# WARSAW UNIVERSITY OF TECHNOLOGY

## Faculty of Electrical Engineering

# Hybrid energy storage system (HESS) in electric vehicle (EV)

## INDIVIDUAL PROJECT

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# INTRODUCTION.

The efficiency and all-electric range of electric vehicles (EVs) depend on the capability of their energy storage system (ESS), which not only is utilized to store large amounts of energy but also should be able to release it quickly according to load demands [1].

The important characteristics of vehicular ESSs include:

- Energy density.
- Power density.
- Lifetime.
- Cost.
- Maintenance.

In battery-based ESSs, several challenges are observed [2]:

- Power density of the battery needs to be high enough to meet the peak power demand. Although batteries with higher power densities are available, they are typically priced much higher than their lower power density counterparts. A typical solution to this problem is to increase the size of the battery, however, this also causes an increase in cost.
- Thermal management is a challenge for the batteries to safely work in high power-load conditions not only to cool down, but also to warm up the battery in cold temperatures in order to reach the desired power limits.
- The life of the battery is affected by the balancing of the cells in a battery system. Without the balancing system, the individual cell voltages tend to drift apart over time. The capacity of the total pack then decreases rapidly during operation, which might result in the failure of the total battery system. This condition is especially severe when the battery is used to do high-rate charge and discharge.
- Also, applications that require instantaneous power input and output typically find batteries suffering from frequent charge and discharge operations, which have an adverse effect on battery life.

For such systems, it is crucial to have an additional ESS or buffer that is much more robust in handling these work conditions. In order to solve the problems listed previously, hybrid energy storage systems (HESS) have been proposed.

The basic idea of an HESS is to combine supercapacitors (SCs) and batteries to achieve a better overall performance. Generally, SCs have specific energy in the range of 1 to 10 Wh/kg and high specific power in the range of 1000 to 5000 W/kg. The charge/discharge efficiency of supercapacitors is very high, ranging from 85% to 98%, and the rate of discharge can be fast, ranging from 0.3 to 30 s. In the other hand, batteries as the lithium-ion rechargeable battery has a higher specific energy in the range of 50 to 500 Wh/kg and a lower specific power between 10 and 500 W/kg. Its charge/dis-charge efficiency is in the range of 75% to 90%, and the rate of discharge is typically between 0.3 and 3 h. These properties allow the combination of these two sources to exhibit both high power and energy density. Also, this combination with the proper configuration allow us to protect the batteries and increase its lifetime [3].

Several configurations for HESS designs have been proposed [1], [2], which range from simple to complex circuits. Most of these configurations share one common feature, which is to efficiently combine fast response devices with high power density (SCs) and slow response components with high energy density (Batteries). For battery/SC systems, bidirectional DC/DC converters are widely used to manage power flow directions, either from the source to the load side for acceleration or from the load side to sources during regeneration. Based on the use of the power electronic converters in the configurations, HESS can be classified into two types: passive or active.

The objective of the paper is to propose different energy management strategies for HESS using batteries and supercapacitors. In this paper, three different types of energy management strategies used in HESS will be proposed to solve the problem of the peak power demands and the suffering of the battery from frequent charge and discharge operations and its thermal-electric consequences. Furthermore, the model and the control of the studied Electric Vehicle (EV) with HESS are presented and designed. This model and control are tested using ideal DC sources instead of the real energy storage systems. Finally, an EV with batteries and supercapacitors are compared for the different strategies on different criteria. In conclusion, one of this strategies is chosen and the proposed HESS will be presented and verified through some simulation in detail.

## ENERGY MANAGEMENT STRATEGIES.

The objective of the energy management strategies of HESS is that the batteries supply the average power and the supercapacitor the power fluctuations. These elaborated strategies are studied to come up with this expectation:

| Supercapacitor | Power density | Power variations |
|---|---|---|
| Batteries | Energy density | Average power |

Controlling the velocity of the EV, it is possible to simulate and control the power demand of the vehicle. This means knowing what the power demand during the vehicle performance looks like, the aim of the strategies is to cover it using the batteries and supercapacitors.

The velocity reference (control) of the EV and the resulting power demand during the operation of the EV is shown in Fig. 1.
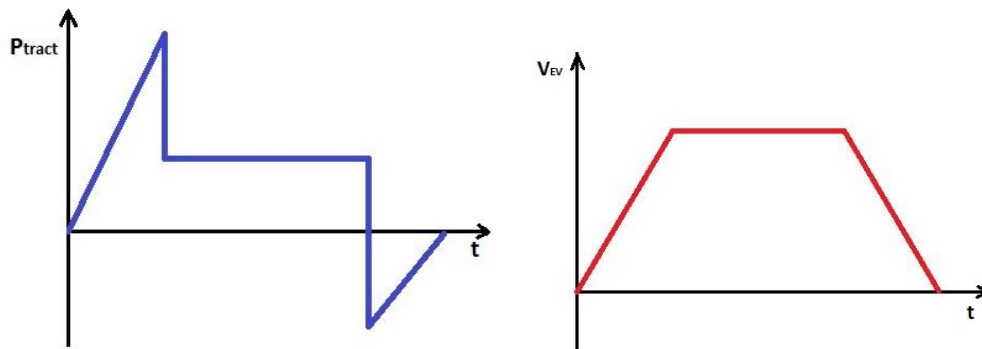


*Fig. 1 – Power and velocity profile of an electric vehicle during a drive cycle.*

For all proposed strategies, the supercapacitors have not to reach their lower voltage limitation. The first idea is to recharge them using the batteries as soon as the vehicle is not moving. The second idea is to use the deceleration energy to recharge the supercapacitors.

For this paper, three energy management strategies are proposed:

### 1) Vehicle acceleration strategy:

Based on the model of an EV, the traction force $F_{tract}$ is composed of a global resistive force $F_{res}$ and an imaginary force function of the vehicle acceleration $F_{acc}$ (force of inertia) which needs the more important power demand $P_{acc}$. For this strategy, the supercapacitor supply and receive the power $P_{acc}$. The batteries supply and receive the rest of the traction power $P_{tract}$, i.e. the power $P_{res}$ [4].

$$F_{tract} = F_{acc} + F_{res} \tag{1}$$

Where: $$F_{acc} = M_{veh} \cdot a_{veh} \tag{2}$$

The power is obtained multiplying all the force by the velocity of the vehicle according Eq. 3:

$$P_{tract} = P_{acc} + P_{res} \tag{3}$$

Where: $$P_{acc} = V_{veh} \cdot F_{acc} \tag{4}$$
$$P_{res} = V_{veh} \cdot F_{res} \tag{5}$$

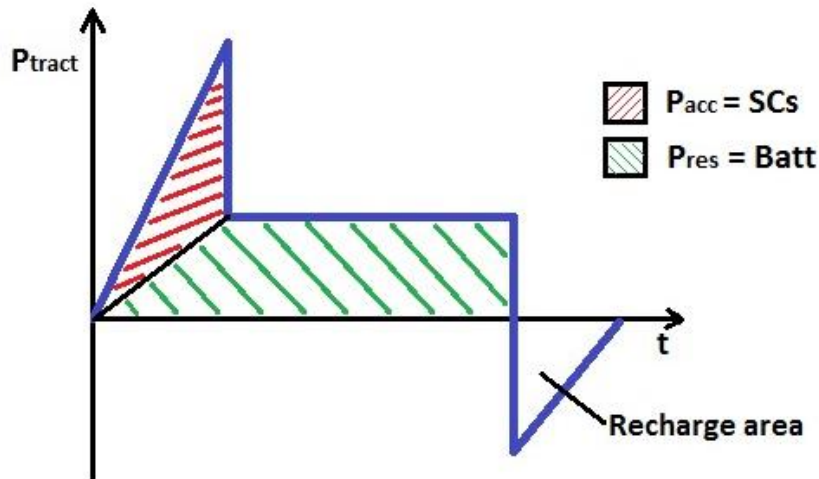The power demand ($P_{tract}$) graph applying this strategy will look like Fig. 2.



*Fig. 2 – Power demand strategy.*

## 2) Limit the power supplied or received by the batteries using a variable saturation current strategy:

The idea of this second strategy is to limit the power supplied or received by the batteries using power electronics. The strategy is based on the possibility of having different topologies when configuring a HESS. In this case, adding a DC/DC converter between the battery and the rest of the components, the battery current can be perfectly controlled and limited anytime. The power demand of the motor $P_{tract}$, depends on the load current $i_{tract}$ and the voltage $U_{DC}$ on the DC Bus. The value of $i_{tract}$ and $U_{DC}$ depend, at the same time, on the topology of the HESS.

$$P_{tract} = I_{tract} \cdot U_{DC} \tag{6}$$
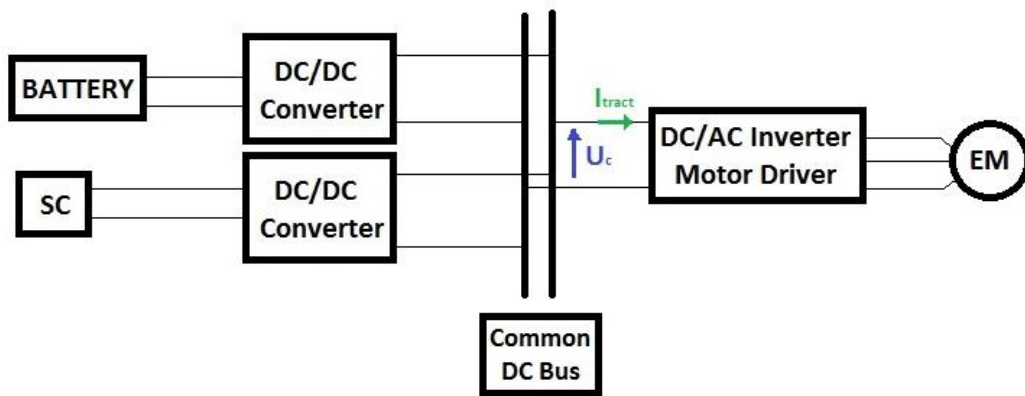
Basic configuration is shown in Fig. 3.



*Fig. 3 – Hybrid Energy Storage System configuration.*

As the DC Bus voltage is maintained constant, the current $i_{batt}$ is limited using the DC/DC converter. The battery supplies and receives $I_{tract}$ as long as it is smaller than the saturation current $i_{batt\_sat.}$ .The supercapacitor supplies the rest of the traction power and it is controlled by another DC/DC converter[4].

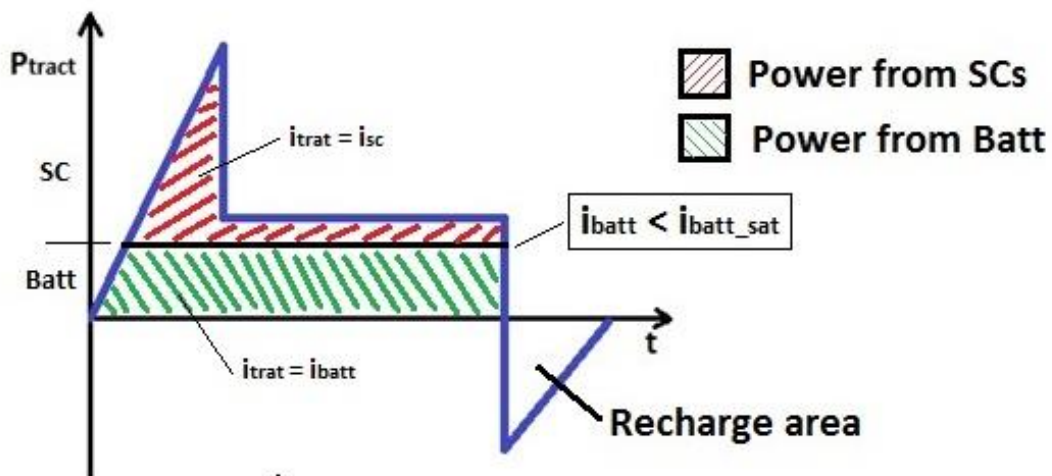The power demand ($P_{tract}$) graph applying this strategy will look like Fig. 4.



*Fig. 4 – Power demand strategy.*

### 3) Control the supply current (power) according to a source resistance strategy

As the second strategy, it is also based in controlling the current flow with the help of the power electronics. The principle of operation of this third strategy consists of two parts that are described as follows [3].

- When the load current is small, the converter is controlled so that the battery discharges at a constant rate regardless of the battery voltage variation, and it charges the supercapacitor. To protect the battery, the current is controlled so as to not exceed a current reference limit.
- Secondly, when the load current is high, both the battery and the supercapacitor supply current to the load. However, the battery current is still controlled at the same constant rate so that the rest of the current, at a much higher level, will be supplied by the supercapacitor.

Generally, the internal battery resistance is more important than the internal supercapacitor resistance. Thus, for a same current, there are more losses in the batteries than in the supercapacitors. As long as there is any load current, $i_{tract}$ (acceleration phase), the control limit of the current is defined from the current $i_{batt\_ref}$, calculated to minimize the global losses of the HESS [4].

By controlling the battery current at a constant value ($i_{batt\_ref}$) throughout the operating cycle, the battery is in an extremely steady state. Therefore, it is electrically and thermally preferred for the sake of a safe and long lifetime. Most importantly, the HESS provides a much higher power without drawing an excessive current from the battery.

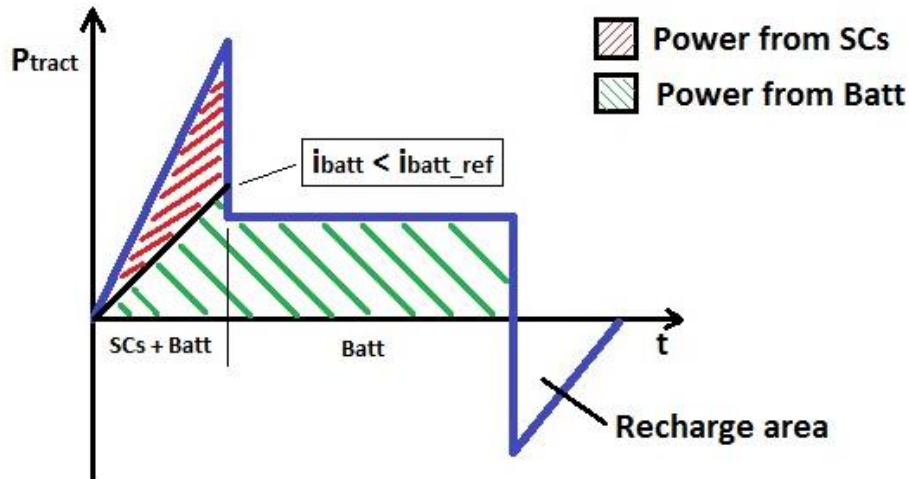The power demand ($P_{tract}$) graph applying this strategy will look like Fig. 5.



*Fig. 5 – Power demand strategy.*

# ELECTRIC VEHICLE (EV) MODEL.

In order to implement the strategies and study the configuration and power flow control of HESS, it is necessary to design a mathematical model of a dynamic electric car [5]. This model must be able to be connected to the future model HESS. With this final model, a study will be carried out using simulations and comparison results, according to the most convenient strategy.

The EV dynamic model is based on the forces involved on the vehicle performance. The forces which the vehicle must overcome are the forces due to gravity, air-wind, rolling resistance, and inertial effect. In this particular model, the traction force from the wheels ($F_{tract}$) must overcome the inertial effect and total resistive force ($F_{res}$), which is formed only by the rolling force ($F_{roll}$) and air friction force ($F_{air}$), neglecting the gravity effect. These forces can be calculated as shown next [6]:

- Rolling friction force: $\quad F_{roll} = C_r \cdot M \cdot g \cdot cos(\alpha)$ (7)
- Air-drag friction force: $\quad F_{air} = \dfrac{1}{2} \cdot C_d \cdot d \cdot A \cdot v^2$ (8)
- Total resistive force: $\quad F_{res} = F_{roll} + F_{air}$ (9)

The EV model is obtained using the Eq. 10, based on dynamic physics. The formula is dependent on the vehicle velocity (v).

$$\frac{dv}{dt} = \frac{1}{M} \cdot F_{tract} - \frac{1}{M} \cdot F_{res}$$ (10)

To complete the model, the following parameters for the vehicle and the external forces have been chosen. There are real parameters taken from a Tesla Car Model. The parameters are shown in Table 1.

| Symbol | Parameter's definition | Value |
|:------:|:----------------------|:------|
| $M$ | Vehicle's mass | 2300 kg |
| $C_d$ | Drag coefficient | 0.24 |
| $d$ | Density of air | 1.29 kg/m³ |
| $A$ | Frontal area of the car | 2.3 m² |
| $C_r$ | Friction coefficient | 0.015 |
| $g$ | Gravity acceleration | 9.81 m/s² |
| $\alpha$ | Inclination of the road | 0º |

*Table 1- Parameters for the electrical vehicle and the external forces.*

The final EV model is implemented using Simulink/MATLAB. The model is controlling with the velocity of the vehicle ($V_{ref}$), as said before. EV model is shown in Fig. 6.
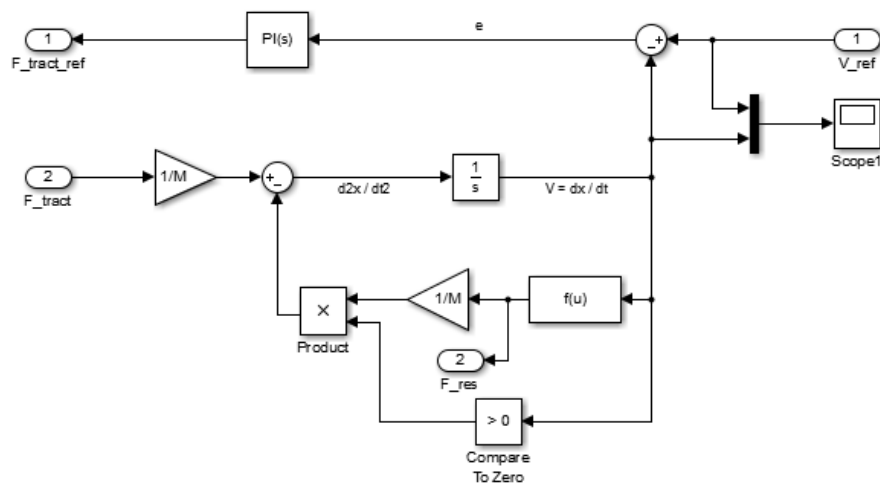
*Fig. 6 – Electrical Vehicle Model.*

The sequence source from Simulink creates the velocity reference sign of the vehicle as wanted (Blue line). Using this velocity reference sign, the real velocity (Violet line) is controlled. Both velocities are on the Fig. 7. Theoretical power demand expected from the EV is obtained from the Simulink model (Fig. 8).
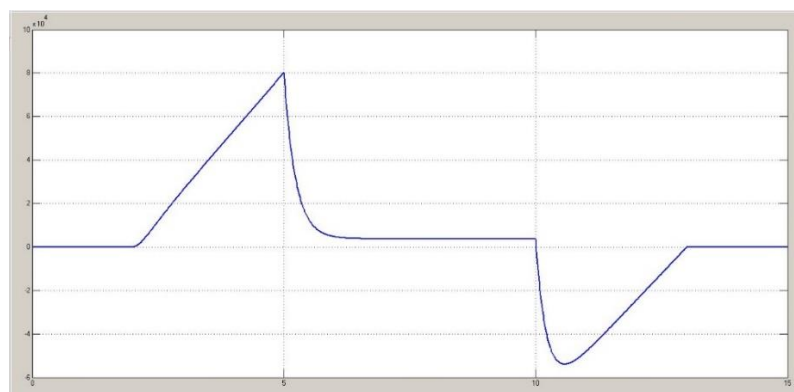


*Fig. 7 – Velocity control.*



*Fig. 8 – Power demand.*

# BASIC HYBRID ENERGY STORAGE SYSTEM (HESS) MODEL.

Limited space is available in the vehicle for energy storage system. This space must be appropriately shared among the energy and power systems. There are different ways for the configuration of the energy storages in a HESS [7].

A simple approach is the direct DC coupling of the two storages. The main advantage is the simplicity and cost-effectiveness of this approach. Moreover, the DC-bus voltage experiences only small variations. The main disadvantage is the lack of possibilities for power flow control and energy management with a resulting ineffective utilization of the storages (small percentage of the supercapacitors capacity can be utilized when operated within the voltage of the battery).

The second energy storage configuration in a HESS is by one bidirectional DC/DC converter. The converter can either be connected to the "high-power" or to the "high-energy" storage. In the latter case the "high-energy" storage can be protected against peak power and fast load fluctuations. The DC/DC converter then operates in current-controlled mode. The main disadvantage of this configuration is the fluctuation of the DC-bus voltage, which is identical to the voltage of the "high-power" storage.

The third and most promising configuration consists of the two DC/DC converters. Here the parallel converter topology is very common (Fig. 9). The additional DC/DC-converter associated with the "high-power" storage is in charge of the voltage regulation of the DC-bus. It helps to operate the "high-power" storage in a broader voltage band, and hereby the available storage capacity is better utilized. Disadvantages of the two converter configuration are higher complexity and slightly higher costs, mostly because of the DC/DC.
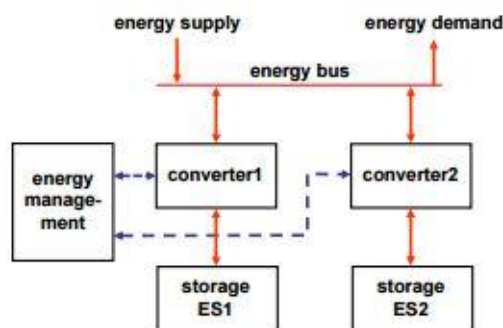


*Fig. 9 – HESS with parallel converter topology* [7]*.*

For the HESS model, the third configuration is used. It consists of two DC/DC converters in parallel with the battery (high-energy storage) and the supercapacitors (high-power storage). For the creation of the HESS model, the voltage of the DC bus is considered constant.

$$U_{DC} = constant \tag{11}$$

However, using multiple different energy storage technologies does not guarantee improved energy efficiency [8]. Intelligent control and optimized management of the power flow distribution is essential for a good operation of any HESS. Furthermore, the energy management system controlling the HESS must also reflect the chosen strategy designed.

From the energy management system, a supervisory controller is defined using inversion rules to arrange the power flow. In particular, it needs a controller to control the DC bus voltage, and two controllers to control the batteries and the supercapacitors currents. The two DC/DC converters used to interface the SC and the batteries with the DC bus is the only actuator in terms of the energy management algorithm.

The supervisor controller gathers the information of the supercapacitors, batteries and power demand and controls the power distribution based on the chosen strategy. A distribution coefficient $k_{ref}$ is introduced to distribute the power between the batteries and the supercapacitors [4]:

$$P_{battery} = k_{ref} \cdot P_{demand}$$
$$P_{supercapacitor} = (1 - k_{ref}) \cdot P_{demand}$$

(12)

When $k_{ref}$ = 0 the power flow is provided by the supercapacitors, when $k_{ref}$ = 1 the power flow is provided by the batteries, when $k_{ref}$ has another value in between it defines the power sharing between both devices. A strategy block called $k_{ref}$ is added in order to impose the power sharing. The based-inversion control of the traction part is focused on the control of the velocity of the vehicle as said. This power flow has a direct relation with the current supply or receive by the storage system (SCs and batteries).

The DC/DC converters play a big role in the design of a good configuration of HESS, so it does for the creation of the HESS model. The simple way to describe a DC/DC converter is based on a relation between voltages and currents in both sides of the converter. This relation is controlled by the modulation coefficient, which is the logical controlling part of the converter. This relation is shown in the next formula:

$$m_1 = \frac{U_1}{U_{DC}} = \frac{i_1}{i_{batt}}$$

(13)

For electric car application, the most popular DC/DC converter use is the DC/DC Bidirectional boost converter (or buck). It allows the power flow for any direction.
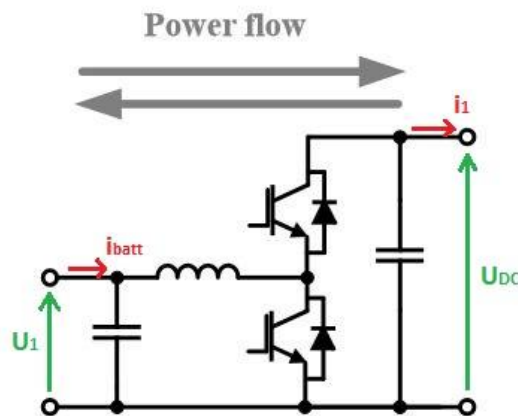


Fig. 10 – DC/DC Bidirectional boost converter (or buck).

### Basic model of HESS with DC source:

Taking in account all the conditions described before and using Simulink/MATLAB, a basic model of the Hybrid Energy Storage System is created. To test the operation of the model, a DC ideal source issued. The basic HESS and the vehicle will be supplied by two DC source replacing the battery and supercapacitor. This first model is simpler than the final one, and the controlling part is not completely design.


### Simulation of HESS with two DC sources:

In order to simulate, some parameters must be chosen and added to the EV parameters to complete the basic HESS model. For the two ideal DC sources, which are replacing the real energy storage systems, the internal resistance value ($R_i$) and the DC source voltage value (E) are equal to: $R_i$ = 0.01 Ω and E = 500 V. Furthermore, the DC Bus line which connects the EV with the energy storage system has a voltage value. This voltage value of the DC Bus is considered constant and equal to $U_{DC}$ = 600 V.

The simulation of the basic HESS model is based on the control of the velocity during the drive cycle (Fig. 11) and the power distribution on the chosen strategy. For this basic simulation, due to the fact that both energy storage systems are ideal and equal DC sources, any strategy has been chosen, however, a $k_{ref}$ value equal 0.3 has been selected for the energy management system to prove the based-inverse control.
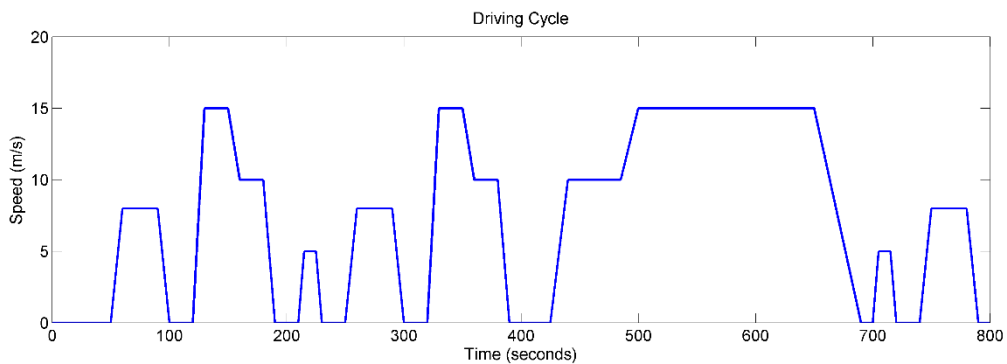


*Fig. 11 – Electrical vehicle's velocity reference profile during the drive cycle of 200 seconds design to control the velocity during the drive cycle.*

# FINAL HESS MODEL WITH BATTERIES AND SUPERCAPACITORS.

### Battery model:

Batteries have been adopted in energy storage system of ground vehicles due to their characteristics in terms of high energy density, compact size, and reliability. New kind of batteries have been developed to propose more efficient ESS which can supply an electric car, such as: Nickel–Metal Hydride (NiMH) batteries and Lithium-Ion Batteries.

The promising aspects of the Li-ion batteries [1] include low memory effect, high specific power of 300 W/kg, high specific energy of 100 Wh/kg, and long battery life of 1000 cycles. These excellent characteristics give the lithium-ion battery a high possibility of replacing NiMH as next-generation batteries for vehicles.

Battery is a storage device which consists of one or more electrochemical cells that convert the stored chemical energy into electrical energy. There are several characteristics that one should take into account in selecting the most appropriate battery for EV. The most significant characteristic is the battery capacity, which is measured in A·h. Besides that, the energy stored in battery (capacity · average voltage during discharge) which is measured in W·h should be carefully calculated [9].

For this particular model, Lithium-Ion Batteries are used. The main parameters of the Lithium–iron phosphate (LiFePO$_4$) battery cell are listed in Table 2. This parameters are available on manufactures data-sheet [10]

| Parameter's definition | Value |
|---|---|
| Nominal voltage, $U_{batt\_cell}$ (V) | 3.2 |
| Nominal capacity, $C_{batt\_cell}$ (Ah) | 45 |
| Specific energy density (Wh/kg) | 146 |
| Internal Impedance AC 1000 Hz (mΩ) | <2 |
| Recommended current charge/discharge (A) | 22.5/45 |
| Max. Current charge/discharge (A) | 45/135 |
| Weight (kg) | 0.99 |

*Table 2 – Parameters of the Lithium–iron phosphate (LiFePO$_4$) battery cell.*

The hybrid supply system is sized according to the energy need. In the HESS, most of the energy is stored in the battery due to the low energy density of the SC. The stored energy is proportional to the vehicle performance. Due to the DC bus voltage ($U_{DC}$) is fixed in relation to the motor power, using the nominal battery cell voltage ($U_{batt\_cell}$), the number of series cells of battery pack ($N_{batt\_S}$) is deduced according to Eq. 14.

$$N_{batt_S} \leq \frac{U_{system}}{U_{batt_{cell}}} = \frac{U_{DC}}{U_{batt_{cell}}} \tag{14}$$

The number of parallel batteries branches ($N_{batt\_P}$) is evaluated according to the consumed energy ($E_{demand}$) for the EV. The characteristic of driving cycle of the simulation are: distance = 6.44 km and $E_{consumed}$ = 769.44 Wh. Considering that the EV should have a range of at least 200 km, the energy consumed is equal to $E_{demand}$ = 2.39 x10$^4$ Wh. The energy demand is calculated by the simulation. The calculations for the number of parallel batteries branches are made according to Eq. 15.

$$N_{batt_P} \leq \frac{E_{demand}}{N_{batt_S} \cdot \left( \left( U_{batt_{cell}} \cdot C_{batt_{cell}} \right) - \eta_{EW} \cdot W_{batt_{cell}} \right)} \tag{15}$$

Where $\eta_{E\_W}$ is the energy-weight efficiency and its calculated according Eq. 16.

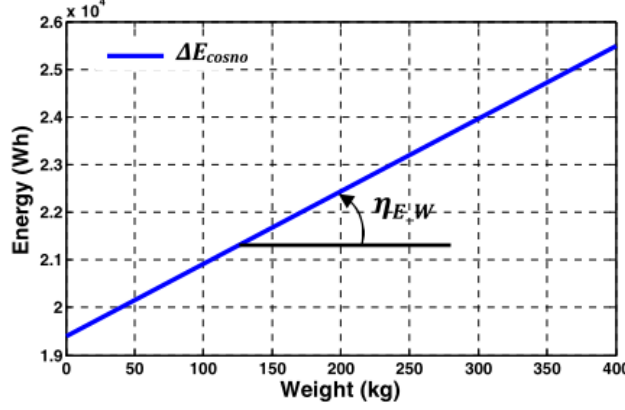$$\eta_{Ew} = tan^{-1} \left( \frac{E_{demand}}{W_{batt_{cell}}} \right) \tag{16}$$



*Fig. 12 – Energy variation versus weight [11].*

The battery pack voltage and capacity is calculated using Eq. 17, respectively.

$$U_{batt} = U_{batt_{cell}} \cdot N_{batt_S}$$
$$C_{batt} = C_{batt_{cell}} \cdot C_{batt_P} \tag{17}$$

The final battery sizing according to the previous description [11], and the driving cycle simulated, is shown in Table 3.

| Battery Pack Parameters | $U_{batt}$ = 384 V; $C_{batt}$ = 45 Ah |
|---|---|
| Battery Pack Configuration | 120 cells in series and 1 parallel battery branches |

*Table 3 – Battery pack parameters and configuration.*

The battery behavior can be represented by the $R_{int}$ model due to its simplicity and sufficient accuracy. However, for the model of HESS, the battery model given by Simulink/ MATLAB library is used.
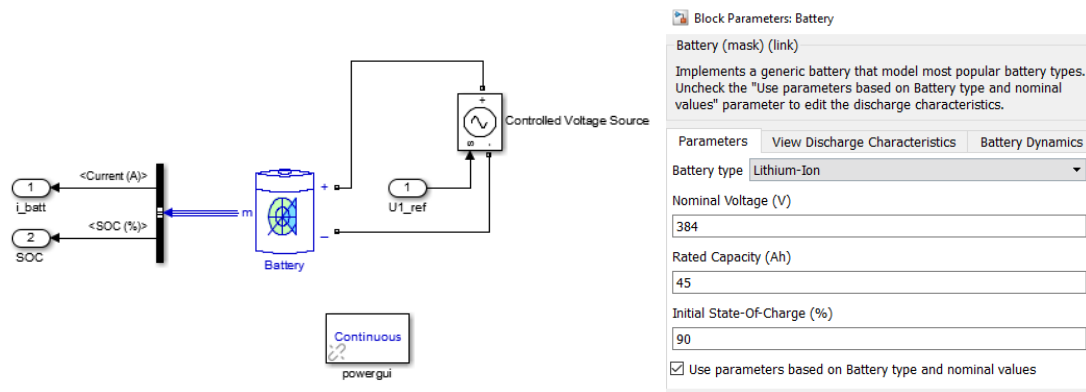


*Fig. 13 – Simulink/ MATLAB Battery model.*

**Supercapacitor model**:

Supercapacitor (SC) has a similar structure with a normal capacitor, but the difference is that SC have high capacitance (high energy capacity with factor of 20 times) than capacitor. The SC stores energy by physically separating positive and negative charges. The charges are stored on two parallel plates divided by an insulator. Since there are no chemical variations on the electrodes, therefore, SCs have a long cycle life but low energy density.

Currently, there are three types SC technologies used in EV: electric double-layer capacitors (EDLC-carbon/carbon), pseudo- capacitors and hybrid capacitors. The difference between those SC is in their energy storage mechanisms and their electrode materials used. There is also some differences in their energy storage characteristic [9].

For this particular model, the supercapacitors Maxwell 2.7/350F are proposed. The main parameters of the Maxwell 2.7/350F supercapacitor are listed in Table 4. This parameters are available on manufactures data-sheet [12]

| Parameter's definition | Value |
|---|---|
| Nominal voltage, $U_{sc\_cell}$ (V) | 2.7 |
| Capacity (F) | 350 |
| Max. Voltage (V) | 2.85 |
| Internal resistance (Ω) | 0.0008 |
| Power density (W/kg) | 4600 |
| Specific Energy (Wh/kg) | 5.9 |
| Weight (kg) | 0.063 |

*Table 4 - Parameters of the supercapacitors Maxwell 2.7/350F.*

After the sizing of battery pack, it can be calculate its maximum charging and discharging powers and the energy available as said. The difference between the power needed for the driving cycle and the battery power, give us the supercapacitor pack power and the value of energy requirement of the SC.

The number of SCs connected in series can be obtained, also, due to the DC bus voltage ($U_{DC}$) is fixed in relation to the motor power. Using the nominal supercapacitor cell voltage ($U_{sc\_cell}$), the number of series cells of supercapacitor pack ($N_{sc\_S}$) is deduced according to Eq. 18.

$$N_{sc\_S} \leq \frac{U_{DC}}{U_{sc\_cell}} \tag{18}$$

To calculate the number of supercapacitors branches in parallel, the values of the power and energy for the two components (battery and supercapacitor) are specified. The limitation of the battery power for the charge and discharge phases give us the power and the energy of the supercapacitor. Obtaining the value of $E_{sc\_max}$ from Eq. 19 according to the simulation of the power demand (Fig. 14), the number of parallel cells of SC pack ($N_{sc\_P}$) is calculated according to Eq. 20.

$$E_{sc}(t_p) = \int_{t_0}^{t_0+t_p} [P_{sc}(t) - P_{sc}(t_0)]dt = Green\ area\ under\ P_{demand}(t) \tag{19}$$

$$N_{sc\_P} \geq \frac{8 \cdot E_{sc\_max}}{3 \cdot U_{sc\_max}^2} \cdot \frac{N_{sc\_S}}{C_{sc\_cell}} \qquad (20)$$
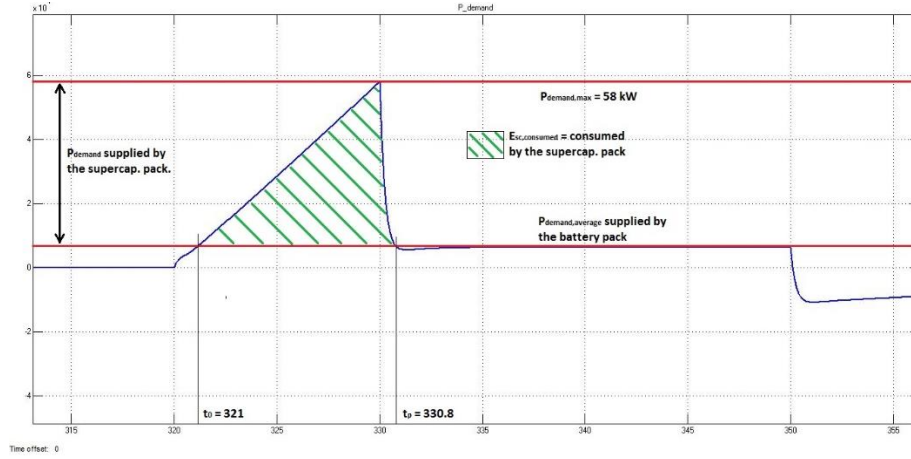


Fig. 14 – Pat of the simulation of the power demand where the peak of power is happening and the energy consumed by the storage systems will be maximum.

The final supercapacitor sizing according to the previous description [11], and the driving cycle simulated, is shown in Table 5.

| Supercapacitor Pack Parameters | $U_{sc}$ = 486 V; $C_{sc}$ = 3.88 F |
|---|---|
| Supercapacitor Pack Configuration | 180 SC cells in series and 2 parallel SC branches |

Table 5 – Battery pack parameters and configuration

For the modeling of the SC behavior, the $R_{int}$-Capacity model [13] is used and shown in Fig. 15. This simply model was adopted to represent the characteristic of the SC pack due to its simplicity and sufficient accuracy. The mathematical equation (21), it is used to implement the supercapacitor model in Simulink/MATLAB. The parameters for the SC bank model are listed in Table 6.

$$U_{sc} - R_{sc}i_{sc} - U_2 = 0 \rightarrow \quad U_{sc} - R_{sc} \cdot C\frac{dU_{sc}}{dt} - U_2 \rightarrow \quad \frac{dU_{sc}}{dt} = \frac{U_{sc}}{R_{sc} \cdot C_{sc}} - \frac{U_2}{R_{sc} \cdot C_{sc}} \quad (21)$$



Fig. 15 - $R_{int}$-Capacity model
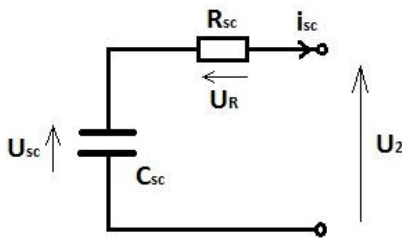
| Parameter's definition | Value |
|---|---|
| Internal resistance of the SC bank, $R_{sc}$ | 0.001 Ω |
| Capacitance of the SC bank, $C_{sc}$ | 3.88 F |
| Initial voltage state, $U_{sc0}$ | 500 V |

Table 6 - The parameters for the SC bank model

# SIMULATION OF FINAL HESS MODEL WITH CHOSEN ENERGY MANAGEMENT STRATEGY.

### Final energy management strategy:

Based on the results proposed in [13], a ruled-based energy management strategy is created and proposed in Fig. 16. This strategy can be combined with one of the previous strategies proposed to obtain an optimal strategy.

The power split processes derived from the proposed rule-based power/energy management strategy and one of the control strategies along the driving cycle created, will be obtained after the simulation. However, firstly this strategy has to be implemented in the EV-HESS model.
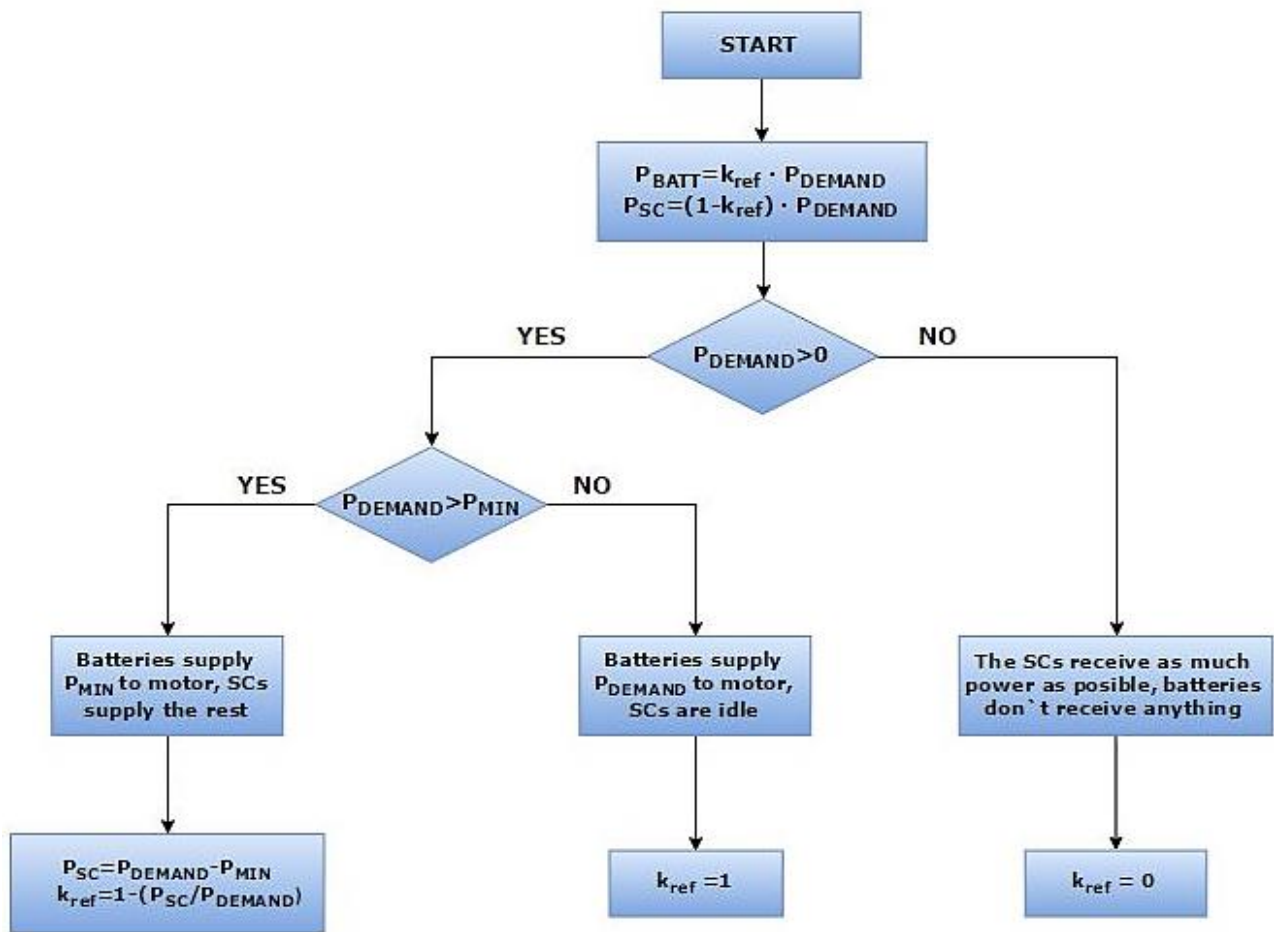


*Fig. 16 – Flow-diagram of the proposed rule-based strategy for the power flow of the HESS.*

To complete the energy management system, the three proposed strategies must be implemented on the proposed rule-based strategy for the power flow of the HESS. By the value of $k_{ref}$, the power is supplied and received by one or both energy storage system. However, this decision is made depending on the value of the power demanded.

As can be seen from the flow-diagram, there are two conditions imposed to the power value: the first condition is whether or not there is power demand ($P_{DEMAND} > 0$). The second condition is related to the three proposed strategies, the power demand is compared to a power limit chosen and calculated value ($P_{DEMAND} > P_{MIN}$).

The value of this power limit, $P_{MIN}$ could be calculated according to the three proposed strategies as follow:

1) Vehicle acceleration strategy:

$$P_{MIN} = P_{res} = F_{res} \cdot Velocity \qquad (22)$$

2) Limit the power supplied or received by the batteries using a variable saturation current strategy:

$$P_{MIN} = i_{batt_{sat}} \cdot m_{1_{ref}} \cdot U_{DC} \qquad (23)$$

Where:
$i_{batt_{sat}}$ = saturation current of the battery.
$m_{1_{ref}}$ = modulation of the DC/DC converter connected to the battery.

3) Control the supply current (power) according to a source resistance strategy

$$P_{MIN} = i_{batt_{ref}} \cdot m_{1_{ref}} \cdot U_{DC} \qquad (24)$$

Where:
$i_{batt_{ref}}$ = reference value of current in the battery.
$m_{1_{ref}}$ = modulation of the DC/DC converter connected to the battery.

Choosing one proposed strategy and taking in consideration one of the previous calculations, the final energy management strategy will be ready. With the help of the block MATLAB Function from Simulink Library, the final energy management strategy is implemented in the HESS model. The MATLAB Function calculate the value of $k_{ref}$ following the proposed strategy and the ruled-based energy management strategy for all the driving cycling designed. Obtaining different values of $k_{ref}$ for every time, the power flow distribution between supercapacitors and batteries pack is controlled and the EV supplied.

## Simulation and results:

The studied EV with HESS designed is compared for the different strategies and is simulated in MATLAB/Simulink. The vehicle is tested on an urban driving cycles designed (Fig. 11) for a two proposed energy management strategies: vehicle acceleration strategy and control the supply current (power) according to a source resistance strategy.

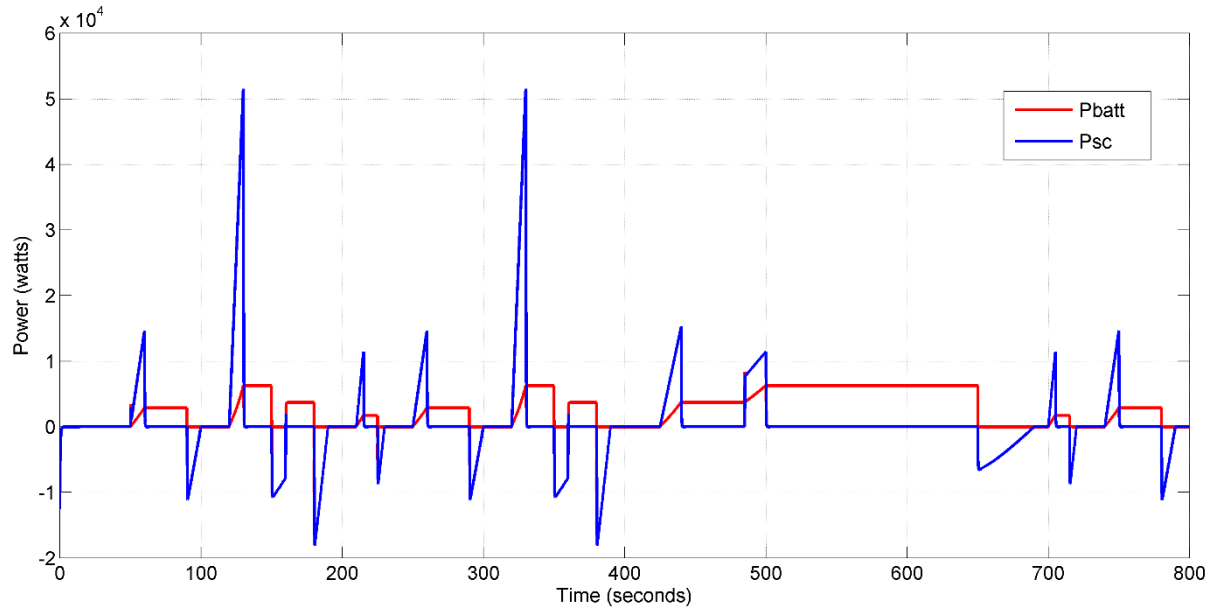For the vehicle acceleration strategy, the power demand plot will look as follow in Fig. 17:



*Fig. 17 – Power flow distribution for the vehicle acceleration strategy.*

For the control the supply current (power) according to a source resistance strategy, the power demand plot will look as follow in Fig. 18:
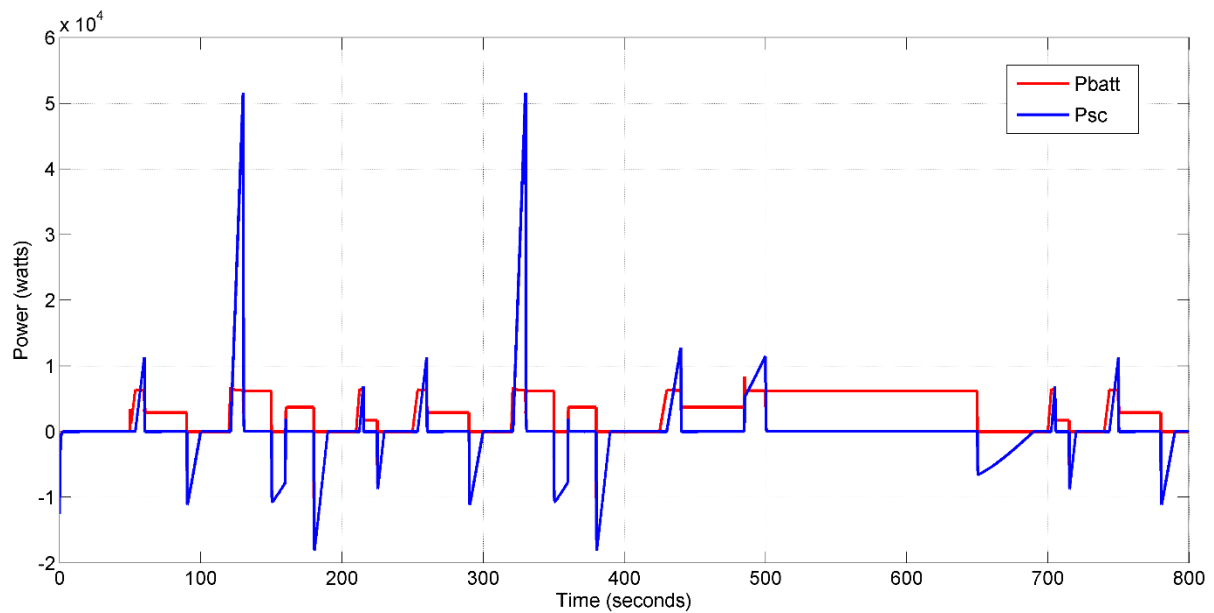


*Fig. 18 - Power flow distribution for the control the supply current (power) according to a source resistance strategy*

It can be noticed that, on this track with a specified sizing, the performances of the EV with HESS are better than any EV with only batteries from the point of view of power and energy consumption. The addition of supercapacitors would allow reducing slightly the electric consumption, reducing the sizing of the batteries and could be a possibility to increase the lifetime of the batteries and cover the power demand peak.

The results are different for each strategy. In this study, the vehicle acceleration strategy seem to be the most interesting due to the power stored in the supercapacitors looks to be more used for the EV performance. However, it is important to notice that the source resistance strategy is directly dependent on the sizing of the batteries and the supercapacitors and that for the vehicle acceleration strategy, the acceleration estimation can be difficult when the velocity fluctuations are frequent, so overall it looks more efficiency. Moreover, the non-simulated strategy is not simulate due to it will look quite similar to the control by a reference current value (source resistance strategy), but with a lower used of the energy stored in the battery pack.

Compared on different criteria the two strategies simulated:

-   Electric consumption (battery consumed charge by SOC):

The electric consumption of an EV with or without HESS is the same. But using HESS, the overall battery consumed clearly decreases. The SCs provides a power/energy boost that allows the battery to charge/discharges themselves in a bigger range without any damage. This means that the energy storage in the battery can be mostly use, because the SC is in charge to the high power fluctuations. For the source resistance strategy, the battery current is limited producing an extremely steady state and it can be discharge/charge without suffering. For the acceleration strategy, due to the battery only supply the power demand from the global resistive force, the battery is also protect and is fully operating. However, the fluctuation of the velocity can be a problem in this strategy.

-   Sizing (in energy and power)

Adding a SC pack, there is no need to increase the amount of batteries to cover the power demand peak. Knowing the driving cycles and the characteristics of the EV, the sizing of the energy storage elements can be made accuracy according to the energy management strategy chosen. For both strategies, the sizing of the energy storages system is the same, however, the vehicle acceleration strategy is using more the energy stored in the SCs.

-   Lifetime (swept State of Charge (SOC), effective current) of the batteries.

The lifetime of the batteries is quite related to the current of discharge/charge and the high power fluctuations. For both strategies, the battery is safe from high power fluctuations. However, only in the source resistance strategy, the battery current is limited producing an extremely steady state and the increase of the lifetime. For the other strategy, the fluctuation of the velocity can be a problem for the lifetime of the batteries.

## Conclusions:

An EV with HESS batteries and supercapacitors using an active association with DC/DC converters in parallel is studied. The energy management strategy of the system enables an inversion-based control using a distribution coefficient. Working with the inversion-based control, a ruled-based strategy controls the power flow distribution. Three elaborated strategies are studied to share the power demand between batteries and supercapacitors. This strategies are implemented in the energy management global strategy and simulated. Two of this strategies are compared in the EV with HESS. It appears that the use of a HESS is interesting for the electric consumption, the size and the expected lifetime of the batteries. For different strategies, there are different results for a same sizing.

In conclusion the HESS are an interesting and very promising flexibility technology, which can help to cover a driving cycle of an Electric vehicle, obtaining good results in performances, energy and power sharing and efficiency. This paper has given a short studied of one HESS-applications, however it can be applied in other systems with energy storages systems.

# REFERENCES:

[1]     A. Khaligh and Z. Li, "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, 2010.

[2]     J. Cao and A. Emadi, "A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles," *IEEE Trans. POWER Electron.*, vol. 27, no. 1, 2012.

[3]     L. Gao, R. A. Dougal, and S. Liu, "Power Enhancement of an Actively Controlled Battery/Ultracapacitor Hybrid," *IEEE Trans. POWER Electron.*, vol. 20, no. 1, 2005.

[4]     A. L. Allègre, R. Trigui, and A. Bouscayrol, "Different energy management strategies of Hybrid Energy Storage System (HESS) using batteries and supercapacitors for vehicular applications."

[5]     K. Ba, "Design and Evaluation of Hybrid Energy Storage Systems for Electric Powertrains by," 2010.

[6]     Erik Schaltz (2011). Electrical Vehicle Design and Modeling, Electric Vehicles - Modelling and Simulations, Dr. Seref Soylu (Ed.), InTech, DOI: 10.5772/20271. Available from: http://www.intechopen.com/books/electric-vehicles-modelling-and-simulations/electrical-vehicle-design-and-modeling

[7]     T. Bocklisch, "Hybrid energy storage systems for renewable energy applications," *Energy Procedia*, vol. 73, pp. 103–111, 2015.

[8]     Y. Kim, J. Koh, Q. Xie, Y. Wang, N. Chang, and M. Pedram, "A scalable and flexible hybrid energy storage system design and implementation," *J. Power Sources*, vol. 255, pp. 410–422, 2014.

[9]     S. Fui Tie and C. Wei Tan, "A review of energy sources and energy management system in electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 82–102, 2013.

[10]    http://www.europeanbatteries.com/upload/files/EB_dataheet_EV45AH_v4.pdf

[11]    R. Sadoun, N. Rizoug, P. Bartholomeüs, B. Barbedette, and P. Le Moigne, "Optimal Sizing of Hybrid Supply for Electric Vehicle Using Li-ion Battery and Supercapacitor," 2011.

[12]    http://www.maxwell.com/images/documents/bcseries_ds_1017105-4.pdf

[13]    Z. Song, H. Hofmann, J. Li, X. Han, and M. Ouyang, "Optimization for a hybrid energy storage system in electric vehicles using dynamic programing approach," *Appl. Energy*, vol. 139, pp. 151–162, 2015.