Power Management Strategies of Electric Vehicle Charging Station Based Grid Tied PV-Battery System

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Abstract- This paper proposes power management strategies for a grid tied PV storage system in electric vehicle charging station (EVCS). The strategy is designed to be implemented in the power control system of the CS. The control proceeds depending on the integration of renewable energy sources by adopting an optimization algorithm, in order to minimize stress on existing power and to reduce the cost of consumed energy based on the electrical grid in standalone mode. This work explains in detail the approach via simulation results of a 15kW PV-Grid system connected with 40kWh lithium-ion battery and a load flow of five EVs. However, a power predictive model is described in this research, it is based on a real time monitoring of power demand and supply, where a reliable data communication between the CS and the plugged EV is achieved. Additionally, various parameters are involved in the approach to set the optimal operation mode of a charging process for instance, the instantaneous power of the PV array, the available energy in the battery storage buffer and the limited power the grid can offer. MPPT algorithm with the voltage source converters (VSC) and also the current control loop are all pillars to build the adopted power forecasting model. To test the validation of this model, simulation results of several charging scenarios express the effectiveness of the proposed CS effectively.

Keywords Electric vehicle charging station, management algorithm, power predictive model, switches control, battery storage buffer.

1. Introduction

The worldwide adoption of electric vehicles (EVs) is significantly on the rise over the classic fossil fuel vehicles. However, the purchase price of an EV may still the main constraint in the market since the batteries are found to be significantly more expensive. Advantageous reasons make the customers prefer EVs such as low ecological impact with no greenhouse emissions and performance improvement, etc. [1]. The energy sustainability requires consumers with environmental awareness and vision to electricity based on renewable, recent research confirms that one percent increase in renewable energies would lead to nearly 2–6% increase in EV demands [2].

The smart grid concept of integrating renewable energy sources (RES) with the grid utility becomes more and more used owing to its reliable outcomes e.g. the improvement of its power system efficiency and the low operating costs [3]. In order to get more revenues, V2G (Vehicle to Grid) technology can also be combined where EVs owners can achieve a balance of demand via charging/discharging modes i.e., charging during non-peak hours and discharging during peak hours. However, this approach would cause a short lifetime of the EV battery and other unsolved issues [4].

This paper focuses on an optimization algorithm of CS power to be allocated to charge EVs, the goal is to use minimum energy from the utility by implementing a subsystem gathered the RES with the energy storage unit. Several research papers have been published to compare between numerous strategies and topologies for a grid tied PV storage system in an EVCS application [5]. From a power management standpoint, is that the EVs are wholly or partially charged by RES with quite level of efficiency. Another perspectives of wireless CS are discussed in order to

increase the reliability of a charging process with less human intervention [6].

Due to the efficiency property and the low investment cost of adopting the PV system, The PV source is recognized as one of the effective alternatives among all the RES to be integrated into the charging station (CS) system. Yet the PV power still suffering from discontinuity over a day [7]. Besides, high charging rates lead to high power demand, which may not be supported by one of the energy sources in a standalone mode [8]. To secure the regulated targets from a robust hybrid electrical system, the intervention of grid is paramount in many levels, as in compensation mode, when an urgent high power demand appears in the CS. So as to optimize the cost and to gain from solar irradiance, the injection of extra energy into the grid from PV-Battery system is also implemented in this management approach.

To some extent, the group gathering the PV array and the battery storage buffer (BSB) to charge EV batteries [9], is considered as a potential strategy for charging EVs when AC load (residential, commercial and industrial customer) is given high priority to be power up from the electrical network. The required purpose of all electrical power system is to achieve an energy equilibrium between demand and supply at any interval of time mostly during peak hours when a further AC load is usually come out [10]. However, the CS costumers are willing to charge their EVs batteries so that some requirements are insured especially, a short time to obtain the required SOC with an appropriate charging cost.

This strategy is based on the change of DC link power, the idea is to make a power forecasting model and observe how fast the controller unit reacts. On one hand, to maintain the continuity of service for the overall system with quite level of efficiency. On the other hand, to decrease the consumption of grid power in order to obtain the required financial outcomes. The CS performance would be improved using an optimization algorithm [11], therefore, the power flow is determined from control switches provided by the energy management unit (EMU). Despite the overloading issue on the grid and the fluctuations of PV power, the EMU must create an alternative solution depending on the available stored energy in the BSB [12]. In this case, the CS would gain as much as possible from the solar irradiance and use the grid as long as the maximum current rate of the distribution Transformer (DT) is not exceeded [13].

2. Architecture of the EV-CS System

The Figure 1 shows the overall CS diagram, it consists of a grid tied PV with BSB. The PV array is tied to DC link via MPPT algorithm based boost converter to extract the maximum power from solar irradiance. The BSB is also connected to the DC link through a buck/boost converter, which adjusts the medium voltage of the battery to a higher rate of DC voltage. Transferring electricity at high power scale during one of the charging modes would requires CS system that meets the appropriate customer needs, technically, buck converters are used to adapt the DC voltage and the current by which the power demand would be achieved [14]. Each charging point is tied in parallel configuration to PV and BSB, it contains a human control panel (HCP) to insert manually specifications to be processed by the controller e.g., the selected SOC of the EV battery and the duration time since the vehicle is connected. Other information is automatically sensed by the HCP as the name of the vehicle company/model and the battery capacity. In this respect, the EMU analyzes the data so that it can determine the optimal scenario of charging the plugged EVs with a smart scheduling of power from the EVCS.

There are two forms of links i.e., AC and DC. This work provides another perspective to frame the problem, where the grid power is assumed limited and shared with other loads via AC link. Therefore, when the PV/BSB is injecting power into the grid, AC/DC converter will be operated in inverter
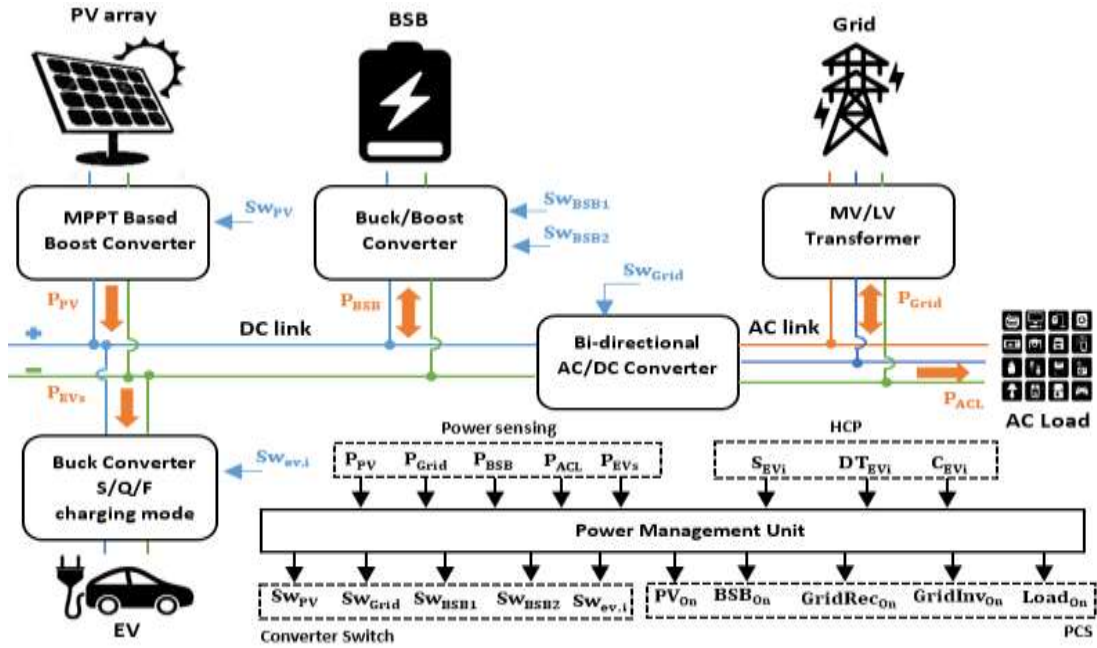
Fig. 1. Block diagram of different block of CS for EV.

mode, and when the CS is absorbing power from the electrical grid, the converter will run in rectifier mode. Smart charging operation should be reliable by enabling a two-way communication between the customers and utilities in order to establish an effective power flow calculation by the EMU [15]. The stochastic process of plugging EVs that occasionally causes a high power demand for the CS, is a major factor to add further complexity in the principal optimization algorithm.

2.1. DC link power

The DC link is the main pillar of the control strategy, in which real time monitoring of its state allows utilities to evaluate the accuracy and the speed at which the EMU responds [16]. Basically, the power flow is generated by PV/Grid and is supported by BSB. Fig.2 depicts the upstream part of DC link which contains PV plugged in EVs and BSB, and the downstream part which consists in grid utility and AC load.
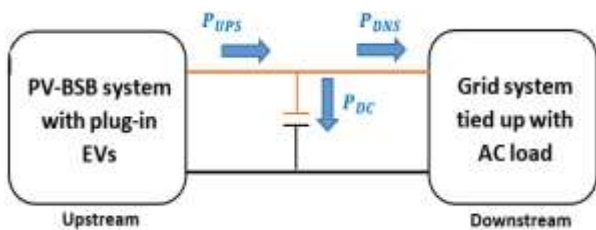

Fig. 2. Power flow at DC link level.

The formula regroups the two units is described in Eq. (1).

$$P_{DC} = P_{UPS} - P_{DNS} \qquad (1)$$

Where, P_{DC} is the DC power, P_{UPS} is the total power delivered by the upstream unit, while the AC load and the DT of electricity network have gathered the P_{DNS}.

The estimated power of the DC link is calculated using Eq. (2), where V_{DC} is the DC link voltage.

$$P_{DC} = CV_{DC} \frac{dV_{DC}}{dt} \qquad (2)$$

Actually, the power rate is basically related to the change of PV cells temperature and solar irradiance, and to the load demand from plugged in EVs and the AC load. Overall, the equation (3) expresses the power flow between sources and loads.

$$P_{DC} = P_{PV} + P_{BSB} + P_{Grid} - P_{EVs} - P_{ACl} \qquad (3)$$

The optimization approach is intended to solve conflict issues when energy sources are under simultaneous power demand from either, EVs batteries or AC load. The purpose is to achieve a compromise between the two types of load, while considering other criteria i.e., priority level and limited rate of allocated power of each load [17].

2.2. AC link power

In the adopted architecture, the electricity network is connected to the CS via AC link, where the power is limited due to the extra burden caused by additional loads, especially in peak hours. Even after installation of high power transformers, an energy management is still necessary to maintain the AC link stable [18]. However, the channelized power flow in the AC part is described in Eq. (4).

$$\qquad (4)$$

$$P_{AC} = P_{Grid} - P_{ACl}$$

Where, P_{AC} is the exchange of power between the DT that represents the grid limitations, and the AC load.

2.3. Battery Storage Buffer

Compared with traditional technologies of battery, lithium-ion charges faster, last longer and has a higher power density for a large number of charging/discharging processes [19]. As per the specification of solar system and electricity network mentioned above, voltage link of 500 VDC is needed to adjust the RES for future power injection mode into the national grid and charging a plugged EV battery as well. Moreover, a medium voltage storage of lithium ion battery is tied to DC link through a bi-directional DC/DC converter, where two transistors are operating under a buck mode and a boost mode.

The control signal of the battery charger uses two kinds of strategy i.e. constant voltage and constant current by which an EV battery can be charged [20]. In order to avoid sudden injection of high current rate when a load connected to DC link, it is recommended at first, to charge it through constant current control, and then to switch the control to the constant voltage. Fig.3 depicts the battery charger operating under the constant current strategy to load the BSB.
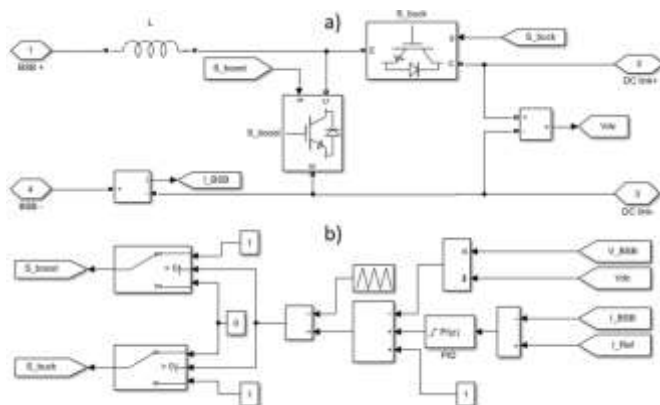

Fig. 3. a) bi-directional DC/DC converter b) Constant current control.

To enable the proper battery charging and discharging via bidirectional converter, a PI control scheme is employed to regulate the margin error between the charging current and the reference value, followed by pulse width modulation (PWM) technique to the switching pulses S_{boost} and S_{buck}. Among the main goals of the EMU is to stabilize the DC link along with sustaining SOC within preventive limits [21].

3. Power Predictive Model (PPM)

In compliance with the applied demand from EVs and the available power in the CS, the charging modes selected by EV customers have been divided into three different rates of power i.e. small, medium, and large. Consequently, a Power Predictive Model (PPM) is built in order to get the

EMU quick and efficient to respond when a huge power demand appears for the CS. The SOC of storage systems i.e., BSB and EV battery are also involved in the optimization approach via equations to settle the optimal power flow for the scheduled charging mode.

The power required for charging *ith* EV is depicted in Eq. (5).

$$P_{EVi} = \frac{(S_{EVi,req} - S_{EVi}) \times C_{EVi}}{PT_{EVi}} \quad (5)$$

Where, $S_{EVi,req}$ is the required SOC applied by an *ith* customer using the HCPi, PT_{EVi} is the plugged time set to adapt the matched charging mode, C_{EVi} is the battery capacity of *ith* EV.

Thus, multiple EVs add further extra power demand as it is mentioned in Eq. (6).

$$P_{EVs} = \sum_{i=1}^{N} P_{EVi} \quad (6)$$

Once the ith EV is connected to the charging point, The EMU will read the plugging-in time data from the *ith* HCP and accumulate it to the others in order to test if the battery storage would be enough to compensate the lack of power of PV system during EVs charging process.

The Eq. (7) expresses the real time monitoring of the BSB power versus PT_{EVi}.

$$P_{BSB} = \frac{(S_{BSB} - S_{BSB,opt}) \times C_{BSB}}{\sum_{i=1}^{N} PT_{EVi}} \quad (7)$$

Where, $S_{BSB,opt}$ is the rate of SOC that BSB should be off service, C_{BSB} is the BSB capacity and S_{BSB} is the instantaneous SOC.

The PPM takes measurements of each CS block power and calculates the others, the goal is to provide the EMU all the data required to determine the optimized power flow for both, the EV user and the CS owner.

The flowchart of the Fig.4 describes the proposed strategy of energy management at the DC link, the algorithm is started by powers sensing and testing if there is an EV plugged in the CS, which leads the EMU to apply one of two scenarios. No EV plugged will active the charging scenario (Case 2) where the PV power would be used to maintain the full charge of BSB, otherwise (Case 1) to inject the extra power in the national grid. At least one EV connected to the system (Case 3) is able to adjust the algorithm to adopt the PPM in the activated charging point. At this case, an instantaneous calculating of EVs power demand using the HCP allows the EMU to set the optimized charging process, taking into account the various powers of PV, BSB and also the real time monitoring of grid.
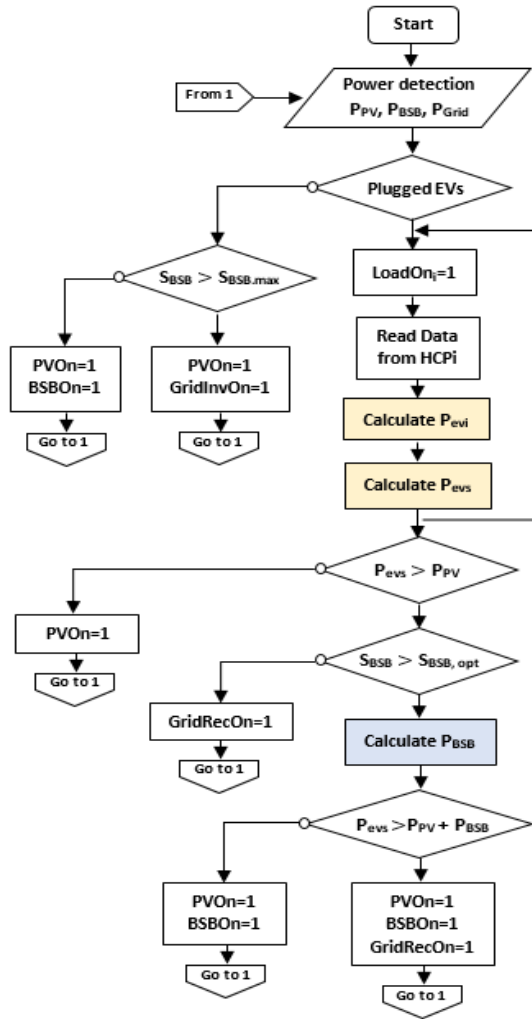
Fig. 4. Flowchart of the energy management approach

Depending on the HCP data, several power switches would be activated to meet the forecasted need of energy. However, the national grid is controlled by two power switches i.e. GridRecOn for rectifying mode (Grid to CS), and the injection mode of extra power from the CS system using GridInvOn switch (CS to Grid). Furthermore, the storage batteries are equipped with a management system to isolate them when a full charge is attended, typically, a BSBOn switch is controlled by a calculated margin of SOC [22]. LoadOni switch refers to an *ith* plugged in EV.

The optimization approach aims to integrate all the energy sources in a hybrid electrical system. In order to get simulation results similar to the proposed goals, and to apply efficiently the approach, the algorithm of energy management requires call control programs i.e., MPPT for boost converter, the voltage source converters (VSC) for inverter and the constant current for buck/boost converter.

The system behavior is evaluated with respect to power tracking reference and solar irradiance perturbations in accordance with developed techniques [23]. MPPT control with INcremental Conductance (INC) method has a good compromise between performance and complexity of

implementation that fits this kind of applications [24]. The adopted MPPT technique is followed by an integral regulator to minimize the error of the duty cycle. Additionally, the voltage source converters (VSC) method used for inverter control is another parallel task of the EMU, is composed of a phase-locked loop (PLL) and a V_{dc} regulator in cascade with a current regulator, followed by a PWM generator to dispatch the gating pulses to the inverter switches [25]. To apply the PPM approach, static and dynamic parameters are implemented in the EMU. Fig.5 depicts the two kinds of control, the first one is dedicated to sending the calculated cyclical ratios to each converter switches of the CS, the second part is where the power switches are controlled.
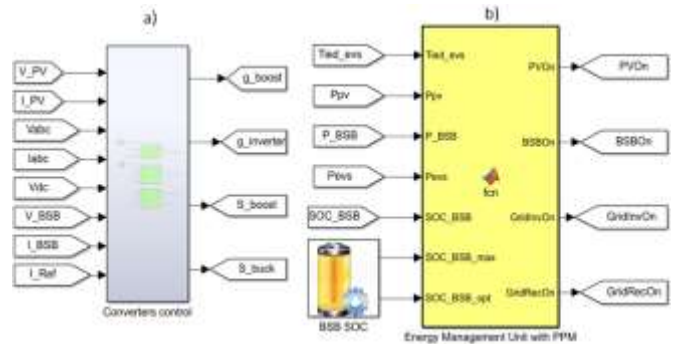

Fig. 5. a) Converters control b) Energy management unit

4. Simulation results

In this section, the validation test of the proposed topology is designed through a 15kW PV array in (5×10) configuration linked to a boost converter delivered 500VDC. The DC link is tied to a 40kWh storage system represented the BSB of 160V/250Ah. In order to get concrete simulation results of the integration of RES in EVCS, we employ the meteorological scenario of temperature and irradiance mentioned in Fig.6.
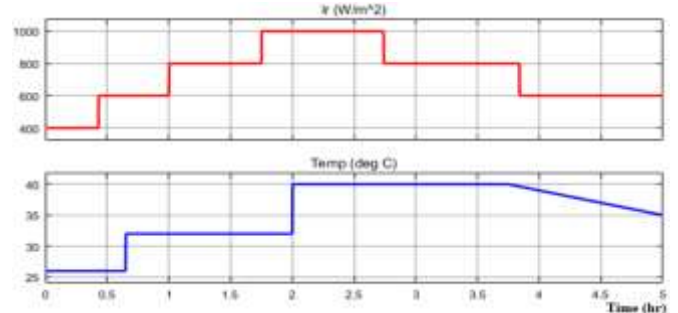

Fig. 6. climatic scenario of solar irradiance and temperature

To depict the control strategy, the system has been modeled and simulated on Matlab/Simulink software, which is carried out to test the CS operation mode via three cases:

Case 1: No EV at the CS, the BSB is already fully charged, injection into the grid from PV system.

Case 2: No EV at the CS, the BSB is in a charging mode via PV system.

Case 3: At least one EV is connected to the CS, the EMU will select the optimal charging process (meet the need of energy for the EV with less relying on the grid) for both, the CS customer and owner.
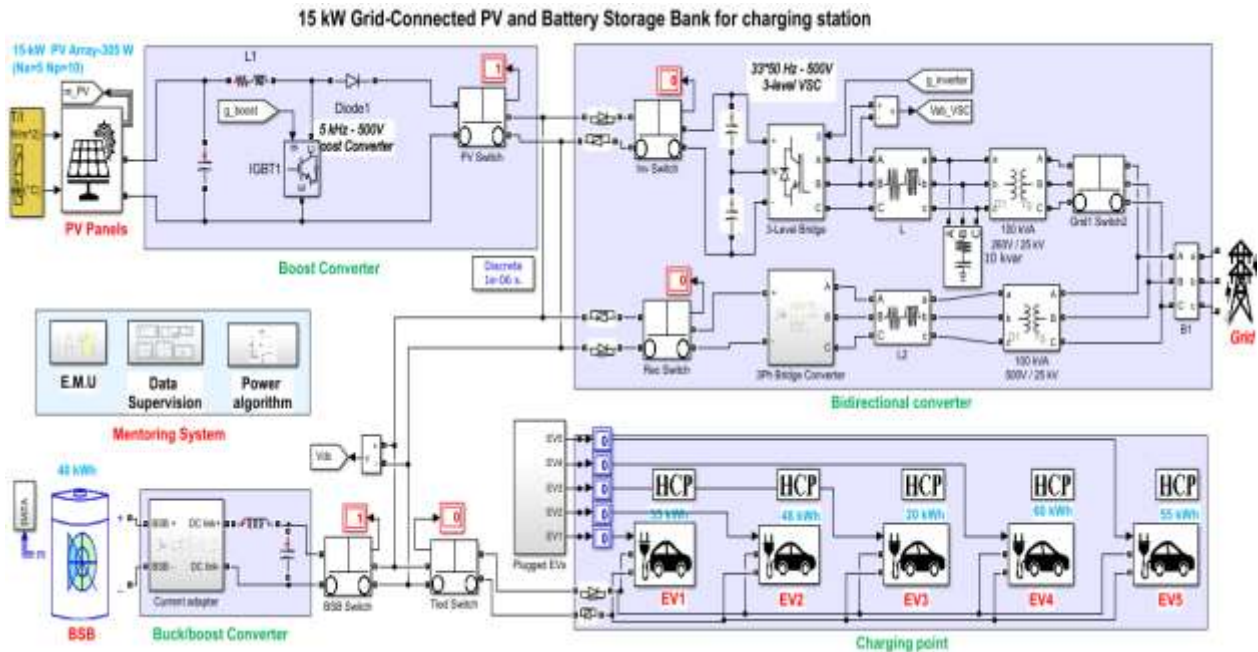

Fig. 7. PVGS of the EVCS

Based on the previous steps to model the PV-Grid system (PVGS) with optimization approaches, Fig.7 illustrates the designed PVGS using Matlab/Simulink interface, the flowchart of power algorithm is converted to a source code program implemented in the EMU block.

The proposed CS is developed for a study case of a small parking place consists of five charging points, each point is equipped with a HCPi so that the user could insert its required power demand. Three types of energy converters (dc-dc, dc-ac, ac-dc) are used to adapt the voltage of each power block to the DC link reference voltage.

Case 1: PV to Grid (P2G)

Since electricity is not stored on a large scale, consumption peaks have a direct influence on the volatility of wholesale prices. The temporal fluctuations remain very marked in the day/night alternation for solar energy where this mode is only possible in a daylight.

At this case, the total energy produced by the 15 kW PV peak power is injected into the national grid, the power curve in Fig.8a matches exactly the variation of solar irradiance in the climatic scenario mentioned above. At t=1.75h the irradiance is up to 1000W/m2 which made the PV system deliver 14.87kW. At t=4h, it is clearly observed once the temperature rises from 32°C to 40°C the power is falling to 14.45kW. The same reaction is noticed after t=4.8h.
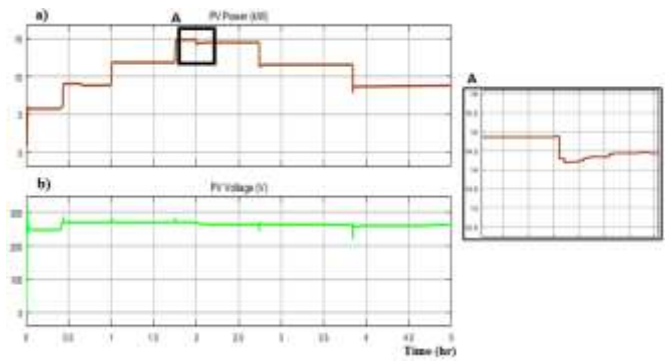

Fig. 8. PV system in P2G mode versus time a) power b) voltage

As shown in Fig.8b, the PV voltage is slightly affected by the temporal variations of temperature and irradiance. The VSC control of the inverter based on IGBTs sustains the DC bus voltage at 500VDC, the transient state fluctuations are minimized with quite level of efficiency as shown in Fig.9
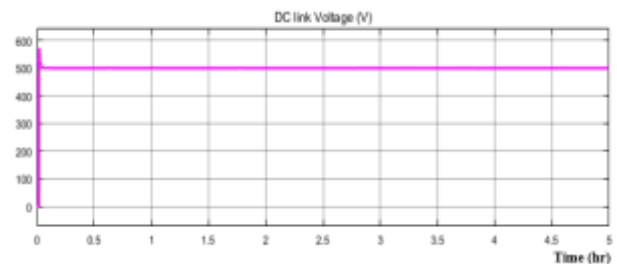

Fig. 9. DC bus voltage versus time

As long as this mode is activated via PVOn and GridInvOn switches, the grid benefits from all power

provided by the PV. Fig.10 shows the data supervision of the electricity network where generation and demand are similar since the PV is considered the main power source of this case.
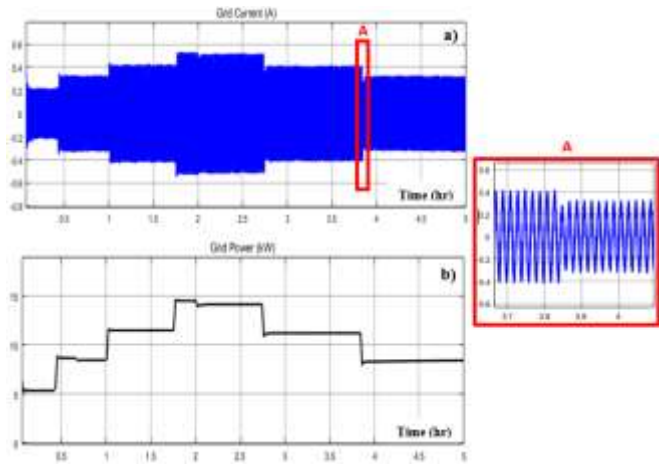

Fig. 10. Grid curves versus time a) current b) power

In order to eliminate the harmonics after the inverter using filters, the modeling of injection mode in Fig. 7 has a capacitor bank to reduce the effective value of AC voltage and to increase the losses in forms of heat. Fig.11 shows a stable AC voltage despite the variations of irradiance of the climatic scenario.
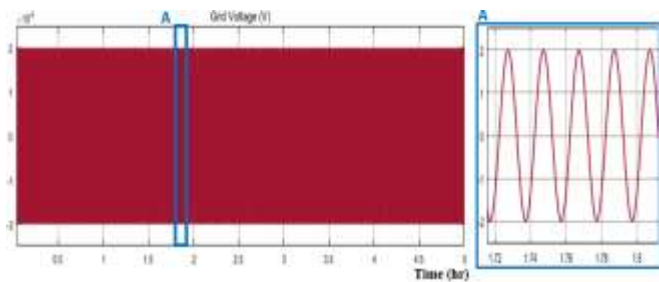

Fig. 11. Grid voltage versus time

Case 2: PV to BSB (P2B)

During a sunny day with no EVs plugged into the CS, the P2B is given high priority to gain energy from the available solar irradiance to load the BSB. Fig.12 shows the power flow of this case describing the curves of SOC, power and current of the 40 kWh storage system.

The power supplied to the BSB via its charging converter together with the evolution of the SOC of its storage cells is depicted in Fig.12b. The curve slope is featured by the SOC inclination which is obviously not constant throughout the charging phase, which is explained by the variation of PV current to be allocated to load the battery as is described in Fig.12c. As soon as the battery voltage is boosted to the DC link voltage, the converter would limit its current to prevent an excessive dissipation of energy and to maintain an accurate charging rate.
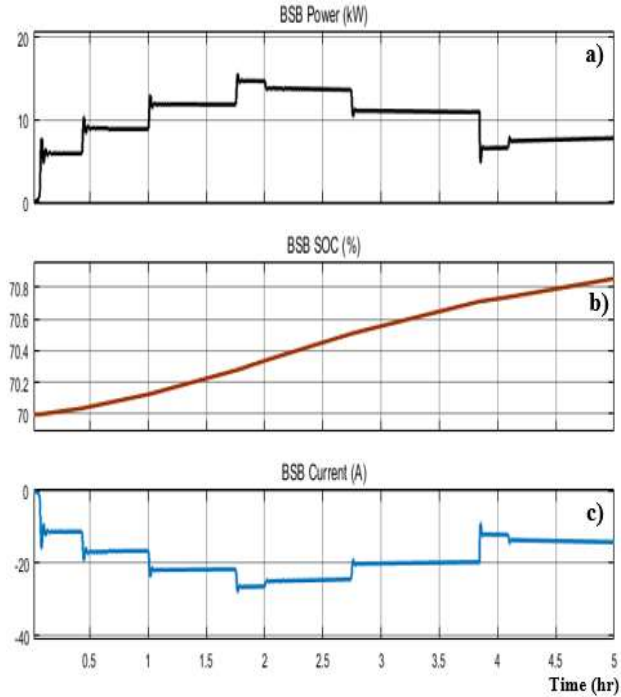

Fig. 12. Charging process of CS storage system versus time.

The SOC values are updated according to the required power flow either charging or discharging [26]. Additionally, the PPM adds further degrees of optimization to have a safety use of BSB by avoiding, on one hand the depth of discharge and on the other hand to operate in the harmful phase of saturation.

Case 3: PV/BSB/Grid to EVs (PBG2V)

The CS system is simulated under this scenario where there is a need to accumulate a calculated amount of power to charge a plugged in EVs batteries. In this mode four switches (PVOn, BSBOn, GridRecOn, and LoadOn) are activated occasionally following the algorithm guidelines.

To move forward in this methodology, a load flow consists of five EVs is proposed in this simulation to set the optimal charging scenario to each charging point from the available energy sources. The HCPs information is given in Table 1.

Table 1. EVs HCPs information for a charging process

EV	Battery Capacity (kWh)	Plugged Time (Hrs)	Initial SOC (%)	Final SOC (%)	EV demand (kW)
1	44	1.5	55	87	9.3
2	60	2.5	45	75	7.2
3	35	1.5	50	85	8.1
4	40	2	60	90	6
5	55	2	70	100	8.2

The next step is to apply the PPM control on every time interval and observe the load process of various EVs, time of entering and leaving are treated in the Fig.13 via plugged time data of the table above. In the meanwhile, the EMU would continuously update the calculation of Pevs so that the

allocation of energy sources can be made, taking into account the energetic criterion of gaining from solar energy in the first place, the BSB and the electrical grid respectively.
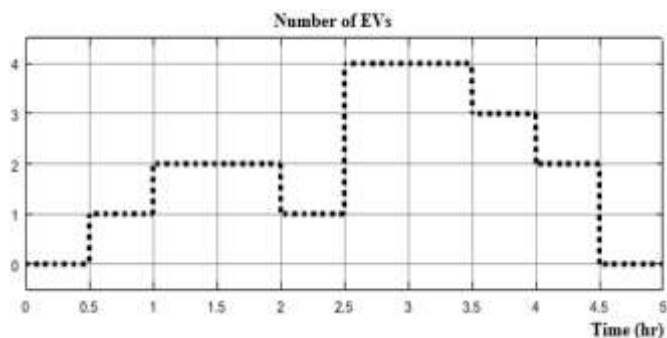

Fig. 13. Load flow of EVs connected to the CS versus time

For finding the appropriate proportion of PV power to be integrated into EVs CS, results of the previous load scenario have been plotted in the Fig.14. The energy stored in the BSB is considered as a second alternative when the PV is unable to meet the required EVs power demand.

From the load flow of EVs above, at t=2.5-3.5h, four EVs are plugged at the same time into the CS, as it can be seen in the results of Fig.14d, there is a 30 kW of power demand from the tied load flow, hence the grid compensates the gap of power between the CS supply and the applied load by providing 7 kW in Fig.14c.
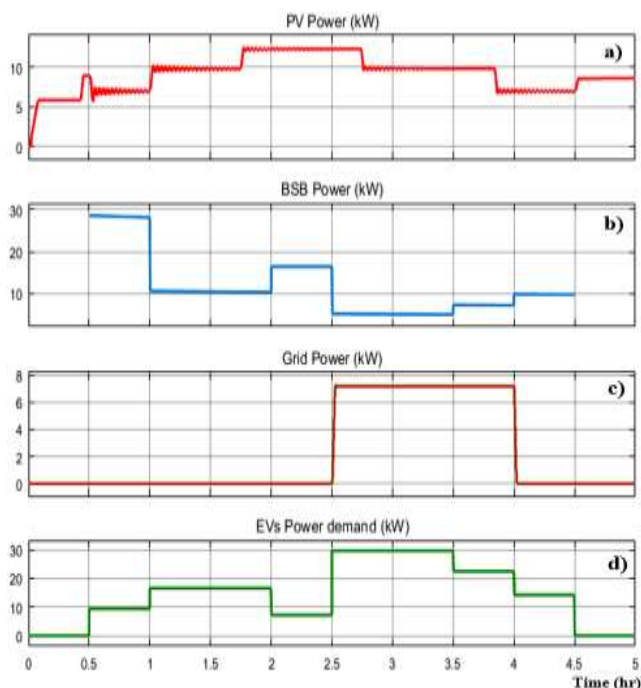

Fig. 14. Powers of charging operation of EVs versus time a) PV b) BSB c) Grid d) EVs

At t=0-0.5h and t=4.5-5h there is no connected EV (Case1 and 2), at these cases the calculation of BSB power based on EVs duration time is not available which leads the EMU to adjust the CS to work on its own power management. Moreover, the goal is to ensure the full charge

of BSB via either, a PV standalone working under high solar irradiance or the grid at off peak hours. Once the CS battery is fully charged, the PV power would be injected into the national grid.

In this case, the EVs enter and leave the CS in different times or at the same time, at t=2.5h four EVs are plugged which made the system behaves as a workspace parking when all employees would enter in the same work timing. The proposed control method ensures that the PV system delivers maximum power energy available via MPPT algorithm, it monitors the injected current in the EV battery within the HCP data provided by the customer.

5. Profitability Analysis

Unlike traditional charging operation from one energy source in standalone mode, that causes inconvenient outcomes e.g., the inefficiency of PV array in low irradiance, the stress on the grid especially during peak hours, and the limited SOC of BSB. As an alternative solution, a hybrid electrical system is considered being solid power supply owing to their beneficial energy features and financial outcomes.

During this study case, there would be a scheduling of sources depending on the instantaneous sensing of powers. Furthermore, at any circumstances and even the load flow of EVs is arriving in different intervals of time, the EMU control will achieve financial goals with less investment in an installed PV power and with a minimal level of relying on the grid. The Fig.15 shows the energy compensation between PV, BSB and grid during the three cases of processes.
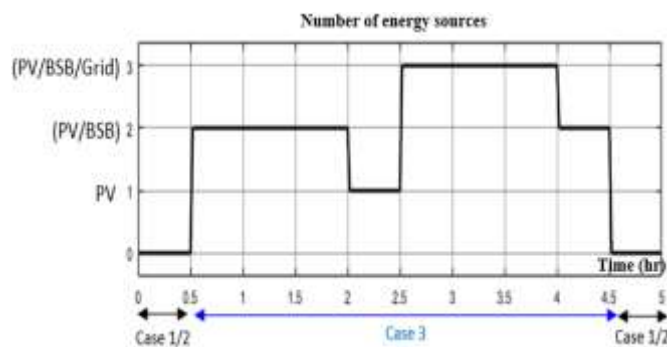

Fig. 15. Intervention of PV/BSB/Grid according to EVs power demand

In addition of the reliable quality of the proposed approach, a financial analysis is identified to test whether or not the CS would achieve a better cash flow comparing the traditional process, using the national grid (NG) in standalone mode, to the adopted topology of a grid tied PV storage battery with optimization algorithm. In France, the price of the Tesla superchargers is set at 0.20 €/kWh [27]. However, the CS purchases its main service supply from the NG according to the power subscribed rate, from 36 kVA the cost is set at 0.1483 €/kWh [28]. Table 2 expresses the percentage rate of profitability of this solution, which is increased to 92.4% instead of 25.8%.

Table 2. Overall profitability comparisons of PVGS

	CS based on NG	CS Based on PVGS		
	Grid	*PV*	*BSB*	*Grid*
Consumed energy (kWh)	72.5	24.75	37.25	10.5
Purchase (€)	10.75	3.67	5.52	1.55
Sale (€)	14.5	4.95	7.45	2.1
Gain (€)	+3.75	4.95	7.45	0.55
		+12.95		
Benefits	25.8 %	92.4 %		

6. Conclusion

In this paper, a power predictive model was presented to forecast EVs power demand and to enhance the CS performance, in order to avoid an extra burden on the grid during peak hours. PV array with storage battery supported by the grid increased the reliability and flexibility of the system.

From the above study case we can adopt the strategy while considering some criteria, as the installed PV array, the BSB capacity and the power rate of the distribution transformer. Simulation results had tested the validity of the adopted optimization algorithm working under three scenarios were: P2G, P2B and PBG2V. In terms of reducing the cost from purchasing a high rate of kWh from grid and for a beneficial integration of RES, the model would select the optimal charging scenario from the PVGS based on a smart scheduling of power.

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