, with the use of one DC/AC converter for each sting (Fig. 2b). The strings can also be connected in parallels by means of a common DC bus (Fig. 2c). In this case, the DC bus is supplied by each string through specific DC/DC converters realizing the DMPPT control, whereas the DC/AC conversion stage is obtained through the use of a DC/AC converter connected on the Point of Common Coupling (PCC). The DMPPT is based on the idea that different strings may have different optimal operative conditions, whereas single strings are generally composed with panels with similar irradiance and temperature values. For this reason, the DMPPT aims to track maximum power for each string. The DMPPT can be also realized by controlling single PV modules (Fig. 1d) in order to reach the optimal operating point for each module. However, at the present state of technology, this solution involves a relevant increase in the cost of the overall system. Other solutions can be considered as a hybrid of the above mentioned techniques and are generally based on the use of modular multilevel converters [3]. For example, some researchers are studying methods to locally balance the PV power reducing the mismatching effects.

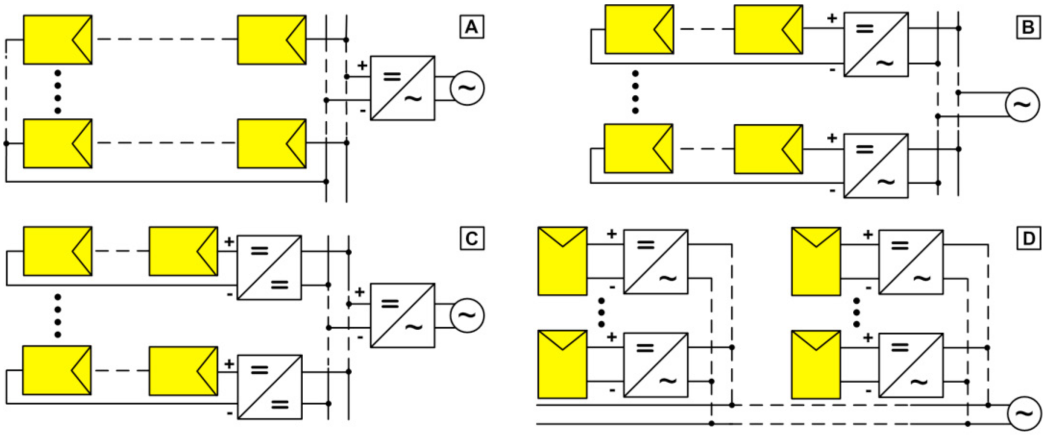

Fig. 2. Power architectures for PV integration: (A) direct DC/AC conversion with CMPPT, (B) direct DC/AC conversion with multi-string input and sting DMPPT, (C) double stage conversion with multi-string input and string DMMPT, (D) direct DC/AC and DMPPT for each PV panel.

At the present state of technology, the CMPPT are the most adopted technique, since it is characterized by reduced costs. On the other hand, this solution generally involves a relevant reduction of efficiency in case of mismatching. The DMPPT presents higher costs but increases the overall power extraction from the PV power plant, with great efficiency advantages over long time usage.

4. Modelling and simulation results

The modeling of the proposed microgrid, with the related preliminary results, has been already reported in [21] by the same authors of this paper. The models include the DC/AC converter, the DC/DC battery charger, the photovoltaic CMPPT model and the proposed energy management strategy. The large signal models have been adopted in order to reproduce low frequency dynamics (inside the control bandwidth) and remove the harmonic content at the switching frequency. This operating mode allows accelerating the simulations with a good accuracy at the system integration level. In particular, fixing the attention on the DC/AC converter, also called active front end (AFE), the adopted modelling approach consists in replacing the switching components with controlled voltage and current sources [21]. Similar modelling approach has been adopted for the DC/DC converter. The PV field has been modelled through a near steady-state approach and CMPPT has been considered as maximum power point tracking algorithm.

Starting from the above considerations, in this paper two different DMPPT algorithms, working at string and PV panel levels, have been simulated and compared with the traditional CMPPT technique. For these evaluations the model of PV panels has been further improved on the basis of the data coming from the datasheets of the manufacturer, which take into account the effects of the irradiance on PV panel current-voltage characteristics. These comparisons are based on the simplifying hypothesis of the ideal efficacy of MPPT algorithms. In particular, the CMPPT algorithm extracts the total power of the PV field by imposing the same operative voltage for all the strings, with all the panels of each string working at the same current level. In this way, some strings can work in non-optimal operative conditions as their voltage is imposed by the CMPPT. The *string DMPPT* maximizes the power supplied by each string by imposing the optimal current-voltage operative conditions at string level. In this case, the DMPPT is independently executed for each string. The *panel DMPPT* technique is based on the use of independent distributed DC/DC converters for each PV panel. In this case, the total maximum power is the sum of the maximum power contributions of all the PV panels.

In order to carry out a detailed comparison among the above MPPT techniques, two different case studies can be considered. In the first case study, all the PV panels work with the same level of irradiance, which is fixed at 600 W/m^2. In the second case study, an uneven distribution of irradiance is considered with different values for each panel. The considered values of irradiance for this last case study are reported in Fig. 3.

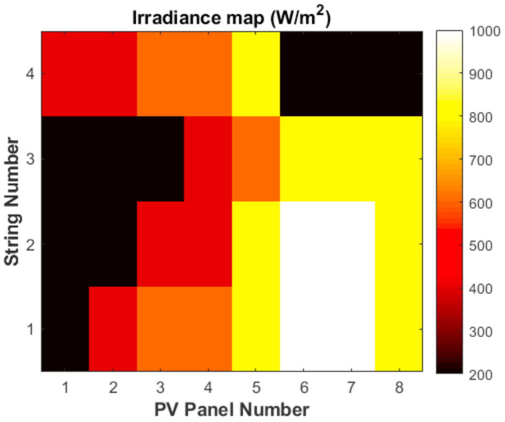

Fig. 3. Case Study 2: PV field with uneven irradiance. Each coloured cell represents the mean irradiance for a PV panel.

It is clear that, in the first case, the centralized MPPT is more convenient as it is characterized by lower cost and equal results in terms of power extraction in comparison with the other techniques. More interesting results are obtained for the second case study, since it is characterized by different operating conditions for each PV panel. In this case, the *string DMPPT* forces all the PV panels to work at the same current level, following the string maximum power point. Therefore, some of the PV panels will be forced to work far from their optimal operating point. The results obtained for the different strings are shown in Fig. 4 A, where the maximum power of each string is reported as a function of the string current value. With the *panel DMMPT* each panel works at its maximum power point. In this case, the string power is equal to the sum of the power extracted from each PV module. The results reported in Fig. 4 B shows the maximum power obtained for each PV module under irradiance map considered in Fig. 3.

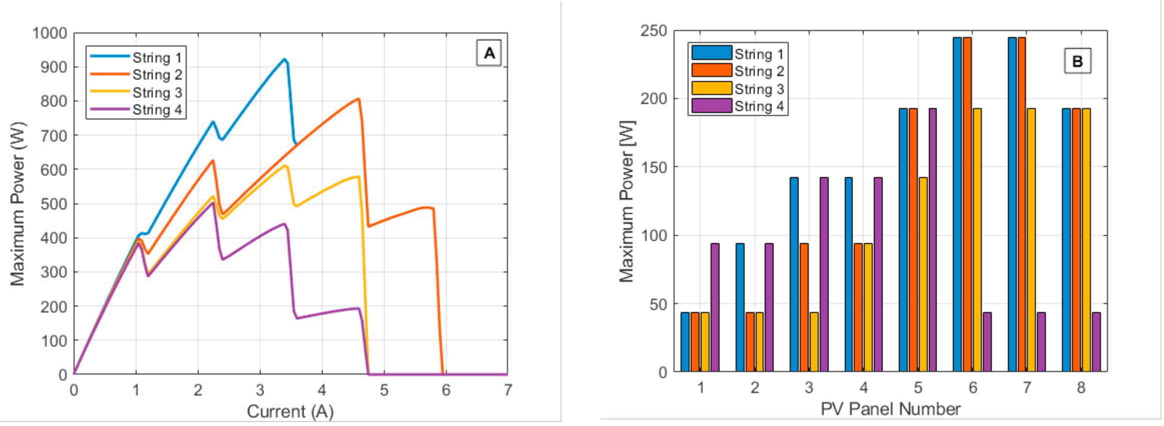

Fig. 4. S*tring DMPPT* (A) and *panel DMPPT*(B)

By comparing the three MPPT techniques different results can be obtained on the basis of the considered solar irradiance distribution as shown in Fig. 5. In fact, for the first case study, with uniform irradiance of 600 W/m2, the three MPPT techniques give the same results, with a maximum power of about 4.5 kW. In this case, the production efficiency is exactly the same and the choice can be based on cost considerations. For the second case study, based on mismatching due to the uneven irradiance, the CMPPT reaches a maximum power of about 2.6 kW, whereas the string DMPPT algorithm reaches a power of about 2.85 kW. The best performance is shown by the *panel DMPPT* with one converter for each PV panel, which reaches a maximum power of about 4.2 kW, increasing the extracted power respectively of 38% and 32% in comparison with the other MPPT techniques.

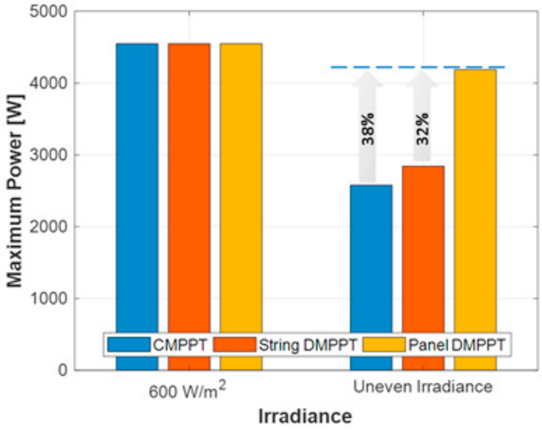

Fig. 5. Comparison among different MPPT techniques for Case Study 1 and 2.

At the end of this analysis it is necessary to clarify that the second case study is considered as a worst case with a large area of PV panels covered by shadows, as clearly shown in Fig. 3. This extreme operating condition limits the performance of CMPPT and *string DMPPT* techniques. In fact, by increasing the extracted power, some PV panels are automatically excluded through their bypass diodes, and the overall voltage drops, reducing the overall resulting power. In this case, the MPPT technique find the best compromise between the number of active PV panels and generated current, maximizing the extracted power of the PV plant/string.

The above theoretical results suggest that, in case of frequent uneven irradiance conditions, MPPT techniques working at string or PV level can involve a large number of advantages in comparison with centralized MPPT techniques. On the other hand, advanced solutions based on the reduction in number of the switching devices could help reducing the costs related to distributed MPPT techniques.

5. Conclusions

In this paper, preliminary evaluations related to the optimal integration of a 7 kW peak power PV field with a laboratory DC microgrid supporting the electric mobility have been carried out. In this regards, concentrated and distributed power architectures have been compared and proposed, with particular focus on topologies and allowable maximum power point tracking (MPPT) techniques. The considered techniques have been compared for two different operative conditions, respectively characterized by balanced and unbalanced irradiance distribution for the analysed PV field.

Simulation results have shown the better performance of distributed MPPT techniques under unbalanced irradiance conditions with an increasing of the maximum generated power up to 38%, obtained with the DMPPT control at panel level.

The evaluations reported in this paper highlight the importance of designing proper power architectures and control techniques on the basis of the PV field expected operative conditions. In conclusion, the performance highlighted in this paper suggests future works on the experimental investigations of possible solutions to implement MPPT control at panel level with low cost components.

6. Acknowledgments

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