A Review on Vehicle-Integrated Photovoltaic Panels

Marwa Ben Said-Romdhane and Sondes Skander-Mustapha

Abstract Vehicular transport is considered as the most important origin of air pollution in cities. However, despite the commercial growing achievement of electric vehicles, there had been no detectable reduction in energy consumption and CO_2 emission, at least in a short-term scenario. Solar vehicles can be considered as an alternative to this problem. Indeed, they are considered as a restricted, but promising technology and they are slowly gaining the interest of several automotive companies and researchers. This is due to several factors such as the rapid rise of photovoltaic technologies due to decreasing cost and improvement of their efficiency in addition to the increasing development of electric vehicles considering their environmental friendliness and their reduced dependence on fossil fuels. This manuscript highlights various aspects, challenges, and problems for solar vehicle development. In fact, this chapter widely reviews vehicle-integrated photovoltaic panels where different power train architectures are highlighted. In addition, a review of different power structures of vehicle-integrated PV is exposed. Also, energy storage system solutions are detailed with possible recommendations. Furthermore, energy management systems for vehicle-integrated photovoltaic panels are discussed and evaluated.

Keywords Vehicle-integrated PV · Photovoltaic technologies · Energy storage system · Power converters · Energy management system

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1 Introduction

The automotive sector has been developed and prospered thanks to abundant, cheap, and energy-efficient oil. For more than a century, its domination was unchallenged. Likewise, for decades, the rise in the power of vehicles was made without taking into account the environmental dimension [1, 2].

Then the tide turned. The time of scarcity and the high price of raw materials has arrived, due to an uninterrupted rise in world demand and the realization that reserves may be depleted. The time to take environmental protection into account has also come, putting oil and its discharges on the spot [3, 4, 5].

It was, therefore, necessary to innovate and find solutions. Subject to increasingly stringent regulations, manufacturers have improved the performance of thermal vehicles, reducing fuel consumption and polluting emissions. At the same time, the automotive industry has invested in developing new engines like hybrid cars and 100% electric cars [2, 6, 7].

Since the invention of photovoltaic cells, engineers around the world have started to explore various prototypes of solar cars. These electric cars use batteries that can be recharged by natural light. When there is insufficient natural light, the car uses the energy stored in the batteries [8]. They are based on the concept that an integrated PV system supplies an electric power train. The electrical energy extracted from solar energy is transformed on motion, so there is no need for the combustion process [7, 9, 10, 11].

One of the biggest hurdles that need to be addressed is the current power of cars, which is limited by the efficiency of photovoltaic cells. The ability of batteries to store a large amount of energy causes also problems. For the vast majority of solar cars, manufacturers prefer to circumvent these problems by reducing the energy requirements of the vehicles, using lightweight materials to reduce weight, as well as an aerodynamic design to achieve less air resistance when in motion [12, 13, 14, 15].

This chapter highlights various aspects, challenges, and problems for solar vehicle development. It is organized as follows, first, in Sect. 2, the electrical vehicle's classification and terminologies are presented. Then, in Sect. 3, the challenges of solar vehicles including emission reduction, as well as the problems of the electric vehicle charging station are detailed. Section 4 present the issues that affect the solar vehicle's performance. These issues are mainly the fast irradiance variability and partial shading of the PV cells, the limited surface area for PV panels, the operating requirements, and the driving constraints in urban traffic. Section 5 describes the vehicle-integrated PV powertrain architecture which is mainly divided into two groups: all-electric architecture and hybrid electric architecture. The most used hybrid electric vehicles are parallel hybrid, series hybrid, series-parallel hybrid, and complex hybrid. Section 6 presents the global power structure of the vehicle's integrated photovoltaic panels. It includes the electric vehicle drives, the power converters in addition to the energy storage system. Finally, Sect. 7 reviews the control strategies and the energy management systems for electric vehicle applications.

2 Electrical Vehicles Classification and Terminologies

The vehicle-integrated PV (VIPV) are vehicles that incorporate PV cells on the roof and body of the vehicle with additional power converters to charge batteries. The PV system is considered as the main source and batteries as an auxiliary source. Based on the classification of electric vehicles (EV) presented in [7], a classification of Vehicle-integrated PV is presented in Fig. 1. Indeed, VIPV can be classified into two groups: hybrid electric vehicles (HEV) and all-electric vehicles (AEV).

- The group of HEV incorporates several propulsion motors (internal combustion and electrical motors [16]) and includes plug-in hybrid electric vehicles (PHEV) which incorporate batteries and plugs for external charging and Hydrogen fuel cell plug-in hybrid vehicles.
- The group of AEV comprises fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV).

PV integrated with EV can be used in varying degrees depending on installation characteristics; it can be just useful for supplying vehicle auxiliary devices such as fan, audio players, etc., or feeding air conditioning systems. But the final object is to charge batteries, this can be done while parking or driving as exposed in Fig. 2 [7, 12, 16]. There are several challenges of VIPV, such as CO_2 emission reduction, no longer need batteries charging stations, etc. But VIPV also faces several problems such as the fast irradiance variability and partial shading of the PV cells, the limited surface area for PV panels, as will be detailed in the next section.

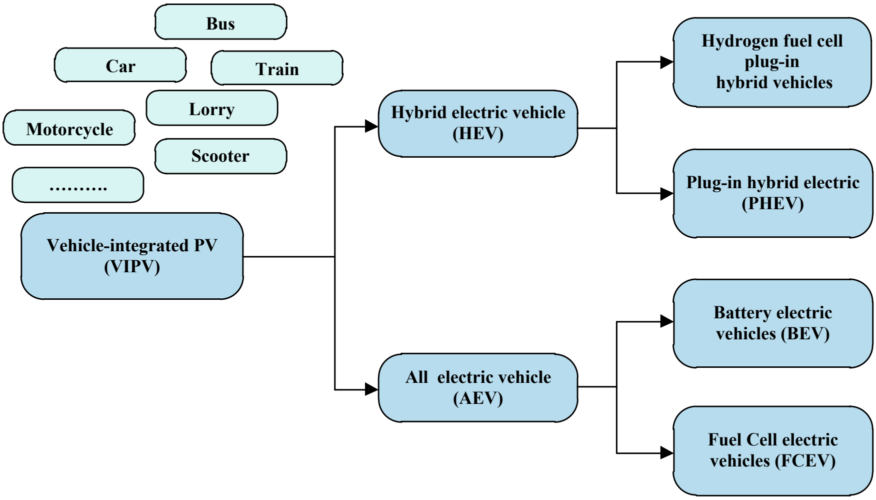

Fig. 1 Classification of vehicle-integrated PV

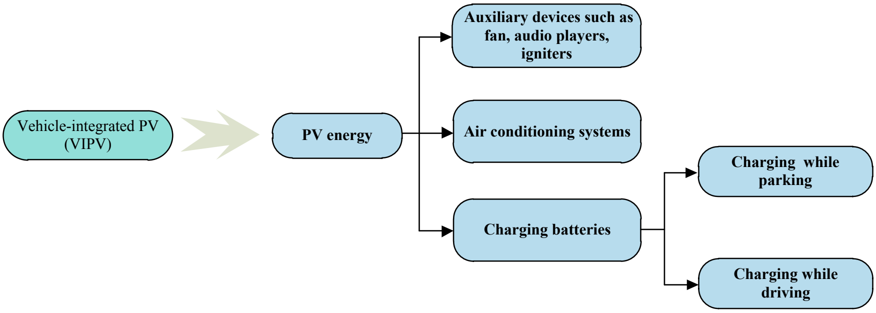

Fig. 2 Use of PV energy in VIPV

3 Challenges of Solar Vehicles

3.1 Emissions Reduction

This challenge concerns environmental pollution taking into account the vehicle's CO_2 emission. In 2015, the transport sector has delivered about 22.9% of total world CO_2 emission [17], in 2018, about 24% [18], and with current circumstances, it is expected to increase to 60% by 2050 [18]. EVs are developed to take the place of the conventional ones gradually, due to their energy-savings and emissions reduction [3]. However, despite their growing commercial achievement, there had been no detectable reduction in CO_2 emission, at least in a short-term scenario [19]. The VIPV presents a long term solution for this issue [20]. The results presented in [21] confirm that the combination generator battery diminishes the environmental effect of the medium-sized ship, and in [4] the authors confirm the necessity to introduce renewable energy to achieve the actual reduction of CO_2.

3.2 Bypassing the Problems of the EV Charging Station

EV charging stations present several problems. Indeed, they amplify the electric load. Consequently, potentially intensify the peak load or produce other peaks. Moreover, EV charging stations can boost load side uncertainties, overload distribution grid devices which reduce their lifetime, augment power loss, and induce important voltage deviations compared to their nominal value [5, 22, 23, 24]. Integrating PV panels in the vehicle will allow the charging battery autonomously. This means no longer needing charging stations or at least reducing their use as much as possible.

4 Issues Affecting Solar Vehicles Performance

4.1 The Fast Irradiance Variability and Partial Shading of the PV Cells

The fact that vehicles are in continuous motion generates variable irradiance, mainly caused by the partial shading of the photovoltaic panels [6] due to the structures close to the road such as poles, chimneys, raised buildings, etc. Consequently, a large changeability in the DC voltage of the solar panel is recorded and PV array efficiency is decreased [8, 16].

4.2 Limited Surface Area for PV Panels

The variable solar irradiance added to the vehicle's curved shape has a big influence on the resulting energy. To overcome this problem, it is imperative to measure and model solar irradiance for the vehicle. Some studies suggest applying the correction of the curved surface of the PV modules in order to take into account the random distribution of shading things and vehicle direction. In [13], the authors propose to install five pyranometers in different axes during one year to deduce the solar irradiance model.

4.3 Operating Requirements

The weight, cooling process, and power conversion are fundamental points to be considered when integrating PV structure in vehicles. Alternative carbon-fiber-reinforced plastic structures were investigated in [25] by finite elements using static and modal analyses, to evaluate numerous proposed approaches considering these criteria: natural frequencies, deformations, flexural stiffness, torsional stiffness, and heat exchange plane. A roof section was tested to verify the theoretical model. An important enhancement compared to the pre-existing solar roof was noticed. Light composites are a good option for solar cars, because the lighter the vehicle, the less energy is used to overcome inertia [26]. In [27, 28, 29], authors investigate a composite monocoque chassis in order to ensure lightweight solar car, for example, in [27] the authors propose an iterative finite element analysis process.

4.4 Driving Constraints in Urban Traffic

Urban driving is characterized by transient traffic situations. Which induces frequent starts and stops [30, 31]. Consequently, the electric vehicle presents a significantly random and fluctuant current. The element most concerned with this problem is the storage item. Indeed, it must be able to follow these fluctuations and adapt to this behavior [32, 33]. This problem is, therefore, not specific to VIPV but it concerns EV in general. But it must be taken into account for VIPV especially if the battery charge source is limited to PV modules.

5 Vehicle-Integrated PV Powertrain Architectures

5.1 All-Electric Vehicle

The all-electric VIPV powertrain architecture is presented in Fig. 3. As it is shown in this figure, this kind of vehicle employs electric power as the only source to move the vehicle.

5.2 Hybrid Electric Vehicle

Nowadays, the most common hybrid VIPV architecture includes the electric motor and the internal combustion engines (ICE). The combination of these energy converters allows to have several possible configurations of the powertrain. The most used ones are parallel hybrid, series hybrid, series-parallel hybrid, and complex hybrid as shown in Fig. 4 [34–37].

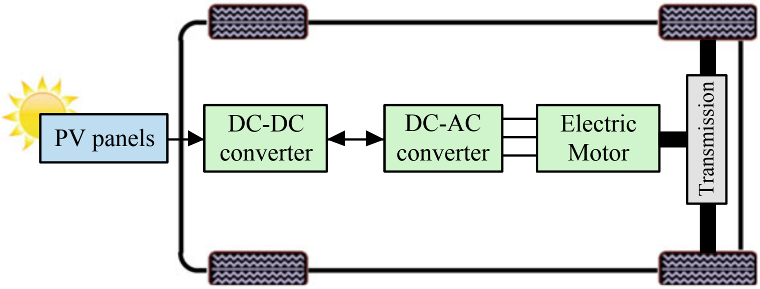

Fig. 3 All-electric vehicle powertrain architecture

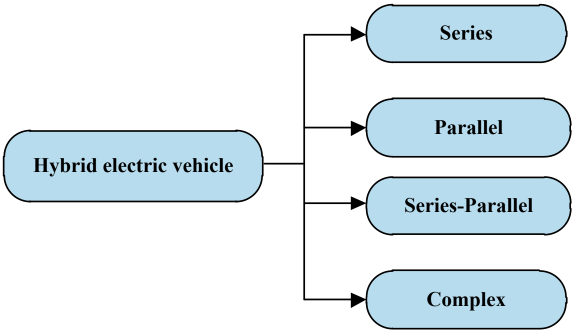

Fig. 4 Hybrid VIPV powertrain architecture classification

5.2.1 Series Hybrid VIPV

The series hybrid VIPV (SHVIPV) powertrain configuration (Fig. 5) is composed of an ICE, a generator, and an electric motor [38]. In this configuration, the SHVIPV is powered solely by the electric motor which can be supplied either from the battery or from the ICE generator unit, or even both. In this case, the ICE can't directly power the vehicle since it has no mechanical link with the traction load. The electric current produced by the ICE can be either provided to the electric motor or stored in the batteries. In case more power is needed, the electric motor acquires energy from both the ICE and the batteries. The advantages of the series configuration are: (i) Increased flexibility due to no common interaction between ICE and electrical motor [16]; (ii) efficiency in driving cycles that require frequent stops and start [39]. The shortcomings of the SHVIPV powertrain configurations are: (i) high losses [16]; (ii) expensive configuration due to the need for a generator [39, 40].

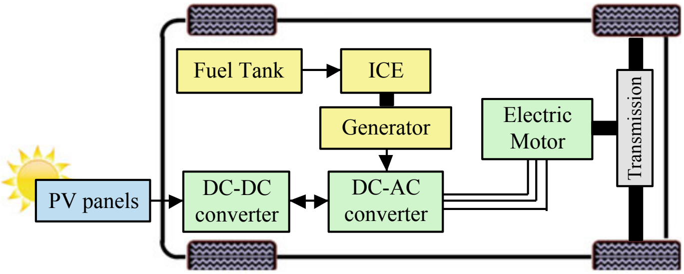

Fig. 5 Series hybrid VIPV powertrain architecture

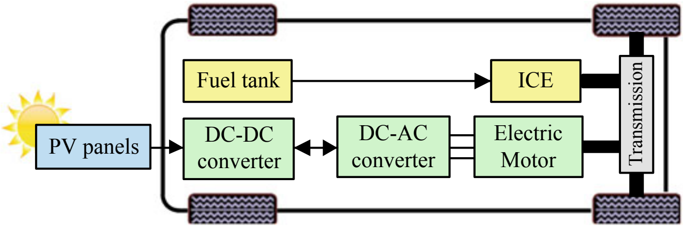

Fig. 6 Parallel hybrid VIPV powertrain architecture

5.2.2 Parallel Hybrid VIPV

The parallel hybrid powertrain configuration (Fig. 6) is composed of an ICE and an electric motor [7, 40]. The electric motor and the ICE are coupled together by a mechanical device. Consequently, during low traction power demand, they can individually propel the vehicle and during high power demand, they jointly propel it. Moreover, this configuration has an electric traction motor that rolls the wheels and can recover part of the braking energy, in order to recharge the batteries (regenerative braking) or to help the ICE in the conditions of acceleration. This configuration makes it possible to reduce the size of the ICE and the electric motor. This helps reduce consumption while maintaining good performance [36].

5.2.3 Series-Parallel Hybrid VIPV

The series-parallel hybrid powertrain architecture (Fig. 7) joins the advantages of both series and parallel architectures. In fact, the ICE can supply the electrical motor and thanks to a generator it can also charge the battery. Although this configuration combines the advantages of series and parallel configurations, it is relatively expensive and more complicated and requires a very complex control system [7, 39, 41].

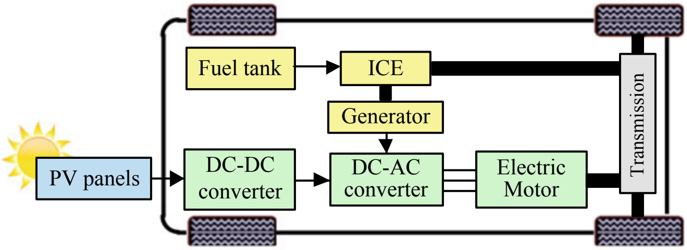

Fig. 7 Series-parallel hybrid VIPV powertrain architecture

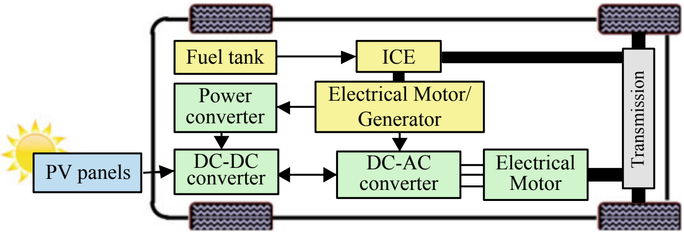

Fig. 8 Complex hybrid VIPV powertrain architecture

5.2.4 Complex Hybrid VIPV

The complex hybrid powertrain configuration (Fig. 8) is similar to a series-parallel powertrain configuration. The difference is that it uses more complicated architectures of many motors and generators. This makes this configuration more controllable and reliable than the other configurations [7, 39].

6 Global Power Structure

6.1 Electric Vehicle Drives

The most essential component in the Electric vehicle is, of course, the motor. Its fundamental characteristics are as follows [42]:

- High torque and power density to pull the load;
- Large speed range;
- High efficiency for a wide variation of torque and speed;
- Extensive ability to work in constant-power;
- Wide ability of the torque for electric startup and raised area climbing;
- Elevated alternating overload ability for overtaking;
- Small acoustic noise

Many classifications of EV drives are given in literature [2, 37, 42, 43]. The main two groups are AC and DC motors including a large variety as Brushless DC Motor (BLDCM) [6, 20, 44, 45], regenerative brushless DC motor [9], permanent magnet brushless DC motor drives (PMBDCM) [20, 44], Induction motor (IM) [2], switched reluctance motors (SRM) [45], permanent magnet synchronous motors (PMSM) [45], and permanent magnet hybrid motor drives [2]. Among these, PMSM is appropriate in terms of power density, reliability, and efficiency [20]. BLDCM is frequently included in EV due to their elevated efficiency and power density in addition to their great starting torque, and their better performance regarding noise [45]. As to SRM, they are considered as an attractive option due to their reduced material costs, high efficiency, and simple control algorithm [46]. The structures integrating two types of motors are also present on the market, such as HEV driven by an Internal Combustion Engine and a PMSM for this structure PV system and energy storage devices supply the PMSM [47]. Furthermore, research regarding EV drives is very diverse. In [48], the authors focus on the EV driving range parameters. In [49], the authors investigate the use of just one electric machine which switches between the two modes: motor and generator. In [50], the issue is to resolve the straight-line driving stability question.

6.2 Power Converter Structures

Highly developed technology of power converters has an important impact on VIPV advancement in terms of energy-saving and control efficiency. The general configuration of VIPV incorporates two major power converters units which are DC-DC and DC-AC converters. In fact, AC motors used in VIPV are fed by DC-AC converters which are fed by DC-DC converters. Figure 9 presents a classification of the DC-AC and DC-DC power converters integrated with the VIPV.

6.2.1 DC-AC Converter Topologies

The bidirectional DC-AC converter is an essential element for VIPV. It is used to convert the DC power from the supercapacitors, the fuel cell, the battery, or their combination into AC power that will be provided to the electric motor. The most used DC-AC converters topologies in VIPV are impedance source converter (ZSI), current source inverter (CSI), and voltage source inverter (VSI). The ZSI is considered

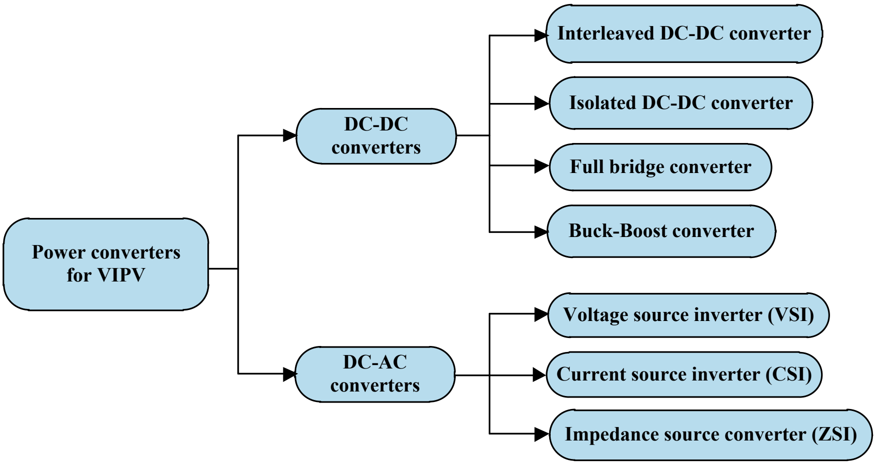

Fig. 9 Vehicle-integrated PV power converters classification

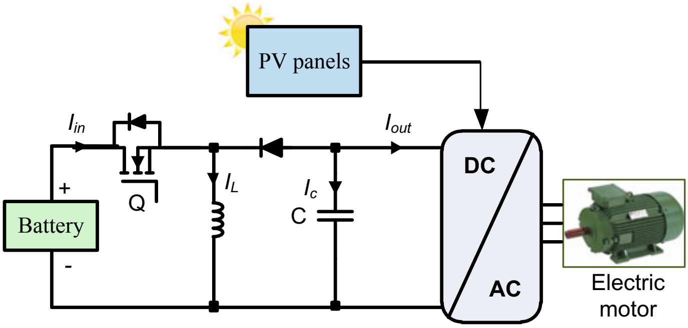

Fig. 10 DC-DC buck-boost converter

to be one of the most promising power electronics converter topologies suitable for motor drive applications. For VIPV, the CSI is employed for the speed control of AC motors, and the VSI is characterized by its multiple motor controls, as well as its good speed range [2, 10].

6.2.2 DC-DC Converter Topologies

The different VIPV powertrain architectures include at least one DC-DC converter. This converter is employed in order to interface between the supercapacitors, the fuel cell, the battery, or their combination to the DC-link. This converter is an electric circuit used to convert a source of direct current (DC) from one voltage level to another. It can be unidirectional or bidirectional. The bidirectional DC-DC converter is very useful for vehicles mainly in regenerative braking since it can move power in either direction. For VIPV, several types of DC-DC converters have been proposed in the literature. Among which, we can cite: boost, buck, full-bridge, isolated DC-DC converter, interleaved DC-DC converter, etc. [10, 51].

Buck-Boost Converter

A buck-Boost converter (Fig. 10) is a power converter which produces a DC voltage that can be either higher or lower than the input voltage [52, 53].

Full Bridge Converter

The full-bridge converter (Fig. 11) is composed of three stages: a DC-AC converter, a high-frequency transformer, and an AC-DC converter [52, 54]. This converter is employed to overcome the drawbacks of the boost converter which are mainly the

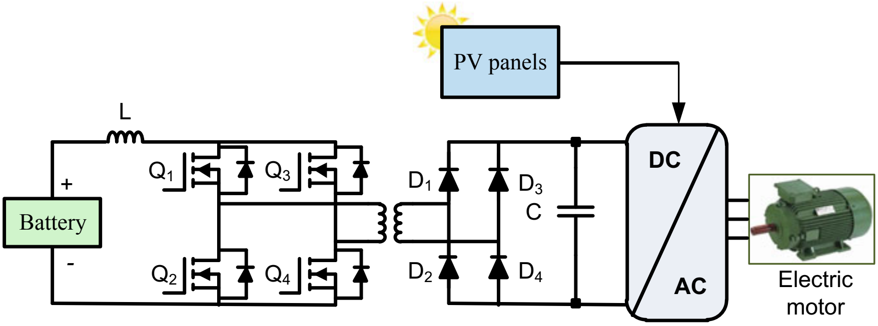

Fig. 11 Full bridge converter

high voltage and current ripples, no electrical isolation, as well as the great weight and volume [55–57].

Isolated DC-DC Converter

In this converter, a high-frequency transformer is employed in order to ensure that the output is completely isolated from the input [52, 58, 59]. Many studies propose this converter for electrical vehicle applications. In [60], a high-frequency isolated bidirectional DC-DC converter is suggested. The proposed converter is based on the grouping of an H-bridge, a three-level half-bridge, and a three-phase full-bridge topology, the voltage rise from 24 V DC to 144 V DC. In [61], the authors suggest using GaN in an isolated step-down DC-DC converter, and the voltage rises from 13.6 to 200 V.

Interleaved DC-DC Converter

The interleaved DC-DC converter (Fig. 12) is a good option to interface the low voltage of the ESS with the DC high voltage of the VIPV. It allows reducing voltage stress, as well as the size of the input filter. However, its elevated number of magnetic cores presents an obstacle for VIPV application given the size constraints. Some researchers suggest a modified configuration of this converter to overcome this problem, for example, in [62], an integrated interleaved ultra-high step-up DC-DC converter incorporating dual coupled-inductors is proposed. In literature, many configurations of the interleaved DC-DC converter are proposed. In [63], the authors propose a system based on three-phase interleaved topology, and in [64], a two legs topology is proposed.

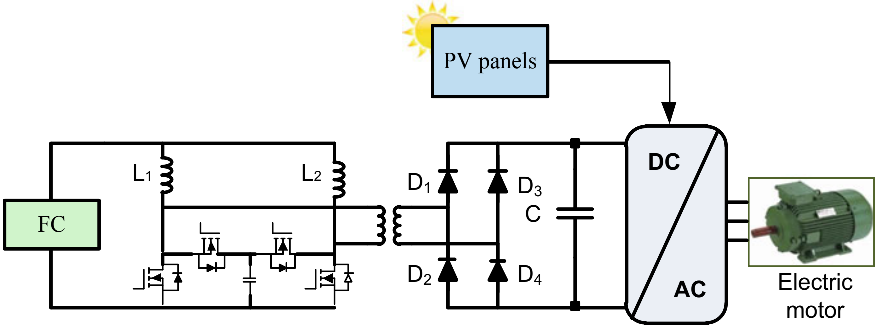

Fig. 12 Interleaved boost DC-DC converter

6.3 Energy Storage System Solution

The energy storage system (ESS) presents a key component for VIPV. To select an adequate solution, many items should be checked, such as the safety, the size, the cost, as well as the management system, etc. Nowadays EVs are mostly supplied by lithium-ion batteries which have the greatest grouping of best properties concerning energy density and cycle life [65–67]. Nevertheless, the solution to mixing several storage devices like batteries, supercapacitors, and fuel cells presents a promising solution for VIPV. Figure 13 exposes the most used ESS for EV, indeed batteries, supercapacitors, and fuel cells, as well as hybrid solutions are frequently adopted for EV [68].

Based on the spider diagram of different ESS characteristics given by [69] a comparative graphic is exposed in Fig. 14. Such a plot will permit the identification of the strengths and weaknesses of some ESS.

6.3.1 Batteries

The use of batteries for EVs has evolved from lead-acid to nickel and presently to lithium, seeking in all this to reach high specific energy, less chemical leakage, and better temperature performance [68, 70–72]. The preference of lithium batteries for EV is due to their elevated energy efficiency and power density, in addition to their fast charging ability and small self-discharge rate [20]. On the other hand, they have a wide range of working temperatures, as well as a compact and lighter weight [65–67]. It is to note that, lithium battery encompasses an extensive variety of chemical substances (LiFePO, Li–titanate, Li–S…) [68, 70, 71]. Safety worry is a major difficulty that encounters manufacturers and users. In fact, the largest detriment of lithium-ion batteries is thermal runaway [66]. The Li-Ion are also characterized by major battery aging factors [69, 73]. Authors in [74] propose some recommendations to reach the maturity of lithium batteries. They suggest optimizing the lithium electrode material to enhance the management expertise while taking into account the

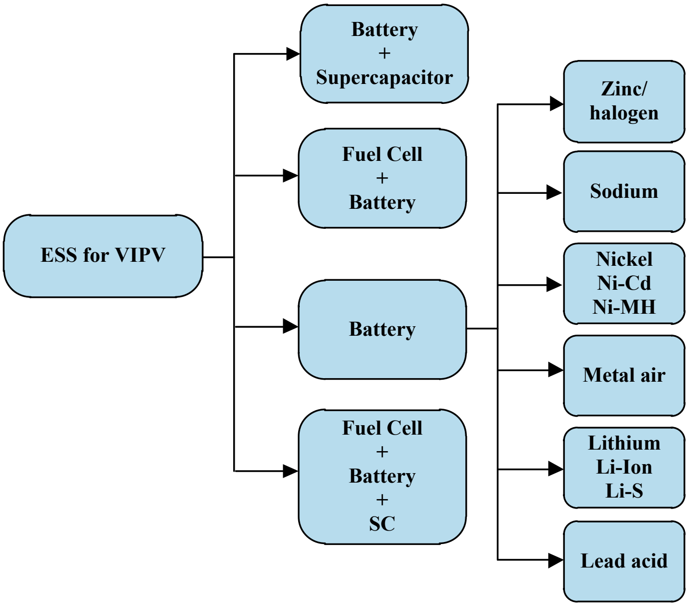

Fig. 13 Energy storage systems the most used for electrical vehicles

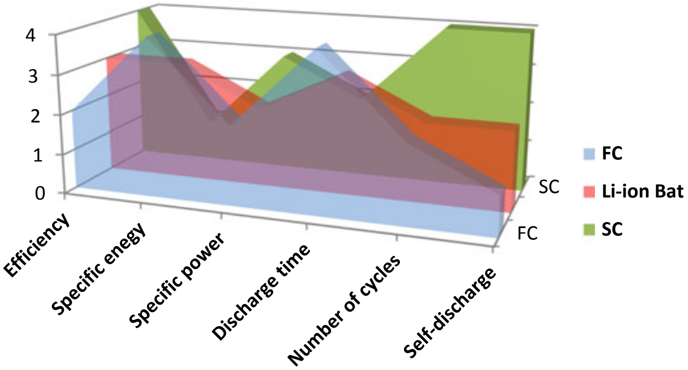

Fig. 14 Comparative study of different ESS

cost, the maintenance in addition to the life cycle. It should also reduce the memory effect and promote second-hand battery employment.

6.3.2 Hybrid Energy Storage System

For VIPV, to get the best from each storage device, hybrid ESS can be considered as an excellent alternative. This solution requires among others an adequate energy

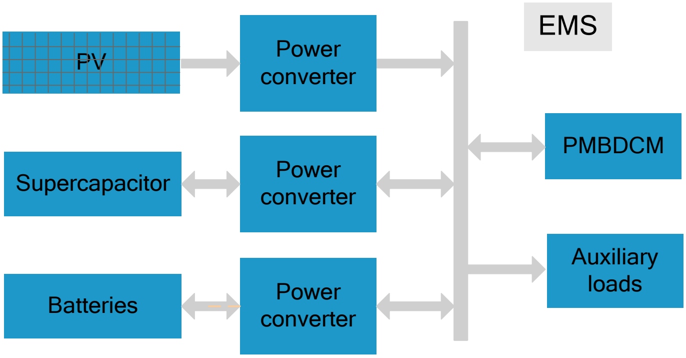

Fig. 15 Example of VIPV equipments including hybrid ESS based on battery and SC

management system (EMS) to maximize PV power and simultaneously respect the dynamic of each storage element. Frequency separation technique is the most popular method to ensure this purpose [46, 75, 76].

Hybrid ESS Based on Batteries and Supercapacitors

Concerning the load mission, the vehicle presents a specific profile. Indeed the peak current can reach 6 to 10 times the nominal current during each startup [77]. Supercapacitors (SC) are specified by their higher power density and lower energy density. These characteristics are complementary to those of batteries. Which supports the solution of the energy storage system based on the association of batteries and SCs [44, 71, 78]. For hybrid ESS, the function of the SC is to smooth out the energy supplied by batteries. The battery supplies steady-state energy and SC supplies the peak power [77, 78] which boost the efficiency of regeneration and support the EV acceleration [71, 78]. Consequently, it reduces battery current fluctuation and increases its lifetime, and leads to meet the limit space and weight restrictions, in addition to better vehicle dynamic [69]. Figure 15 presents an example of the integration of hybrid ESS for VIPV [44, 71]. As demonstrated in [44], the hybrid ESS based on batteries and supercapacitors monitored by an appropriate energy management algorithm is able to reduce the losses of the EV DC motor starter, further, a total disconnection of the batteries is possible for the duration of the regenerative braking.

Hybrid ESS Based on Batteries and FC and Eventually SCs

FCs present several variants, such as proton exchange membrane FC (PEMFC), alkaline FC, and solid oxide FC. The more suitable variety for automotive propulsion applications is the PEMFC [2]. This does not alter the fact that the PEMFC presents a major disadvantage, indeed they have slow responses to ensure the power demand

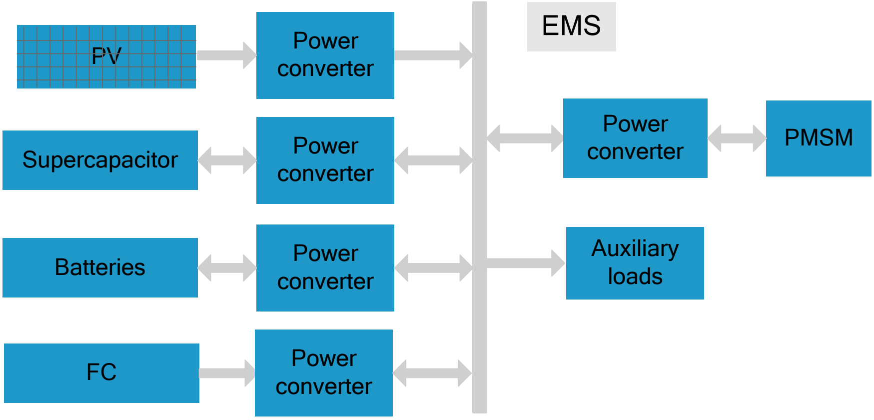

Fig. 16 Example of VIPV equipment incorporating hybrid ESS based on batteries, FC, and SC

of vehicles [46, 79, 80] To overcome this, in general, FC is associated with other types of storage devices. The use of hybrid ESS based on batteries, FC, and SCs has been investigated with accomplishment in several areas of automobile sector research and it is expected to be valuable as an onboard power generation for EV in the near prospect [69, 81–83]. For VIPV, PV system and FC are considered as primary power sources, and batteries with SCs are considered as secondary sources. Figure 16 presents an example of hybrid ESS that power VIPV, all storage devices are connected to the DC bus in parallel via their DC-DC converter, The motor is connected to the same bus via a DC-AC converter, This design presents additional flexibility in the control of the DC bus voltage that must be preserved stable during function [47, 69]. According to [84], the general objective for vehicles including PEMFC is to reach the cost, the durability, and the performance of conventional automobiles. Authors confirm that both performance and durability of the main FC stack components are considerably enhanced in the previous decade and it is currently possible that the cost and the sustainability purposes will be achieved during the upcoming decade.

7 VIPV Control and Energy Management System

For the VIPV application, the energy management system (EMS) is introduced to meet all power requirements while making the most of the PV panels. The EMS takes into account many other constraints such as reducing the overall weight of the vehicle and extending the life of energy storage devices. Fixed targets and constraints depend mainly on the adopted storage technologies. The EMS is based on several control levels with a wide variety of algorithms [85]. In literature, diverse control strategies are exposed, but in general nonlinear controllers have better performances, because these controllers take into account the model parameters variation which enlarges the operation range and guarantees the system overall stability [86]. For example, fuzzy techniques added to artificial intelligence are commonly proposed for EV [87]. Results presented in [88] demonstrate a reduction of fuel consumption from 0.46% to 3.39% when applying EMS based on the fuzzy technique. Lyapunov and sliding mode controllers are also proposed in the literature [86]. Moreover, many studies propose predictive algorithms for VIPV. In [89], deadbeat predictive controllers are investigated to control a bidirectional three-level cascaded converter connected to the used hybrid energy storage system. The control ensures the power management between PV and energy storage devices in addition to control the DC bus voltage. In [90], the MPC predictive controllers are used, authors propose a hierarchical control process through the virtual droop control. On another side, the Maximum Power Point Tracking (MPPT) algorithm including its different varieties is typically used for this application [91]. Indeed, the VIPV presents a continuous moving partial shading situation which includes a rapid variation of the irradiation applied to the vehicle solar panels. In [11], the authors investigate a modified incremental conductance MPPT process in order to better follow quick-shifting irradiation parameters. In [14], a fast MPPT algorithm is proposed and then compared to conventional P&O MPPT one [75]. In [15], a fuzzy logic based MPPT approach is considered. In [92], the authors propose the MPPT technique to control the proton exchange membrane fuel cell integrated into the EV. The proposed control is based on a radial basis function network algorithm. Furthermore, the Bandwidth allocation technique (Fig. 17) is commonly used to synchronize the hybrid power supply of the electrical vehicle [47, 93, 79]. This technique is based on the principle of respecting the specific dynamics of each component. In general, supercapacitors are dedicated to supply pulse demand, fuel cell and batteries provide the rest according to the adopted strategy.

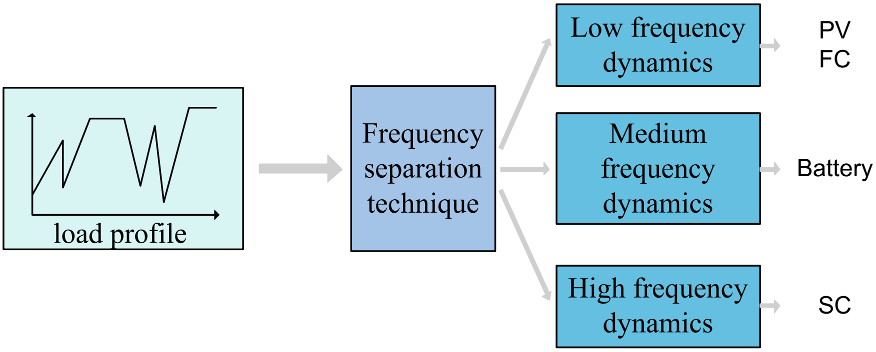

Fig. 17 Example of Frequency separation technique applied to VIPV

8 Conclusion

With the rapid expansion of the world's population, production, and consumption, the demand for transport has registered significant growth. Then, driving in city traffic induces repeated starts and stops which causes additional consumption of fuel and consequently less efficiency. In addition to gas emission, the VIPV presents a solution to all these problems. Actually, the attention of car manufacturers for vehicles incorporating photovoltaic panels remains ambiguous and still does not respond to large production. They are facing several obstacles as global size reduction, batteries location, luggage compartment, the variability of PV power, etc. But with the scientific and industrial developments in PV panels, control algorithms, and storage system devices, the VIPVs are expected to grow rapidly in the coming years.

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