Environmental Engineering and Management Journal January 2020, Vol.19, No. 1, 121-129
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

ANALYSIS OF HYBRID ENERGY STORAGE SYSTEMS BASED ON PHOTOVOLTAIC PANEL, SUPERCAPACITORS AND BATTERY FOR ELECTRIC VEHICLES

Florin Andrei Rusu*, Gheorghe Livint, Alina Baciu

"Gheorghe Asachi" Technical University of Iasi, Faculty of Electrical Engineering, Department of Electrical Drives and Industrial Automation, 23 Prof. D. Mangeron Street, 700050 Iasi, Romania

Abstract

Nowadays, with the evolution of technology, energy storage systems have become a concern for automotive industry. It is intended to develop, through different methods, green energy systems to power up electric vehicles. During the last years, several energy storage systems have been tested and implemented, but each solution has brought advantages and disadvantages regarding infrastructure, charging stations, speed of charging or autonomy.
This paper proposes to study a power management strategy for a hybrid energy system which consists in a photovoltaic panel (PV), as main power source and super-capacitors and batteries. The last two energy storage devices, due to the various power densities, will provide the steady and transient power demand. For each power source of hybrid storage energy system, dynamic and mathematical models are described and a strategy of power sharing is presented.
The experimental stand, represents the main contribution to this paper, and is made on small scale using low voltages and currents. The entire purpose of this paper was to build a system for energy management, controlled by a microcontroller ArduinoNano.
The overall objective of present work is to analyze the distribution of energy between existing sources in the system according to their characteristics. During simulations, each energy storage device is predominant in either charging or discharging mode and different control strategies for sharing energy will be developed and studied.

Keywords: battery, energy storage system, hybrid system design, super-capacitor

Received: March, 2019; Revised final: September, 2019; Accepted: September, 2019; Published in final edited form: January, 2020

1. Introduction

In the last years, researches are oriented to green energy, yielding some promising technologies that can reduce the dependence on fossil fuel. Green energy comes from natural sources, being renewable and having a much smaller impact on the environment than fossil fuels which produce pollutants (Novelli et al., 2019).

Green energy can replace fossil fuels in all major sectors of use, including electricity, water and space heating or automotive. Starting from these considerations, concerns increasingly higher on green energy in different areas, like public transportation, residential applications or energy power generation. All of these aspects conducted to development of distributed energy resources in electrical power systems or electric vehicles. The definition of an electric vehicle is simple, a vehicle which doesn't contain internal combustion engine, but has electric engine and several power sources (Watson, 2018).

Over the years, distributed energy resources have been built based on photovoltaic systems, super-capacitors technology or fuel cell, due to their energy storage characteristics and being compatible with environmental problems. For example, compared to batteries, super-capacitors (Wenlong and Chean, 2017; 2018) can be charged and discharged more than

*Author to whom all correspondence should be addressed: e-mail: florin.rusu@tuiasi.ro; Phone: +40745832900

150000 times without affecting their lifetime or having significant energy loss. Up to this moment batteries and super-capacitors have been studied under equivalent circuits, used in simple models development for each component. Based on these models, simple measurements can be made in order to compare the performances. Also, for designing the voltage balance circuit, the dynamic response characteristics must be understood, so the trigger voltage must be precise and without variations.

In a classical battery, as energy storage device, the energy can be stored in two ways:

- basically, indirect, as available chemical energy, which require faradic oxidation;
- directly, in electrostatic way, as negative and positive electric charges.

Most of batteries, no matter if they are lithium-ion, Lead-Acid or other type, are characterized by high energy density, but at the same time, they present some disadvantages like low power density, cyclic lifetime and low efficiency at charging and discharging. Also, their integration on a vehicle requires space because of their large volume and weight. Nevertheless the enormous increase in energy density has been brought by Li-Ion batteries compared with nickel-metal batteries, which were not offering enough power (Eckard and Marx, 2012).

On the other side, super-capacitors have the advantages of high-power density, high storage efficiency, long cycle life and fast charge and discharge. Main characteristics of lithium-ion batteries are listed in Table 1 (Hammani and Sadoun, 2012).

Table 1. Characteristics of Li-Ion batteries

Parameter	***Li-Ion batteries***
Nominal capacity	18650 mAh
Minimum capacity	750mAh
Nominal voltage	3.7V
Charging method	CC/CV (constant current/ constant voltage)
Discharge cut-off voltage	2.75V
Lifetime	up to 10000 cycles
Operating temp	Charge: 0° - 45° Discharge: -20° to + 65°C
Energy density	120 – 150 Wh/kg

2. Hybrid storage energy sources configuration

In this paper, it is considered a hybrid energy storage system (HESS) which consists in a PV panel, 10000mAh, on small dimensions 142x75x13.9 mm, as primary power source, a super-capacitor bank and a battery pack (Pranoy et al., 2019), which provide a long term energy demand and a transient load demand. The block diagram for the proposed hybrid energy storage system is presented in Fig. 1.

It is well known that batteries and super-capacitors, as energy storage devices, are complementary and working together will improve greatly the performances of energy storage. Compared to super-capacitors, batteries have a large energy density, allowing a long-term storage of energy, but they also have the disadvantages of a small power density, low charge and discharge efficiency and short cycle lifetime. Adding a super-capacitor bank to the storage system, the size of the battery can be reduced and the efficiency and the lifetime are improved because the super-capacitor has the advantages of high power density, high storage efficiency, long cycle life and fast charge and discharge.

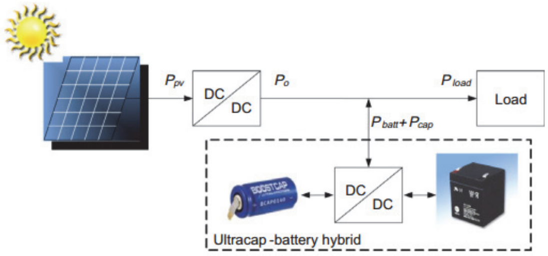


Fig. 1. HESS block diagram

In general, a photovoltaic panel consists in several photovoltaic cells connected in series or parallel, depending on situation. In application with high voltages are used photovoltaic panels connected in series or parallel – for high current, which represent an Array (Myungchin and Sungwoo, 2017).

To extend the applicability of photovoltaic panel to a real vehicle, the dimension should be established according to the batteries and super-capacitors capacity. It is possible to integrate the photovoltaic panel on the roof of the vehicle, being exposed to the light and in this way charging cycle is continuous, without using any plug-in cables or other adaptors.

2.1. Photovoltaic panel model

A photovoltaic panel represents a semiconductor device that is able to convert solar illumination power into electric energy. In high-power applications, photovoltaic cells are connected in series to obtain high voltages, and in parallel to obtain high current and to form a PV module.

The most used model for a photovoltaic panel is a simple equivalent circuit represented by a current source I_{ph} in parallel with a diode, a parallel resistor R_p to indicate a leakage current and series resistor R_s, as inner resistance for current flow. The schematic diagram of a PV panel is shown in Fig. 2. The nonlinear equations which define the model can be expressed as Eqs. (1-2).

$$I_{PV} = I_{ph} - I_D - I_P \quad (1)$$

$$I_{PV} = I_{PH} - I_S\left[\exp\left(\frac{q\left(V_{PV} + R_s I_{PV}\right)}{A_C k_B T} - 1\right)\right] - \frac{V_{PV} + R_s I_{PV}}{R_P} \quad (2)$$

where: I_p represents a shunt leakage current; I_D is the diode current; I_{PH} is the light generated current; I_S is the saturation current; q is the electron charge; k_B is Boltzmann's constant (1.38x10^{-23} K); A_C is the ideal factor (at 28°C $\rightarrow A_C$ =28); T is the photovoltaic (PV) cell temperature; I_{PV} is the photovoltaic cell current (A) and V_{PV} is the photovoltaic cell voltage (V). Parameters like I_S, I_{PH}, R_P, R_S, T must be specified before applying *I-V* relationship (1) and (2).

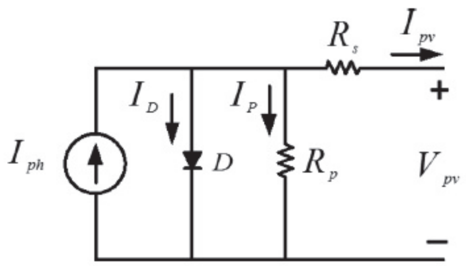


Fig. 2. Equivalent circuit model of a PV cell

A photovoltaic panel can be used to charge batteries to full capacity in three stages:

- stage 1-directly charge batteries from solar panel until reaches overcharge point;
- stage 2-maintain battery voltage at fixed overcharge point for completing remaining capacity;
- stage 3-charging voltage is reduced to avoid overcharge and maintain the state of charge of battery at 100%.

The equivalent circuit model from Fig. 2 (Fathabadi, 2016) can be implemented in Simulink/Matlab to estimate the characteristics of *I-V* curve for a photovoltaic panel, considering environmental parameters like irradiance (G), temperature (T) and cell parameters (parasitic resistance and ideal factor). Based on the model from Fig. 2 can be analyzed the maximum power point tracking, using a Shockley diode equation (Djellad and Logerais, 2014).

Considering the environmental/ irradiance level and panel temperature, was developed a Simulink model for PV cell to understand the power voltage curve, which is important in designing the converter. The Simulink model and current voltage characteristic are shown in Fig. 3.

Prior to simulation, were obtained some specification for A-300 Solar Cell from (https://www.cs.wmich.edu/~sunseeker/files/A-300%20data%20sheet.pdf) and shown in Table 2.

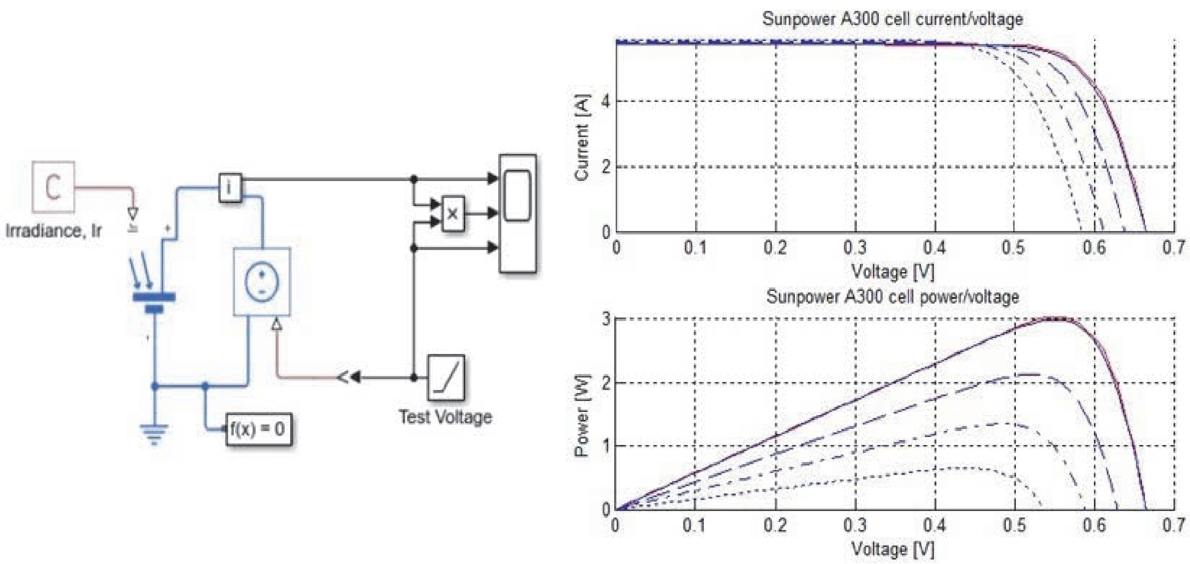
The standard test conditions for obtaining the maximum power are: irradiance of 1000W/m^2.

Table 2. Electrical characteristics for a photovoltaic typical cell

Parameter	*Specification*
Open circuit voltage	0.670 V
Short circuit current	5.9 A
Maximum power voltage	0.560 V
Rated power	3.1 W
Efficiency	Up to 21.5 %

The simulation results are shown in Fig. 4 where are plotted the I-V characteristics. Influence of the ambient irradiation G and a certain cell temperature T can be obtained from the model equation. The photovoltaic cell photocurrent is directly proportional to solar irradiance G (W/m^2). If photovoltaic panel is short circuited, currents flows are negligible in the diode. Also, solar intensity is quantified taking in consideration solar radiation, average humidity and aerosol concentration.

In Fig. 4, 1Sun=1000 Watt/m^2 and one important aspect is related to the fact that, the solar panels performances, are not degraded significantly when it is full sun and cloudy conditions. As a conclusion for the simulation can be said that the output power decreases linearly and efficiency is nearly constant.



(a) (b)

Fig. 3. (a) Simulink model for solar cell power curve (b) current-voltage characteristics and power-voltage characteristics

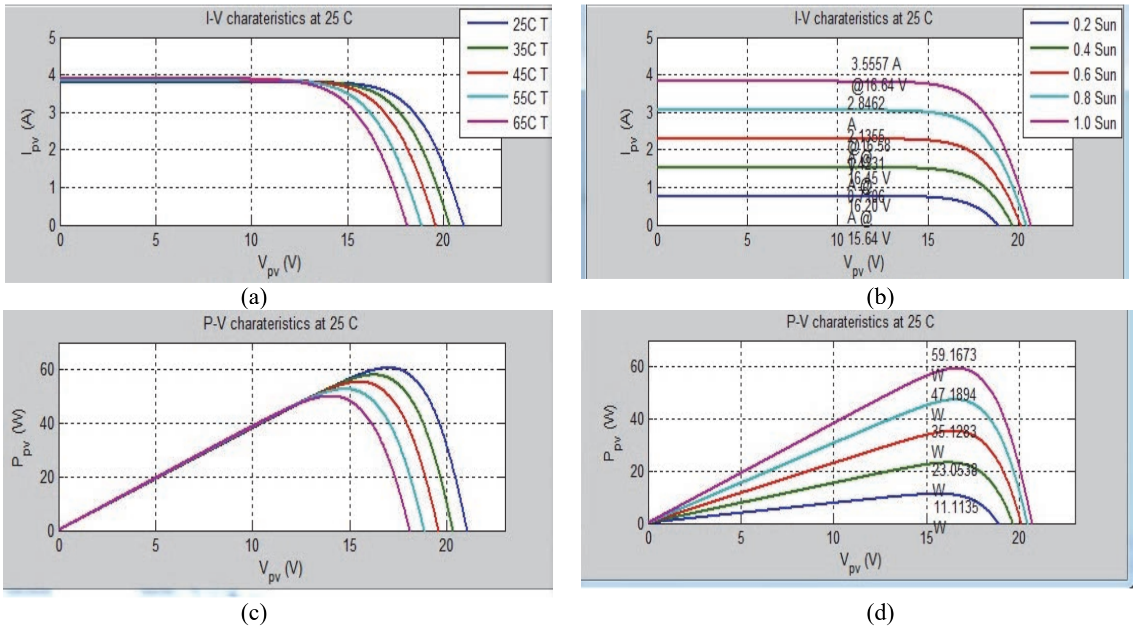


Fig. 4. Characteristics: (a) Current-voltage depending on temperature, (b) power-voltage characteristic based temperature, (c) current-voltage characteristics depending on irradiance, (d) power-voltage characteristics depending on irradiance

2.2. Super-capacitor model

For modelling the super-capacitor, it was considered the equivalent circuit of a super-capacitor represented in Fig. 5.

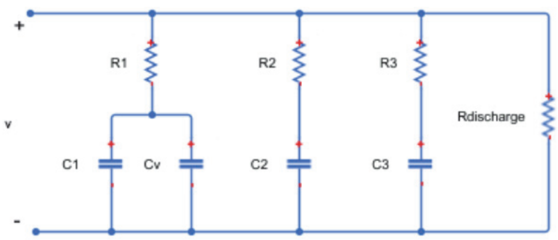


Fig. 5. Equivalent circuit model of a super-capacitor

$$V_{SC} = \frac{N_S Q_T d}{N_P N_e \varepsilon \varepsilon_0 A_i} + \frac{2 N_e N_S RT}{F} \sin h^{-1}\left(\frac{Q_T}{N_P N_e^2 A_i \sqrt{8RT}\,\varepsilon \varepsilon_0 C}\right) - R_{SC} \cdot i_{SC} \quad (3)$$

$$Q_T = \int i_{SC} dt \quad (4)$$

where the parameters are as follows: V_{SC} super-capacitor voltage (V); i_{SC} super-capacitor current (A); R_{SC} total resistance (Ω); N_p number of parallel super-capacitors; N_S number of series super-capacitors; N_e number of electrode's layers; Q_T electric charge; R ideal gas constant (8.3144598 J·mol^{-1}·K^{-1}); T operating temperature; F Faraday constant (96485.33289 C mol^{-1}); d molecular radius; A_i boundary region among electrolyte and electrodes; ε permittivity of the material; ε_0 permittivity of free space and c molar concentration.

According to Eqs. (5-6), it can be calculated the self-discharge of super-capacitors, when $i_{SC} = 0$.

$$Q_T = \int i_{self\_disch} dt \quad (5)$$

$$i_{self\_disch} = \begin{cases} \dfrac{C_T \alpha_1}{1 + sR_{SC} C_T} \\ \dfrac{C_T \alpha_2}{1 + sR_{SC} C_T} \\ \dfrac{C_T \alpha_3}{1 + sR_{SC} C_T} \end{cases} \quad (6)$$

where C_T is the total capacitance and $\alpha_1, \alpha_2, \alpha_3$ represents the voltage change rates of super-capacitor.

Capacitors C_1, C_2, C_3 and resistances R_1, R_2, R_3 have fixed capacitance, respectively resistance and the capacitance of capacitor C_v depends on the voltage across it.

The output voltage of capacitor can be calculated by using Eq. (7):

$$V_{cap} = \frac{v}{N_{series}} - i_n R_n \quad (7)$$

where: v is the voltage across the block; N_{series} is the number of series cells; n= [1, 2, 3] is the branch number; i_n is the current passed to n' th branch; R_n is the resistance in the n' th branch and V_{cap} is the voltage across the capacitor in the n' th branch.

Based on Eq. (7) the current will depend on the voltage across each capacitor branch and can be calculated according to Eqs. (8-9):

$$i_1 = \left(C_1 + K_v V_{C_1}\right) \frac{dV_{C_1}}{dt} \quad (8)$$

$$i_1 = C_1 \frac{dV_{c1}}{dt} \Leftrightarrow i_n = C_n \frac{dV_{cn}}{dt} \tag{9}$$

where: V_{c1} -voltage across the first branch; C_1-capacitance of the first branch; K_v -voltage-dependent capacitance gain and i_1-current in the first branch. In the equivalent equation n is the branch number and C_n is the capacitance of the n' th branch.

The total current of super-capacitor block is calculated according to Eq. (10):

$$i = N_{parallel}\left(i_1 + i_2 + i_3 + v \cdot \frac{1}{R_{discharge}}\right) \tag{10}$$

where $N_{parallel}$ represents the number of cells connected in parallel; $R_{discharge}$ is the self-discharge resistance of the super-capacitor and i is the current through the super-capacitor.

2.3. Battery storage system model

In control applications are prefered battery models based on equivalent circuits, due to their simplicity. It is quit difficult to develop a general model for batteries, having a complex behavior, taking into account thermal aspects. Thus the electrical behavior of a battery is a nonlinear function of a number of constantly changing parameters, such as internal temperature, state-of charge, rate of charge/discharge, etc.

In Fig. 6a (Knauff and McLaughlin, 2014) is represented the equivalent circuit model of a Lithium-Ion battery, used to test and monitor the behaviour of the battery bank. Based on this model can be express the equivalent ordinary differential equation (Eq. 11):

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -(R_1C_1)^{-1} & 0 \\ 0 & 0 & -(R_2C_2)^{-1} \end{bmatrix} x + \begin{bmatrix} -C_{capac}^{-1} \\ -C_1^{-1} \\ -C_2^{-1} \end{bmatrix} u \tag{11}$$

$$y = g(x_1) + x_2 + x_3 + R_S u$$

where R_1 and C_1 represents the resistance and the capacitance in short time constant of the RC circuit in the short time constant; C_{capac} is the overall capacitance of the battery; R_2 and C_2 are the resistance and capacitance in the longer time constant; R_s is the series resistance and $g(x)$ is a non-linear function used to define the relationship between state of charge (SOC) and open circuit voltage (VOC) of the battery. Input u of the system is the current entering in the battery and the output y is the voltage accross the battery terminals.

During tests, voltage and current at the battery terminals are monitored, internally based on the battery management system. Data, collected once per second, are saved via RS232 port, through the microcontroller, in a document from where can be interpreted. In test setup, the load is represented by a DC motor capable of discharging batteries and supercapacitors. Eq. (12) is used for state of charge calculation, where $V_{SOC}(0)$ represents the moment when the battery is fully charged and C_{capac} is the capacitance of battery.

$$V_{SOC}(t) = V_{SOC}(0) - \frac{1}{C_{capac}} \int_0^{\tau} i(\tau)\, d\tau \tag{12}$$

The power source, which connects the circuits from Fig. 6, is used to represent the nonlinear element of the relation between state of charge SOC and the open circuit voltage V_{OC} from battery. This relationship is normalized, so when the overall capacitance of the battery $C_{capac} = 1$, state of charge of battery is SOC =100. The equivalent circuit model does not include a self-discharge resistance and also the thermal effect.

Fig. 6(b) illustrates the equivalent circuit of the battery implemented in Matlab/Simulink. The equations (13, 14) for charging/discharging model for a lithium-ion battery are:

$$f_1(it, i^*, i) = E_0 - K\frac{Q}{Q-it} i^* - K\frac{Q}{Q-it} it + A\exp(-B \cdot it) \text{ (discharging model, } i^* > 0) \tag{13}$$

$$f_2(it, i^*, i) = E_0 - K\frac{Q}{Q-it} i^* - K\frac{Q}{Q-it} it + A \cdot \exp(-B \cdot it) \text{ (charging model, } i^* < 0) \tag{14}$$

where E_o is the constant voltage (V); $Exp(s)$ is the exponential zone dynamics (V); $Sel_{(s)}$ represents battery mode, 0 – discharging, 1 – charging; K is the polarization constant (Ah^{-1}), i^* is the low frequency current dynamics (A); i is the battery current (A); Q is the maximum capacity of battery (Ah); A is the exponential voltage (V) and B is the exponential capacity (Ah^{-1}).

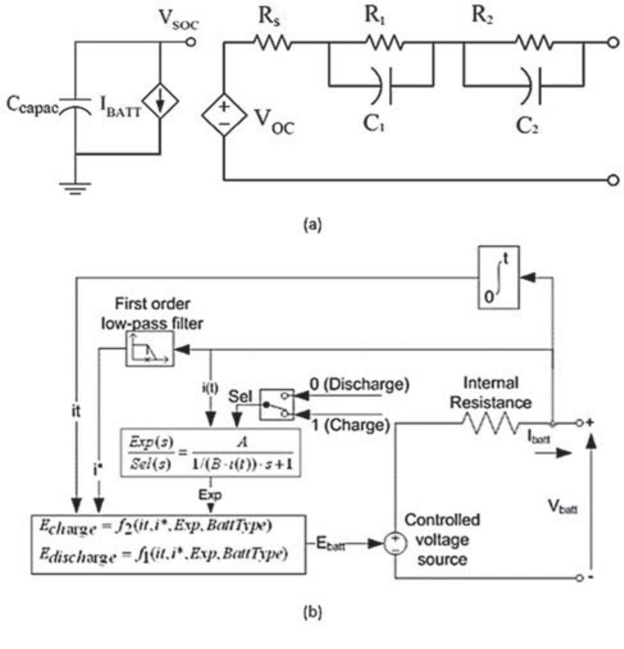


Fig. 6. (a) Equivalent circuit (b) simulink model of the li-ion battery

2.4. Energy management strategy

On electric vehicles, a very important aspect is the energy management system, which can be split in:

- ✓ hardware–components like sensors for measuring currents, voltages, systems for data acquisition;
- ✓ software–for calculation of state of charge, cell balancing, fault detection or user interface.

The performances of a hybrid energy system is strongly depend on the energy management strategy among energy sources. It is represented by a variety of algorithms that distribute the power between the energy storage devices, taking into account the dynamic characteristics of each one, so that they operate optimally.

Management algorithm has the purpose to satisfy the load demand and to produce renewable energy (Bendjedia and Alloui, 2016). This means that all of energy storage devices must be used in its most efficient way in order to maximally benefit from the hybrid concept. It is recommended to use safety circuits and the software to be designed in a „safety" mode to protect batteries to overcharge, over-heat or over-discharge. The proposed test bench is working with small voltages and currents (mA) and the objective of the model is to examine the power flows in the system and the behaviour of each energy source.

Depending on the energy management strategy, several objectives can be taken in consideration:

- protect energy sources-battery, supercapacitor and PV panel;
- ensure energy source life as long as possible;
- obtain at any moment of time electric energy available to power up an electric vehicle.

All three objectives mentioned above have been achieved by using on test bench systems to measure continously the voltage of each energy source and the current on the motor (Fathabadi, 2017). To protect all energy sources, battery and supercapacitor, software conditions have been imposed to keep a certain level of electric energy all time (Njoya and Dessaint, 2014). In battery case, the maximum discharge voltage is around 3V, considering that, if all the energy is dry completely, than for sure, the battery will be damaged.

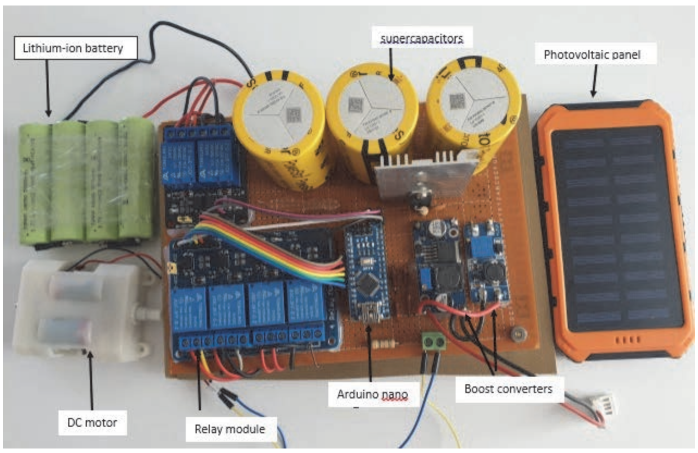
Energy management strategy is taking in consideration state of charge, charging time of each energy source, level of voltage and current suction by the motor (Koubaa and Krichen, 2017). During charging and discharging cycles on electric vehicle, it is mandatory that voltage and current in each energy source to be closely and as accurate as possible monitored, because any over-voltage or under-voltage conditions will damage the source.

In this paper, the energy management strategy it based on a simple algorithm, which keep the level of voltage in battery on min 3V and the supercapacitor voltage between 4V and 7V. Monitoring continously the voltage of each energy source, the PV panel delivers energy for charging either battery pack or supercapacitor, by coupling a set of relays. With this strategy, safety conditions are achieved without overheat of any energy source and protect the component itself.

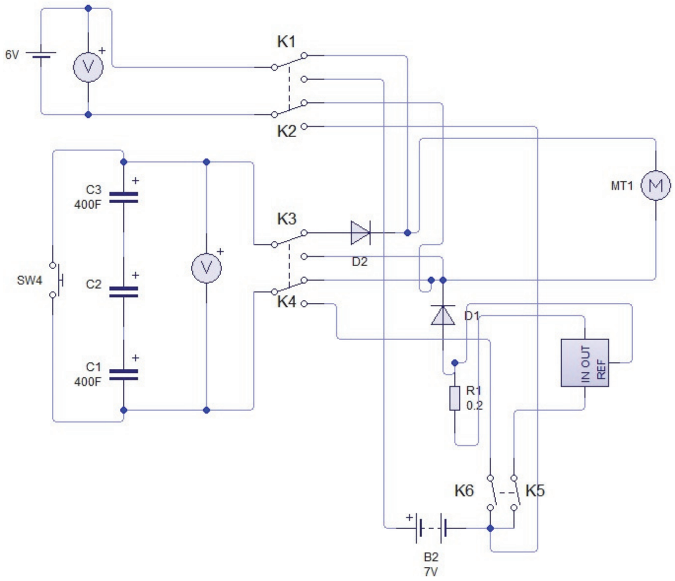
3. Case study

The test bench used in this paper (Fig. 7(a)) was created at small scale to study the behaviour of energy storage systems: batteries, super-capacitors and a photovoltaic panel. Also, it is provided with a monitoring system for voltage and current of all the power sources (Segundom and Cocota, 2015). The main components of the test bench are as follows:

- 3 super-capacitors in series of 2.7V, 400F Power Store XV series each;
- 4 batteries Li-Ion type, in series of 3.7V, 18650 mAh;
- a photovoltaic panel 10000mAh, which represent the power source for batteries and ultra capacitors;
- Arduino Nano, a type of programmer used to control electricity supply of a DC motor;
- two analogue channels, used to measure the voltage of each power energy source, super-capacitors and battery;
- a relay module, to control and to interchange the energy source, which gives power to the motor.



(a)



(b)

Fig. 7. (a) Experimental test bench; (b) Wiring diagram of the test bench

The 3 ultra-capacitors of 2.7V have been connected in series to obtain an equivalent voltage around 7V. The energy stored by a super-capacitor can be obtained according to (Eq. 15):

$$E_{supercap} = 0.5 * C*V^2 \tag{15}$$

where: *C is* the capacitance and *V is* the voltage.

If, it is taking account that the charge current of super-capacitor is 2A, and charging voltage, without boost converter is 5V, and with converter is 10V, it can be calculated the charging capacity with (Eq. 16):

$$I = C\frac{dv}{dt} \quad \Leftrightarrow \quad \frac{I}{C} = \frac{dv}{dt} \tag{16}$$

In this case study, supercapacitors are charged from solar panel, which has the output voltage of 5V, through a boost converter. In Table 3 are presented the characteristics of super-capacitors, which were used for test bench.

4. Proposed system, simulations and results

The analysis of hybrid energy system has been made by using the Livewire software, which represents a software package for designing and simulation of electronic circuits. Engineering software represents one of the most important tools in engineering education and also is very useful in teaching the working principles of electric circuits.

Using a circuit wizard can be identified faults in circuit design, saving a lot of time and money, before starting the production of PCB's. Different electronic components like resistors, capacitors, transistors and many other can be connected together to simulate and investigate the behaviour of circuits. Livewire software offers the possibility to choose components from a variety of libraries make different circuits and generate PCB layouts. Overall, circuit wizard represents an important tool for learning, designing and illustrate graphics for components, which are very realistic and intuitive to use.

The proposed system consists of solar panel, battery, supercapacitor, DC motor and relays, for switching to charging mode or supplying power mode. Solar panel acts as the main energy source of the system, battery and supercapacitors representing the power sources for the motor.

As it was mentioned above, the objective of the system is to study the power flow between energy sources. During simulations, it was observed that at high power demand of the system, for example in acceleration phases or climbing mode, both, battery and super-capacitor, provide power to the load, in this case a DC motor of 12V (1A, 2500rpm). Also, the battery fulfils the supply of continuous energy, while the super-capacitor provides the peaks power demand. When super-capacitors are not providing energy to the motor, then they will be switched to charging mode from photovoltaic panel.

Table 3. Characteristics of super-capacitor

Capacitance (F)	***Part number***	***Equivalence series resistance ($m\Omega$)***	***Max continuous current (A)***	***Peak current*** (A^3)	***Max power*** $(W)^5$	***Stored energy (Wh)***	***Typical mass (g)***
400	XV3560-2R7407-R	3.2	26	220	570	0.41	72

The actual configuration of the energy system has the advantage of providing energy to the motor, by battery, with voltage drop. The large discharging current is avoided, increasing in this way the life span of battery. Fig. 7 (b) illustrates the electrical drawing, which contains the main components of the model and the energy flow. Each energy source is provided with two relays, one for connecting/disconnecting from charging mode and one for supplying or not electric energy to the motor.

The microcontroller reads the voltage of battery and supercapacitor and set to operate at their minimum value to protect them. Also, the microcontroller decides the operating mode of each power source, charging mode, inverter mode based on the input parameters and the output energy that must be provided to the motor. During simulations, battery, having 14.8V in open circuit, will provide electric energy to the motor and when voltage drops under 4V, microcontroller will switch on charging mode and super-capacitors continuing to provide energy to the load. In this paper, it was not possible to introduce regenerative braking or any other method to recover energy. The only possibility to extend the autonomy of the vehicle is through the photovoltaic panel, so, even if the vehicle is parked somewhere, then charging mode is active. Solar panel in automotive industry can bring many advantages, being installed on the roof of the vehicles. Without depending on the number of charging stations, infrastructure or other inconvenient, photovoltaic panels can be installed on the roof of vehicles to absorb all the time energy from sunlight.

In Fig. 8 can be observed the Simulink model implemented in Matlab/Simulink and the results obtained with the test bench, discharging curve of battery and current of the motor. As a conclusion of simulations, batteries combined with super-capacitors, can represent a good solution for electric vehicles and photovoltaic panels can offer an important possibility to extend the range of the vehicle.

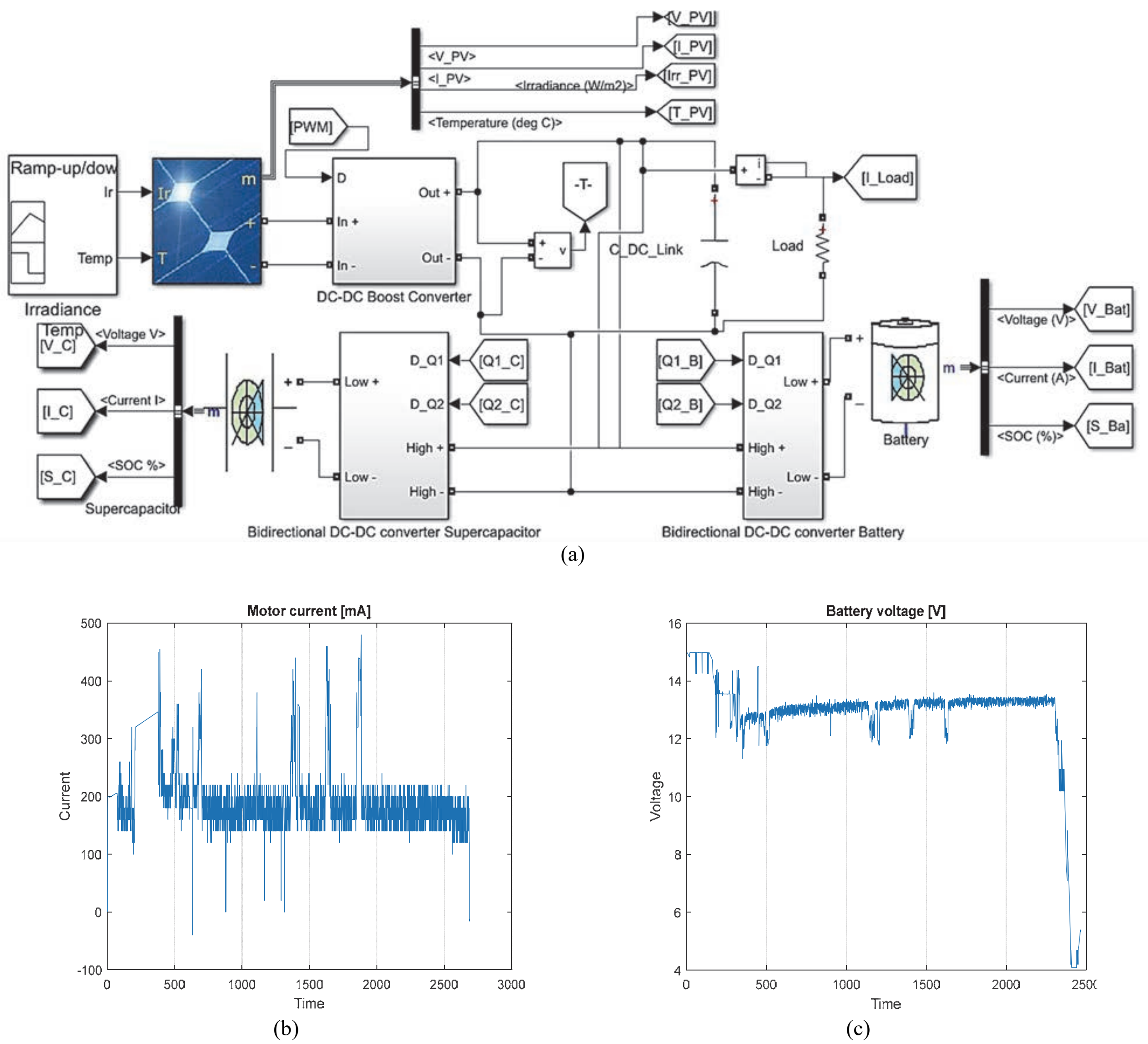


Fig. 8. (a) Simulink model of hybrid power source (b) Voltage of battery (c) Motor current

5. Conclusions

Using super-capacitors bank with batteries in the same time and photovoltaic panel as power source can represent a viable solution for different applications like electric vehicles, public transportation, electric ATV. An optimal use of super-capacitors requires a power controller, which means that a control strategy needs to be design.

As power source, has been considered a PV panel due to the fact that, this kind of energy source can be charged even if the vehicle is stationary, without being connected to any charging station or other device that requires cable, high current to charge in short time. It is, of course, a problem of sizing each power device, battery, super-capacitors and photovoltaic panel to obtain an optimal control.

The purpose of this paper is to bring into discussions aspects regarding a power energy solution, which can be continued with studies and extrapolated to a large scale stand. The objective of experimental test bench is to validate the performances of hybrid energy system with super-capacitors-battery, combined with a PV panel. At this moment, installing super-capacitors in an electric vehicle can represent a feasible method to improve performances and autonomy. The following aspects are the main advantages: better working conditions for battery, increasing the lifetime of battery, avoiding the large currents, which discharge batteries. Additionally, introducing a photovoltaic panel, the use of green energy can be increased.

To illustrate the performances of the energy sources, integrated in an energy storage system, there were used software like Matlab/Simulink, Livewire and Arduino. The system can monitor internal voltages of each energy source and display either on a plotter or register data in an excel file.

As future work, the test bench can serve for studies on higher scale and several solar panels can be used to obtain a fast charging of each energy sources.

References

Bendjedia B., Alloui H., Rizoug N., Boukhnifer M., Bouchafaa F., Benbouzid M.E., (2016), *Sizing and Energy Management Strategy for Hybrid FC/Battery Electric Vehicle*, IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, 2111-2116.

Djellad A., Logerais P.O., Omeiri A., Riou O., Durastanti J.F., (2014), Optimization of the energy transfer in a system combining photovoltaic source to ultracapacitors, *International Journal of Hydrogen Energy*, **39**, 15169-15177.

Eckard H., Marx P., (2012), Electric cars: technical characteristics and environmental impacts, *Environmental Science Europe*, **24**, https://doi.org/10.1186/2190-4715-24-14.

Knauff M., McLaughlin J., Dafis C., Niebur D., Singh P., Kwanty H., Nwanpka C., (2014), Simulink model of a lithium-ion battery for the hybrid power system testbed, On line at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.597.1705&rep=rep1&type=pdf.

Koubaa R., Krichen L., (2017), Double layer metaheuristic based energy management strategy for a fuel cell/super-capacitor hybrid electric vehicle, *Energy*, **133**, 1079-1093.

Myungchin K., Sungwoo B., (2017), Decentralized control of scalable photovoltaic (PV) – battery hybrid power system, *Applied Energy*, **188**, 444-445.

Njoya M., Dessaint S., (2014), A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft', *IEEE Transactions on Industrial Electronics*, **61**, 1320-1334.

Novelli V., Geatti P., Ceccon L., Gratton S., (2019), Biomass exploitation for energy supply and quality compost production. An exemplary case of circular economy in the north east of Italy, *Environmental Engineering and Management Journal,* **18**, 2163-2169.

Pranoy K.S., Bora K.H., Yanjun Y., Yazan A., (2019) Investigations into best cost battery - super capacitor hybrid energy storage system for utility scale PV array, *Journal of Energy Storage*, **22**, 50-59.

Segundom A.K., Cocota J.A., Hilário R.Q., Gomide V., Ferreira D.V., (2015) *Low Cost SCADA System for Education*, IEEE Global Engineering Education Conference, Tallinn, Estonia, 536-542.

Wenlong J., Chean H.L., Wallace S.H., Dennis M.L., (2017), Dynamic power allocation of battery-supercapacitor hybrid energy storage for standalone PV microgrid application, *Sustainable Energy Technologies and Assessments*, **22**, 55-64.

Wenlong J., Chean H.L., Wallace S.H., Dennis M.L., (2018), A comprehensive study of battery-supercapacitor hybrid energy storage system for standalone PV power system in rural electrification, *Applied Energy*, **224**, 340-356.

Web site:

https://www.cs.wmich.edu/~sunseeker/files/A-300%20data%20sheet.pdf