A Simplified Power Management Strategy for a Supercapacitor/Battery Hybrid Energy Storage System using the Half-Controlled Converter

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***Abstract*—Hybrid Energy Storage Systems (HESS), which is commonly used in Electric Vehicles (EV), is a combination of two energy storage devices. Supercapacitors (SC) due to their high charge/discharge rate, high power density, long lifetime in comparison to batteries, and capability of supporting high stress represent an optimal solution for HESS when combining with batteries. In such HESS configuration dc-dc converter is needed. Half-Controlled Converters (HCC) is an excellent solution due to their low cost and similar efficiency in comparison to the most used types of converters. In this paper, a strategy for power distribution between SC and battery, based on current control and a filter decoupling technique is proposed, along with the method to evaluate the decoupling frequency. The proposed strategy overtakes other approaches, such as fuzzy control or neural network, in terms of a faster and less complex implementation.**

I. Nomenclature

$SC,0$	Uncontrolled supercapacitor
$SC,1$	Controlled supercapacitor
$C_{\mathrm{SC},0}$	Capacitance of the uncontrolled supercapacitor
$C_{\mathrm{SC},1}$	Capacitance of the controlled supercapacitor
E_{sc1}	Energy at $SC,1$
E_{sc0}	Energy at $SC,0$
V_{dc}	Battery's voltage
V_{sc0}	Uncontrolled supercapacitor's voltage
V_{sc1}	Controlled supercapacitor's voltage
$I_{\mathrm{sc},0}$	Uncontrolled supercapacitor's current
$I_{\mathrm{sc},1}$	Controlled supercapacitor's current
I_{dc}	Battery's current
I_{sc}	Current in the main inductor
I_{load}	Load's current
D	Duty at the main circuit

II. Introduction

The energy storage system, generally applied in Electric Vehicles (EV), is one of the solutions for environmental issues due to zero emissions of Greenhouse gases. However, the widely used energy storage system based on batteries (NiMH, Lead-Acid, Lithium-ion, e.g.) has some disadvantages such as high cost, long charging time and relatively short lifetime. Thus, consumers often choose for economically viable, but non-ecological, ways of energy systems.

One solution for this problem, other than improving the storage device technology, is the use of Hybrid Energy Storage Systems (HESS). The HESS is based on the combination of at least two energy storage devices with combined features. Herein, it is analyzed a well-known HESS with Supercapacitor (SC) and battery, also studied in [1] and [2].

When comparing between SC and the most common types of batteries applied for Energy Storage System, the principal advantages are:

- High power density;
- Charged and discharged unlimited times;
- Rapid charging;
- Easy estimation of their energy level;
- No heavy metal used for its manufacturing.

However, SC's also present some disadvantages:

- Low energy density;
- Low voltage range by cell;
- High self discharge.

Despite of those advantages, creating a commercial EV fully powered by SC is not possible yet because its energy density is low. However, when applied in a HESS with batteries, the SC provides features such as high charge/discharge rate and high power density, and the battery provides high energy characteristic to the HESS. Consequently, this combination has a direct impact over EV's autonomy, because the SC can recover more energy from regenerative braking than the normal battery actually does. Moreover, SC application reduces the stress on the battery [3].

For interfacing both energy storage devices, dc-dc converter is necessary. Among several structures and topologies, it was analyzed in [4] a system that yield the best cost and benefit for a HESS system using SC and battery. Following this approach, the Half-Controlled Converter (HCC), proposed in

[5], provides an exceptional solution, because it focus on reducing the components size and reducing losses, with the same efficiency as other common converters applied for HESS.

Furthermore, in order to apply and enhance the HESS system, it is necessary to adopt Power Management Strategy to extract the best performance from both energy storage devices. Therefore, this paper presents a study over the power distribution strategy between SC and Battery while applying the current control using the HCC for this system.

Several studies regarding Power Energy Management were verified in [6][8] for a different HESS system using Fuel Cells and SC. This method differs from other control strategies since it allows the regulation of the dc bus voltage by using the frequency decoupling of each source. In particular, this work aims on both simplification of the HESS structure and power management control with considerable effectiveness.

In section 3, the structure for the HESS will be discussed due to its importance for the system modeling, and also, the HCC [5] that interfaces the connection SC/Battery.

In section 4, the HESS's Power Management Strategy is introduced, as well as its methods and application using the HCC control. Section 5 presents the achieved experimental results, and finally in section 6, the conclusion for this work.

III. HESS STRUCTURE

One important aspect about the HESS is the topology, which can be chosen among several types [7]. But according to [4], the best topology is the one represented in Fig.1, since it allows bi-directional power flow with a constant dc link using a single dc-dc converter. The SC voltage is independent from the voltage of the dc link, and a wider voltage range is achievable.

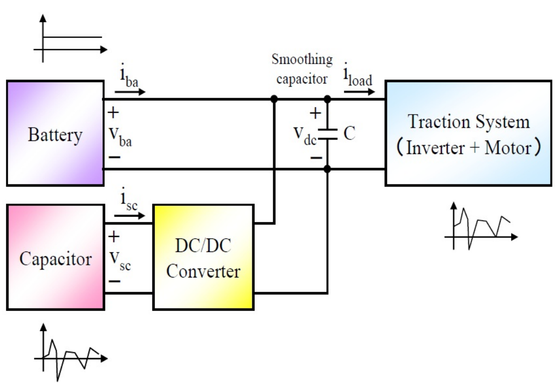

Fig. 1. HESS topology

The Half-Controlled Converter, which separates the SC into two banks, SC0 (Uncontrolled) and SC1 (Controlled), is shown in Fig.2 . By having to control just SC1, the converter requires smaller components which directly influence the system loss. As a result, while maintaining the same efficiency of the HESS, the total cost of the system decreases.

A comparison between the HCC and the Half-Bridge Converter, which is the most commonly used dc-dc converter for HESS application, is formulated in [5]. It is demonstrated that

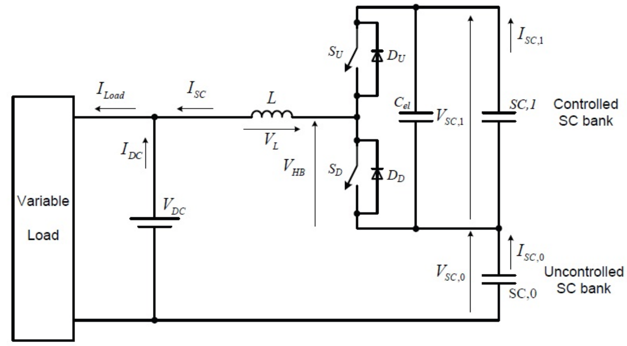

Fig. 2. HCC Structure [5]

in a proportional HESS, the HCC can employ an inductor with nearly half of the size and also have switches with lower rated voltages, in comparison to the Half-Bridge (HB). Even though a balancing circuit is needed to balance the charges between the controlled (SC1) and uncontrolled (SC0) banks, its significance to the total cost of the converter is low due to the smaller size components in relation to the HCC main circuit.

Advantages in the HCC:

- Costs are reduced in the HCC system because the components are smaller than the ones in the HB topology;
- The space occupied by the system is smaller;
- It present lesser losses than in the HB topology.

Disadvantages in the HCC:

- The HC system needs to be pre-charged to the minimum voltage level to ensure current control;
- A regulator is needed in the HCC system.

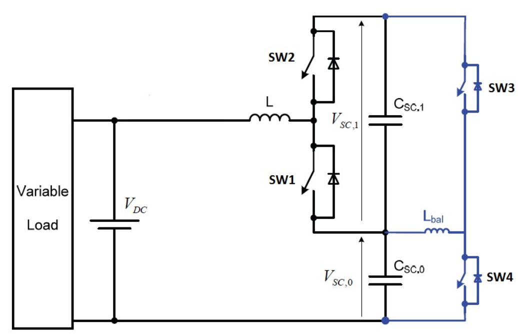

Fig. 3. Half-Controlled Converter full structure

By the energy sources disposal, it is implied that the principles of function depend on the following conditions:

$$V_{dc} \geq V_{sc0} \tag{1}$$

$$V_{dc} \leq V_{sc0} + V_{sc1} \tag{2}$$

$$I_{load} = I_{sc} + I_{dc}. \tag{3}$$

From the topology of the converter, the relationship between the input power and output power of the converter is derivable:

$$P_{out} = P_{in}$$

$$I_{sc}(DV_{sc1} + V_{sc0}) = V_{sc1}I_{sc1} + V_{sc0}I_{sc0}$$

$$I_{sc,0} = I_{sc}$$

$$I_{sc,1} = I_{sc}D. \tag{4}$$

The control applied to the HCC aims to control the current I_{sc}, which is demonstrated at the control diagram in Fig.4. The current control is based on a feed-forward combined with feedback control.

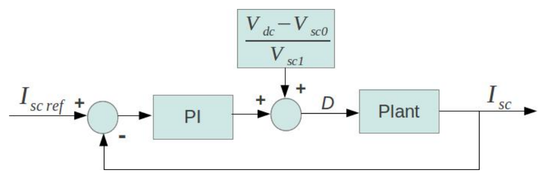

Fig. 4. HCC control diagram

IV. Power Management System

The next step for applying the HESS is to fulfill some requirements regarding the HESS's Energy Management Control. Research in this topic can be divided into three major areas:

- *System Management*: This is actually the main part of the HESS Management Control as it defines the proper duty control for the switches in converter. This control is defined in microseconds.
- *Power Management*: It represents the power distribution control between the two energy storage devices, or in other words, the share of power that each of the energy storages devices needs to supply to the load. It is a medium term goal defined in terms of milliseconds.
- *Energy Management*: It is the control system for making both energy storage devices working with the proper temperature, state of charge (SOC) and discharge ratio. This represents the long term goal of the HESS, and its control is defined in terms of seconds.

The present study proposes a Power Management Strategy in order to enhance the HESS using HCC. Within this strategy, the best performance is extracted from both energy sources depending on its combined characteristics.

The SC high power density needs to be emphasized, giving the prospects of supplying the load quickly and also increasing the energy recovered from regenerative braking. On the other hand, the SC does not have a high energy density, so it can not withstand a long period of discharge as the battery usually does. Furthermore, it is important to protect the battery from possible stress placed in the system by a non-proper current discharge, which increases its internal temperature affecting its life expectancy [3].

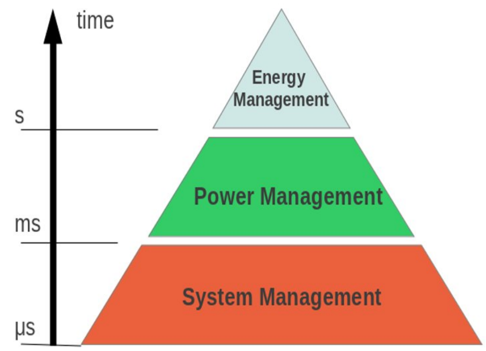

Fig. 5. HESS Management

A. Battery discharge configuration

According to Peukert's law, the discharge capacity of a battery can be expressed in terms of a rate:

$$C_n = I_{dc}^k.t \qquad (k > 1),$$

where C_n is the nominal capacity of the battery, I_{dc} is the battery discharge current during a certain time t, and k is the Peukert's constant which differs depending on the type of battery. Therefore, a maximum discharge time can be expressed as represented in (5).

$$t_{\max} = \frac{C_n}{(I_{dc\max})^k} \tag{5}$$

The battery can only withstand a maximum discharge current for a limited time, but in extreme cases of high discharge currents the battery internal temperature increases. The main reason is the power dissipation by its internal resistance, which can be expressed in terms of the State of Charge (SoC)[8].

$$V_{\mathrm{dc}} = V_o(SoC) - [R_i(SoC) + R_c]I_{dc}. \tag{6}$$

The open circuit voltage $V_o(SoC)$ and internal resistance of the battery $R_i(SoC)$ are strictly related to the battery state of charge, while the conductor resistance R_c is constant. Thus, the power extracted from the terminal voltage V_{dc} is expressed according to (7), which also demonstrates the power dissipation inside the battery.

$$P_{\mathrm{dc}} = I_{dc}V_0(SoC) - [R_i(SoC) + R_c]I_{dc}^2 \tag{7}$$

Assuming the internal temperature of the battery to be strongly related to the battery life, one shall consider two possibilities in order to avoid high power dissipation inside the battery. One is limiting the maximum battery discharge $I_{dc\max}$, using another energy storage device to provide surplus of power. The second method is controlling the time $t_{\max}$ in which the battery provides this sort of maximum discharge, having a second energy storage device working along with the battery in order to provide a smooth discharge pattern.

B. Supercapacitor discharge configuration using the HCC

Supercapacitors are devices capable of high discharge rates with less consequences regarding their lifetime. Thus, the perspective for supporting the battery in high discharge dynamics, such as in EV, increases by providing the HESS with this sort of energy storage device.

However, although the projected maximum current discharge is easily achieved by the supercapacitor, the total energy available for supporting the battery is limited. The energy available in a supercapacitor is expressed as:

$$E_{\text{sc}} = \frac{C(V^2_{(\max)} - V^2_{(\min)})}{2}$$

By using the HCC, the total energy for utilization in the system is defined as a sum of the energy in both $SC0$ and $SC1$.

$$E_{\text{sc}} = \frac{C_{sc1}(V^2_{sc1(\max)} - V^2_{sc1(\min)})}{2} + \frac{C_{sc0}(V^2_{sc0(\max)} - V^2_{sc0(\min)})}{2} \tag{8}$$

Where the voltage of both SC banks should follow the requirements of the system described by (1) and (2). Then, for maximum and minimum energy storage it is assumed that,

$$V_{\text{sc1(max)}} = V_{\text{sc0(max)}} = V_{\text{dc}} \tag{9}$$

$$V_{\text{sc1(min)}} + V_{\text{sc0(min)}} = V_{\text{dc}} \tag{10}$$

At minimum energy level, it is assumed the working principles of the balancing circuit [5], which converge both supercapacitor banks to the same voltage level ($V_{\text{sc1(min)}} = V_{\text{sc0(min)}}$) during the discharge process. Therefore, the maximum energy storage in the SC banks is expressed as,

$$E_{\text{sc}} = \frac{3}{8}(C_{sc1} + C_{sc0})V^2_{dc} \tag{11}$$

This relationship is important for the HESS project, because it specifies the desired energy according to the SCs total capacitance and dc link voltage. Furthermore, it determines the total energy available for supporting the battery in a power management strategy.

C. Power Management Control

In previous section, two actions for diminishing the power dissipation inside the battery were described. One is based on restricting the battery discharge within a certain limit, having the SC to assume surplus of power requirements. Herein, however, a method to control the time $t_{\max}$, in which the battery provides the maximum discharge current is proposed.

In this power management control, the power provided to the load is separated in real-time by a frequency-decoupling technique, which transfers the transient part of the load to the SC bank. Therefore, the battery can perform a smooth discharge without peaks of current.

This method is achieved by defining the control reference of the HCC duty, $I_{\text{sc(ref)}}$ presented in Fig.4, to be strictly related to a filtered I_{load} signal, as demonstrated in (12).

$$I_{\text{sc(ref)}}(s) = \frac{\tau s}{\tau s + 1} I_{\text{load}}(s) \tag{12}$$

By stipulating this reference, the current from the battery I_{dc} can be represented as (13), according to (3).

$$I_{\text{dc}}(s) = \frac{1}{\tau s + 1} I_{\text{load}}(s) \tag{13}$$

The decoupling frequency, $\frac{1}{\tau}$, is applied to the power distribution control, and by modifying it, both SC and Battery participation changes. This is verified in Fig.7, where the system behavior for a step response is analyzed using different decoupling frequencies.

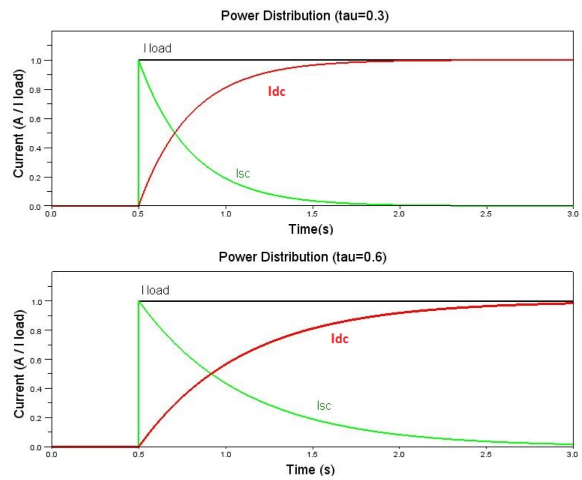

Fig. 6. Power Distribution step response

It is noticed that by decreasing this frequency, the participation of the SC bank increases. Likewise, increasing the decoupling frequency increases the participation from the battery, respecting the relationship set by (3).

Furthermore, adjusting the decoupling frequency could provide the means to determine an optimum value according to the HESS State of Charge (SoC). But for this purpose, it is important to analyze whether the HESS can afford to function within worst case scenarios of low SoC and high discharges requirements.

Therefore, it is defined that the decoupling frequency has a minimum and maximum value with the following characteristic:

- $f_{\min}$: Decoupling frequency where the utilization of the battery is minimum, due to its low State of Charge.
- $f_{\max}$: Decoupling frequency where the utilization of the SC should be minimum while the battery SoC is maximum.

Considering the behavior presented in Fig.6, it is being considered that the battery discharge shall reach the maximum rated current in a controlled period rated by its delay. The battery discharge delay is expressed as

$$\mathrm{Delay}(\%) = \frac{\mathrm{t_r}}{\mathrm{t_{max}}}, \tag{14}$$

where t_r is rising time necessary for the battery to achieve its maximum rated discharge current, and t_max is the maximum discharge period set by (5). The relationship between the rising time period until 90% of its final rated value, t_r, and the decoupling frequency are defined as following:

$$\frac{1}{\tau} = \frac{2.2}{t_\mathrm{r}}. \tag{15}$$

With the battery fully charged (SoC_max) and the SC in critical charge level, the decoupling frequency assumes f_max, maximizing the battery usage. Even though the battery can provide all the maximum discharge current during t_max, the power dissipation will increase internal temperature. Therefore, this parameter should be set for a considerable participation from the SC bank in order to minimize these effects. It is being assumed that for a certain minimum charge level at the SC banks, f_max allows a 10% delay in the maximum discharge current from the battery.

On the other hand, when the SC is fully charged and the battery is at a critical SoC (SoC_min), the control system set the decoupling frequency to f_min, which avoids the battery from achieving the maximum discharge current within t_max. Therefore, the range for the decoupling frequency is expressed as in (16).

$$\frac{2.2}{t_\mathrm{max}} < \frac{1}{\tau} < \frac{2.2}{0.1t_\mathrm{max}} \tag{16}$$

V. Experimental Setup and Results

For the experiment, a TI DSP32028355 controller is used to control the HESS. At the battery bank, five GS Yuasa Lead-acid batteries are connected in series. The SC bank is built with two modules (SC1 = 25F 100V, and SC0 = 58.8F 100V) also connected in series. The HESS specification is presented in Tab.1, and the hardware can be verified in Fig.7.

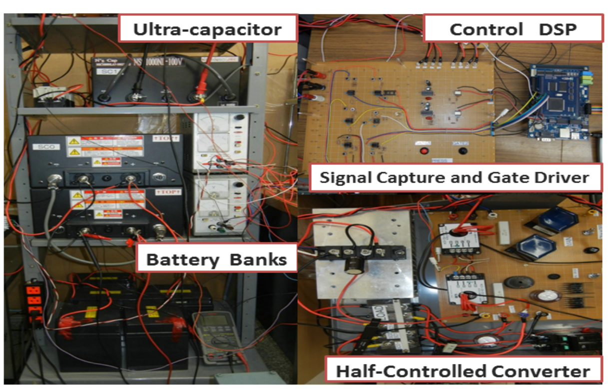

Fig. 7. Experiment Bench

First, the decoupling frequency is selected in order to give a rising time for the battery current according to its maximum and minimum values expressed in (16). t_max is stipulated for nearly 10 seconds and a variable resistor is used as the load.

TABLE I
Experiment Set up

Battery - GS Yuasa PWL	
Nominal voltage	12 V
Rated Capacity	24 Ah
Fixed Constant Voltage V/Cell	2.23 +/-0.02
Maximum charging current	0.25 CA
Mass	8.9Kg
Supercapacitors - Nisshinbo	
Capacitor SC1 (1 module)	25F 100V
ESR SC0	0.069Ω
Capacitor SC0 (2 modules)	58.8F 100V
ESR SC1	0.035Ω
DC-DC Converter	
Main Inductor	1.5mH 12A
Main switch	2MI50F-050
Working Frequency	25kHz
DC motor Specification	
Output power	0.4 kW
Poles	4
Rotational Speed	1200 rpm
Nominal voltage	60 V
Nominal current	8.7 A
Rotor Inertia	$5.88 \times 10^3 kg.m^2$
Torque factor	0.35 N.m/A
Armature resistance	1.4Ω
Armature inductance	3.98 mH

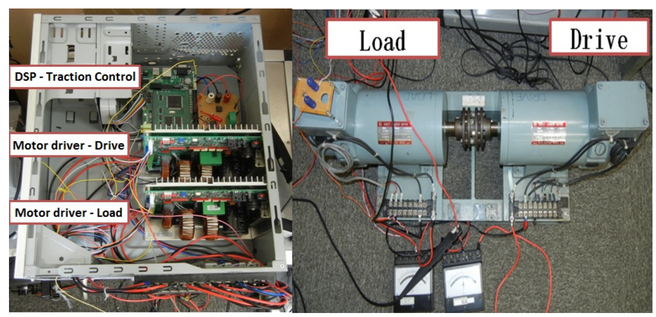

Fig. 8. Experiment Set up for the dc motor

In the experiment result Fig.9, the application of the maximum and minimum decoupling frequency is verified. The energy provided by the SC is enough for preventing the battery from achieving its maximum rated current in the specified time. Also, it is noticed that the energy share provided by the SC varies from 34% with f_min,and 4.7% applying f_max.

In order to verify the applicability of the proposed method in a highly dynamic discharge, the system is configured to drive a dc motor simulating the ECE-15 (European Driving Cycle) pattern for urban drives. The motor specification is presented in Tab.1, and the motor set up is verified in Fig.8.

The energy share between battery and capacitor, and the regenerative braking recovery can be compared using different decoupling frequencies, as presented in Tab.2. The experiment confirms that the participation of the SC in the energy share increases by decreasing the decoupling frequency. The opposite is also observed, but the regulation of the energy share in high decoupling frequencies requires greater variations when compared to the ones at low decoupling frequencies.

Therefore, and ideal range for the decoupling frequency can be defined for the energy management considering several criteria such as state of charge, road condition or energy storage system configuration.

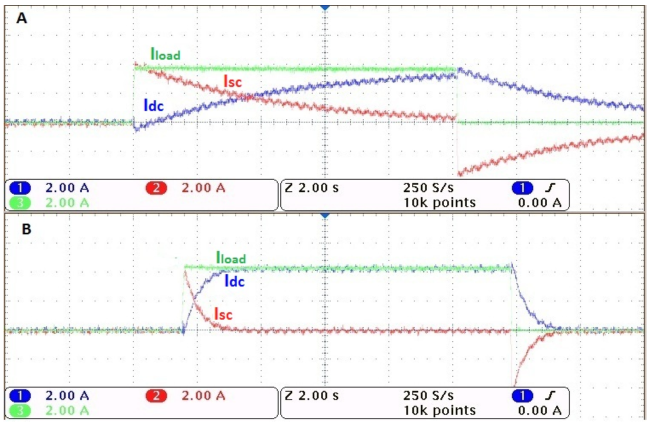

Fig. 9. Limits of the Decoupling frequency using a variable resistor as load (A- Minimum, B- Maximum)

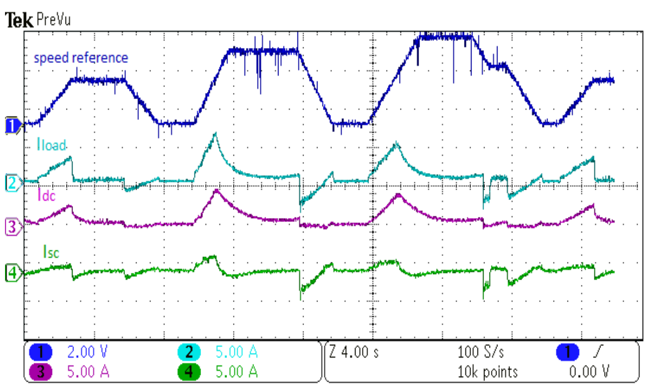

Fig. 10. Experiment Result Analysis for ECE-15 Driving Cycle

TABLE II
Energy Share according to the decoupling frequency

	Decoupling frequency (rad/s)			
Energy (kJ)	0.0126	0.122	0.56	2.2
Required by the motor	1.672	1.9134	1.915	1.891
Provided by the Battery	0.426	1.146	1.468	1.544
Provided by the SC	1.240	0.768	0.448	0.361
Regenerative Braking	0.304	0.286	0.292	0.304
Recovered by the SC	0.237	0.239	0.239	0.250
Efficiency (%)	78.16	83.61	81.80	82.23

VI. Conclusion

In this paper, an overview of a simplified HESS structure using the Half-Controlled Converter is presented. Also, a proposal for Power Management Strategy using current control and frequency decoupling is formulated. This method emphasizes the simplicity, which is a relatively important factor in terms of cost. The current from the SC acts during current peaks, making the battery's current ascend in a smooth pattern within a controlled rising time.

The rising time defines the period in which the battery avoids the maximum current discharge rate, preventing it from achieving its operational limits. Depending on the specification of the battery for high current discharge and SoC, an ideal decoupling frequency can be selected for increasing or decreasing the SC support.

Some advantages and remarks of this methods are the following:

- Peaks of current from the battery are highly suppressed;
- The SC supports the battery during all the discharge period, and not only after a certain current discharge limit;
- Recharge of the SC by the battery when the motor reaches constant velocity, is observed.

The experiment driving a dc motor powered by the HESS demonstrated that the energy share is defined by changing the decoupling frequency. However, the decoupling frequency selection between the extremes depends on both battery and SC state of Charge. For future analysis, the development of a Energy Management System based on variation the of the decoupling frequency due to the battery SoC estimation will be considered.

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