# Charging electric vehicles from photovoltaic generation with intermediate energy storage

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*Abstract*— The consumption of fossil fuels on a large scale and the environmental problems resulting from the emission of polluting gases into the atmosphere, created the need for change in mobility habits in today's daily life. Responding to these new challenges, strong investments have been made by companies and governments in the automotive sector being the development of electric vehicles and the technologies associated with them an assumed priority by all the stakeholders. Fast charging of batteries is one of the technical issues that have been addressed. In addition, fast charging of electric vehicles in remote locations can be implemented taking advantage of renewable energy systems and avoiding power demand from conventional power grids. In this paper, the power can be supplied by a photovoltaic generation system and is managed taking advantage of an intermediate energy storage system based on a battery bank and supercapacitors. The operation of the proposed system is observed performing simulations conditions, which allow checking the correct operation of the system and its response to possible failures of the subsystems that constitute it.

*Index Terms*-- Isolated location; Fast charging; Single phase electric grid; Photovoltaic power generation system; Intermediate energy storage system; Power flow.

## I. Introduction

Coming back to the industrial revolution, it represents one of the key moments in the development of means of transport, since it is a result of this that appear the main engines used by today automobile industry: the internal combustion engine and the electric motor.

Among other solutions, electric vehicles (EVs) are presented as one of the best solutions to address the problems of dependence on fossil fuels, the release of high levels of carbon dioxide and other gases to the atmosphere responsible for increasing the greenhouse effect and depletion of the ozone layer [1]. These vehicles began to gradually rise again in the 90s, a time where record values were verified for the price of oil, which led to the start of a strong investment in exploration of energy production from renewable sources and the development of technologies used by EVs, with special emphasis on the batteries [2-4].
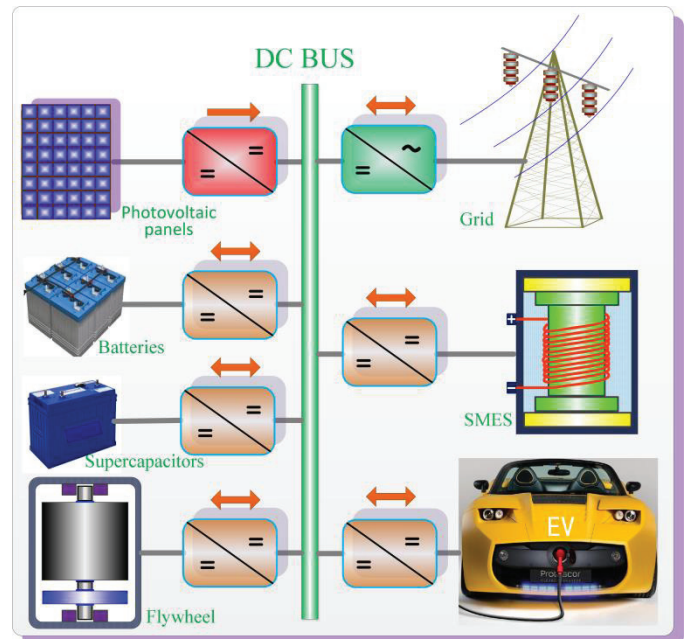
Fig. 1. General scheme of the power system.

Currently it is possible to separate the charging of EVs into three major groups, taking into account the battery charging times [5]:

- Slow Charging: the charging of the EV is made through monophasic alternate current (AC) sockets similar to domestic ones and the charging takes between 6h-8h.
- Semi-Fast Charging: AC charging mode taking between 1h-1.5h to charge the EV batteries and usually uses three-phase outlets that can be found in public spaces.
- Fast Charging: is characterized by using direct current (DC) and is capable of charging 80% of the capacity of the EV batteries in a period of 10 to 30 minutes.

The development and installation of a large number of Fast Charging Electric Vehicle Stations (FCEVS) is the next step of the electric mobility needs to move forward full mobility of EV users [4],[6-9].

Taking as example the Portuguese case, the charging network has been increasing over the last few years having at this point 1300 normal charging stations and 50 fast charging stations, which make it possible to travel crossing the country from north to south using EVs.

Although the number of EVs in circulation today does not strongly press the installation of charging stations in many urban sites, it becomes a reality day after day. For other hand, regarding remote places, the picture is slightly different.

Considering a remote location, in this paper, a model to a fast charging electric vehicle system using different subsystems of power generation and an intermediate energy storage system is considered. This system is analyzed simulating the solution under different operation conditions, for which are observed the response of the different sub-systems.

## II. System Description

A fast charging electric vehicle system can be composed by a DC bus and following subsystems [2]:

- Generation and supply:
  - a Photovoltaic Power Generation System (PV);
  - a grid connection system.
- Storage:
  - an Energy Storage System (ESS);
  - a superconducting magnetic energy storage (SMES);
  - a flywheel (FW).
- Load:
  - a Charging System (CS).

The general scheme of the proposed system is presented in Figure 1.

At this stage, the fast charging system is analysed neglecting the contribution of SMES and of the FW being described the operation and presented the main characteristics of the other sub-systems.

### A. Energy Storage Systems

To store energy, the proposed solution combines a bank of Lead-Acid batteries and supercapacitors (SC) taking advantage of the high specific energy value of the batteries and the high value of specific power of a SC [10-13].

The use of an intermediate energy storage system allows, as important feature, to decrease the power demand from the generation and supply systems. In particular, when charging an EV, it is possible to compensate great power demands and current peaks from the single-phase network, for instance, which when occurring can unbalance and stop the charging process.

The SC are connected to the DC bus through a buck/boost converter, which not only allows the transfer of energy into the DC bus, but also in the opposite way if it is necessary to absorb energy, as for instance, when current peaks are observed [14-16]. Since the battery bank acts as an auxiliary ESS to the SC, it is used a boost converter to link the battery bank and the DC bus allowing the energy transit towards the DC bus.

The battery bank is based on Lead-Acid batteries connected in series with the parameters presented in the Table I.

TABLE I
PARAMETERS OF THE BATTERY BANK

| Parameters | | Value |
|---|---|---|
| | Number of batteries | 20 |
| $V_{N(BAT)}$ | Nominal Voltage | 240 V |
| $C_{N(BAT)}$ | Nominal Capacity | 105 Ah |
| $I_{N(BAT)}$ | Nominal Discharge Current | 21 A |
| $R_{INT}$ | Internal Resistance | 5 mΩ |
| $V_{BAT(max)}$ | Maximum Voltage | 264 V |
| $C_{BAT(max)}$ | Maximum Capacity | 105 Ah |

The circuit used to simulate the battery bank and the boost converter system is shown in Fig. 2.
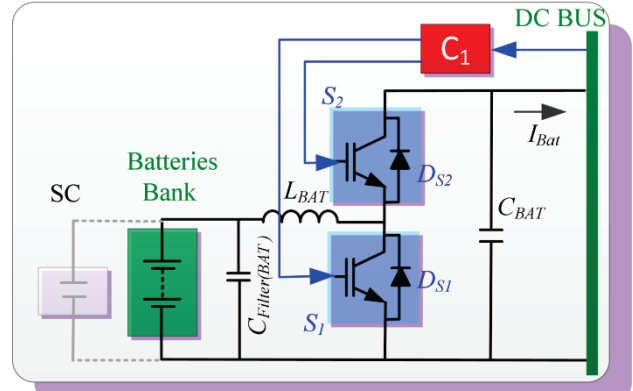


Fig. 2. Buck-boost bi-directional converter associated to the battery bank.

Being the battery bank connected to the DC/DC boost converter, it elevates the $V_{BAT}$ to a value of 400 V. In order to ensure that the voltage fluctuations are below 10% of this value it is necessary to implement a voltage control system.

To simulate the SC storage system are used as reference the parameters of a single supercapacitor presented in Table II.

TABLE II
PARAMETERS OF THE SUPERCAPACITOR

| Parameters | | Value |
|---|---|---|
| $C_{N(SC)}$ | Nominal Capacity | 5.8 F |
| $V_{N(SC)}$ | Nominal Voltage | 160 V |
| $I_{N(SC)}$ | Nominal Current | 35 A |
| $ESR$ | Equivalent Series Resistance | 240 mΩ |
| $\tau$ | Lifetime (High Temperatures) | 1500 h |

The circuit used to simulate the SC system and the buck/boost converter system is similar to the topology shown in Fig. 2.

The buck/boost DC/DC converter used in this case also requires a voltage control system to maintain the $V_{DC}$ around 400 V.
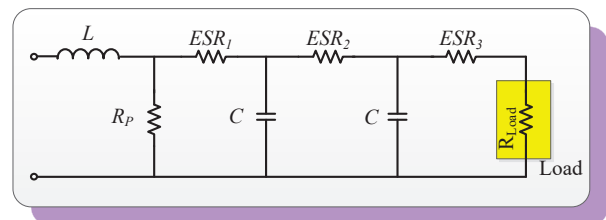


Fig. 3. Equivalent electric circuit of a supercapacitor.

In order to simulate the operation of the supercapacitors in a more realistic way, the model represented in Fig. 3 is used [17].

The model presented in Fig. 3 takes into account the non-linear behaviour of the SCs. The three equivalent series resistances ($ESR_i$) correspond to the representation of the physical system (the two electrodes and the dielectric), while the value of the resistor $R_P$ is determined taking into account the time constant ($\tau = R_p C$) of an RC circuit.

### B. Photovoltaic Power Generation Systems

The photovoltaic power generation system consists of an array of PVs, connected in series and in parallel, which are working at its maximum power point due to the operation of a Maximum Power Point Tracking (MPPT) system developed, which is presented in Fig. 4 [18-21].
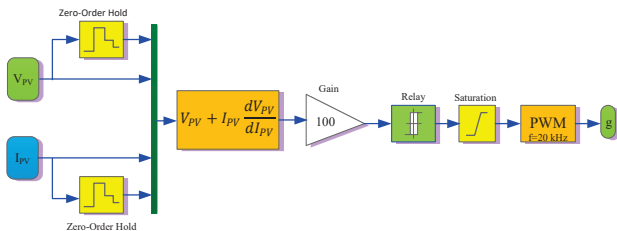


Fig. 4. MPPT system used by the PV panel.

The PV equivalent characteristics resulting from 8 PV panels associated in series and 5 in parallel, which accounts for a total of 56.25 m$^2$ are shown in Table III.

TABLE III
CHARACTERISTICS OF THE EQUIVALENT PV PANEL

| Parameters | Value |
|---|---|
| $P_{MAX}$ | 7601.04 W |
| $V_{MP}$ | 194.4 V |
| $I_{MP}$ | 39.1 A |
| $V_{OC}$ | 244.8 V |
| $I_{SC}$ | 42.5 A |
| $N_S$ | 400 cells |
| Length | 13.44 m |
| Width | 4.185 m |
| Weight | 639 kg |

Assuming that the behaviour of the individual modules is maintained when these are connected in series or parallel, thus, the series connected modules are responsible for increasing the voltage available at the output of the PV, while the modules connected in parallel increases the current available.

As mentioned above, the connection between the photovoltaic panels and the DC bus is made through a DC/DC converter, which is composed by "two levels". The circuit model used to simulate this sub-system is shown in Fig. 5.
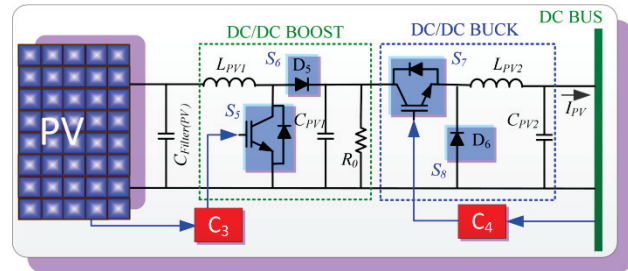


Fig. 5. Converter associated to the photovoltaic system.

As can be seen in Fig. 5, the first level consists in a boost converter which is controlled by the MPPT system and extract the maximum power possible from the PV panel and elevates its output voltage. The second one is composed by a buck converter controlled by the voltage control system and that is responsible to reduce the power provided by the first level and maintain $V_{DC}$ around 400 V.

### C. Charging System

The EVs charging system is responsible for the connection between the DC bus and the batteries bank of the vehicle connected to the charging system. This system is based on a bi-directional buck-boost DC/DC converter to allowing energy transit towards the EV (Grid-to-Vehicle - G2V), working as a buck converter, or towards the DC bus (Vehicle-to-Grid - V2G), working as a boost converter. The option to use this type of converter is due to the use of a smaller number of semiconductors by comparison, for example, with a DC/DC Dual Active Bridge converter or a DC/DC 3 level buck/boost converter.

To simulate this system it is used the data corresponding to a Lithium- Ion type battery, which parameters are presented in Table IV.

TABLE IV
PARAMETERS USED FOR THE EV BATTERY

| Parameters | | Value |
|---|---|---|
| | Battery Type | Lithium-Ion |
| $V_{N(EV)}$ | Nominal Voltage | 360 V |
| $C_{N(EV)}$ | Nominal Capacity | 66.6 Ah |
| $I_{N(EV)}$ | Nominal Discharge Capacity | 28.9 A |
| $R_{INT}$ | Internal Resistance | 0.054 Ω |

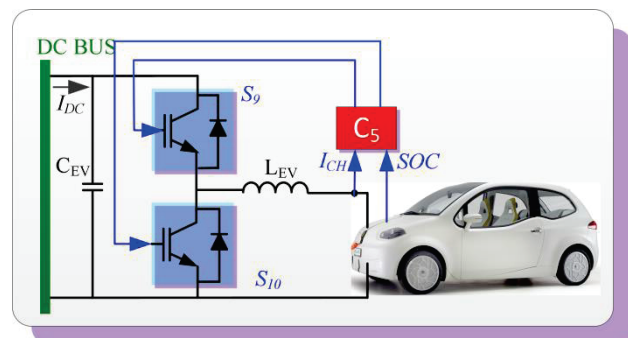The circuit model used to simulate the charging system is shown in Fig. 6.



Fig. 6. Converter associated to the charging system.

Along with the converter is designed a control system to determine the operating mode of the charging system, depending on the State- Of-Charge (SOC) of the EV battery connected to the system.
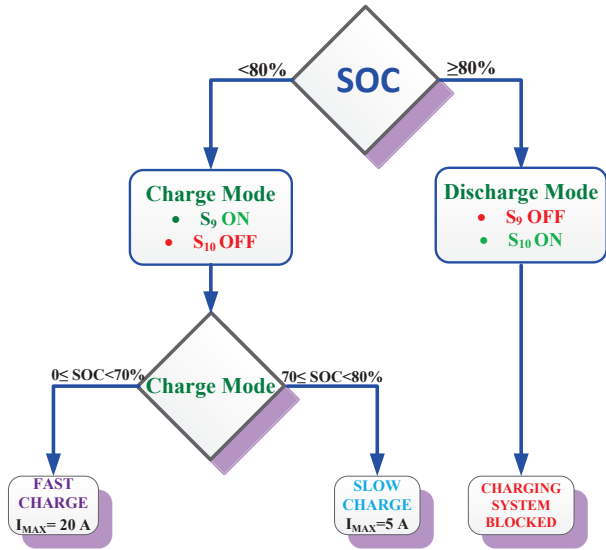
Fig. 7. Flowchart of the decisions used to control the charging system.

Essentially when an EV is connected to the fast charging system, the control system check the SOC of the EV battery, in order to decide whether to start the charge (SOC<80%) or the discharge mode (SOC≥80%). In case the charge mode is activated, the control system carries a second check to verify if should activate the fast charge (0%≤SOC<70%), which is characterized by a charging current of 20 A, or the slow charge (70%≤SOC<80%), which uses a charging current of 5 A. In Fig. 7 is presented the flowchart for controlling the charge/discharge process.

*D. Grid Connection*

In the developed model, the connection to the monophasic grid is made through a full wave diode rectifier, which implies that the power only flows from the electric network to the system, and therefore, it is not possible to inject power into the grid (Fig. 8) [22-23]. In general this connection is bi-directional but in the present study only this feature was considered since the AC grid is considered the ultimate power source satisfying the power needs of the charging system.

Besides the rectifier, there is also used a low frequency transformer ($T_1$) which ensures the galvanic isolation of the system, the adaptation of the rectifier input voltage level and the elimination of the continuous components present in the rectifier input currents, considering the electric network point of view [24].

So that, the characteristics of the transformer used to analyse the proposed system are summarized in Table V.
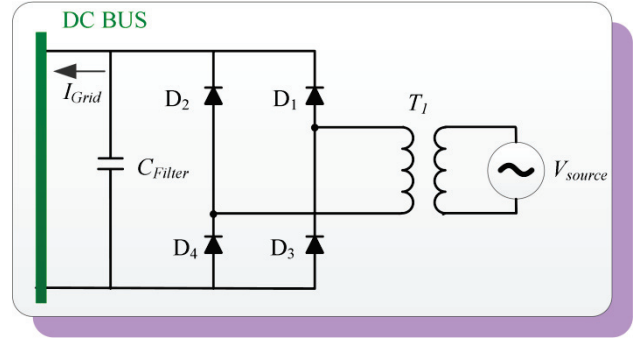
Fig. 8. Grid to DC bus connection.

TABLE V
TRANSFORMER CHARACTERISTICS

| Parameters | | Value |
|---|---|---|
| $S_N$ | Nominal apparent power | 30 kVA |
| $f_N$ | Nominal frequency | 50 Hz |
| $V_1/V_2$ | Voltages | 230/450 V |
| $R_m$ | Magnetization resistance | 881.67 Ω |
| $L_m$ | Magnetization inductance | 2.8064 H |

III. SIMULATION RESULTS

The fast charging system can be analysed considering different scenarios. In this section are presented the results obtained under the following conditions:

i) Initially all the subsystems are in normal operation and at the instant $t$=0.25 s the ESS is switched off, stopping to supply power to the system;

ii) The initial SOC of the battery EV is: $SOC_{Initial}$=69.9%.

iii) The equivalent load at the DC bus is: RL Load → R = 250 Ω and L=2 mH.

This scenario allows to check the response of the charging system to the "failure" of one of his subsystems and, due to the initial SOC chosen to the EV battery, it is possible to check the robustness of the control system.

In Fig. 9, it can be seen the evolution of the EV battery SOC between 69.996% and 70.001%, illustrating the change between charging modes, as the Fig. 7 flowchart. For the period illustrated, during the charging are observed two charging modes: the fast charge mode for a SOC below 70%, which is reached at t=0.587 s, and after that the slow charge mode (70%<SOC<80%). Due to the lower value of current imposed in the slow charge mode, it is verified that the "speed" of charge of the EV battery slows down, as expected.
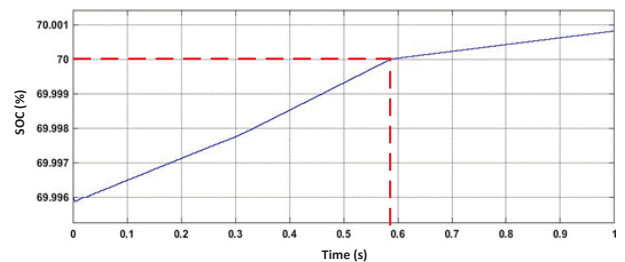
Fig. 9. Evolution of EV battery SOC during the charging.

As described above, the ESS is switched off at

$t$=0.25 s not supplying power to the DC bus after this instant as it can be confirmed by the output current of the ESS ($I_{ESS}= I_{SC} + I_{Bat}$) in Fig. 10, joining the contributions of the battery ($I_{Bat}$) and of the supercapacitor ($I_{SC}$).
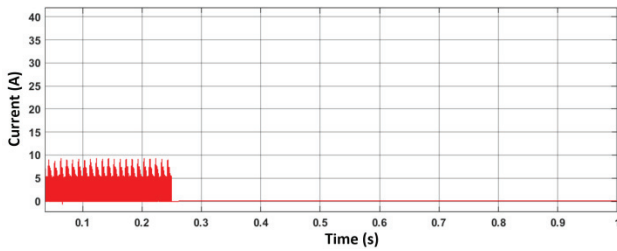

Fig. 10. Output current of the EES system.

The current in the DC BUS ($I_{DC}$) for charging the EV results from the contribution of the current $I_{ESS}$, with the current of the photovoltaic system ($I_{PV}$). In Fig. 11, it is possible to observe that after the shutdown of the ESS ($t$=0.25s), there is an increase of the value of $I_{PV}$, to compensate the existing failure. It is also possible to verify that after the change to the slow charge mode $I_{PV}$ decreases from 20A to 5A in accordance with the current levels defined.
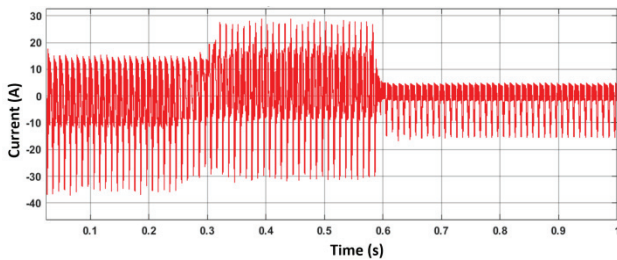

Fig. 11. Output current of the photovoltaic system.

In order to observe the behaviour of the system for different operation conditions, in Fig. 12 is shown the DC bus voltage.
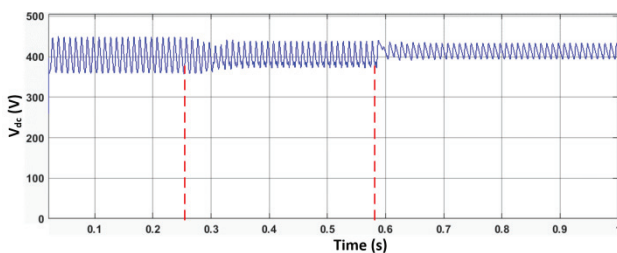

Fig. 12. DC bus voltage.

During the simulation, $V_{DC}$ oscillates, as desired, around the value of 400 V, as a result of the action of the voltage control system.

## IV. CONCLUSIONS

This paper proposes a fast charging system to be installed in remote locations, which uses multiple power supplies and an intermediate energy storage system. The proposed charging system performs the charging of the batteries of the EVs through a DC/DC converter that makes the link between the EV and a DC bus, which is held around 400 V through a control system of the output voltage of each subsystems that provide power: a photovoltaic generation system and an energy storage system (consisting of a batteries and supercapacitors).

Through the performed simulations it can be concluded that the system is operating using the ESS as an equilibrium point, preventing current peaks and contributing to the efficiency of the charging process.

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