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Fuzzy Controller for a Battery and Ultracapacitor Hybrid Energy Storage System Vehicle

Taysa Marques[1], Gabriel do Carmo[1], Matheus Laia[1], Daniel Batista[1], Hugo Valadares Siqueira[1], Fernanda Cristina Corrêa[1]

[1]*Electrical Engineering Department, Federal Technological University of Paraná, UTFPR*
Monteiro Lobato Avenue, Jardim Carvalho, 84016-210, Ponta Grossa/Paraná, Brazil
taysa.banik@gmail.com, gabcar@alunos.utfpr.edu.br, laia@alunos.utfpr.edu.br, danielbatista@alunos.utfpr.edu.br, hugosiqueira@utfpr.edu.br, fernandacorrea@utfpr.edu.br

Abstract. With the increase in transportation electrification, one of the biggest challenges is to improve battery performance and autonomy. A battery normally has a high energy density with a low power density, while an ultracapacitor has a high power density but a low energy density. Therefore, this paper has proposed associating more than one storage technology generating a Hybrid Energy Storage System (HESS), which has a battery and ultracapacitor, whose objective is to improve the electric vehicle (EV) driving range. When batteries and SC are associated, the power management complexity increases considerably. In this work, a fuzzy logic power management control for the HESS is developed for the best use of the regenerative energy released for charging the capacitors and minimizing battery wear in urban driving cycles. Therefore, it is necessary to determine the correct power distribution between the storage devices to enhance the system efficiency by saving the battery from excessive efforts. The topology used considers bidirectional converters, coupled to the bus and connected to the electric motors which propel the EV. For the simulations, Matlab and Simulink software is used, where it is possible to analyze the dynamic behavior of the electric vehicle.

Keywords: Electric vehicle, energy storage, HESS, fuzzy logic control.

1 Introduction

In recent times, the transport sector electrification has been the focus, due to the need to reduce pollutant gas emission rates and the burning of fossil fuels and develop a sustainable mobility option [1–3]. In these vehicles, the energy storage system (ESS) is essential for storing all the vehicle's energy, being the power source, and being responsible for regenerative braking [4]. Therefore, to ensure commercial success electric vehicles (EV) must ensure security and efficiency, associated with low cost and long-life ESS.

In most cases, are composed of many batteries, consistently sized to operate with high power to supply the energy demand of the vehicle according Zhu et al. [3].It is known by Li et al. [5] that batteries composed of materials such as lithium, nickel-cadmium, and nickel-metal-hydride, in addition to having metals in their composition, have a short lifetime and low power to what the vehicle demands, sensitivity to temperature, and a higher cost. Because of this, an ESS composed only by the battery becomes unfeasible Li et al. [5].

Besides, in an urban driving environment, the frequent stops and accelerations generate many charges and discharge operations associated with the high current peaks, which can damage the ESS device, reducing its lifetime [6–8]. One alternative to minimize the ESS current peaks are the hybrid energy storage systems (HESS) [4, 9–11]. HESS usually combines two or more energy storage devices, such as battery and fuel cells or battery and ultracapacitors (SC) [12]. The main objective of these devices is to minimize the battery effort, extended their life cycle and decrease their size and cost [9]. Unlike batteries, which have high specific energy and low specific power, SC has a high specific power and low specific energy. Therefore, the SC is able to fulfil power peaks for short periods, which can be useful for EV startups and also enhance the HESS capacity to recover energy for braking by regeneration using the electric motor. These characteristics of the SC, associated with a battery, become the recommendable device association for vehicle applications [9, 13].

However, the association of two energy storage devices increases power management control (PMC) complexity. The PMC needs to correctly distribute the power between the available devices, considering the advantages of each one, to ensure the maximum efficiency of the HESS [14]. As in the work of Eckert et al. [4, 9], an optimized fuzzy logic controller (FLC) can be applied in power-split systems. Moreover, Wu, Zhang, and Cui, [15] also applies FLC to an energy management strategy based on driving cycle recognition for a parallel hybrid electric vehicle. The developed FLC controls the engine and electric motor torques based on the required torque and battery state of charge (SOC), improving the vehicle fuel economy. On the other hand, rule-based controllers also can minimize HESS energy consumption, extending autonomy by regulating the power distribution and mitigating the current peak impact on the battery [16]. Finally, Hu et al. [7] highlight that general control rules exist to ensure better HESS power allocation, at the same time that the fuzzy controller grants better performance, acting on the allocation correction. The PMC performance directly depends on three aspects: An effective analysis method for optimization; Real-time power managing; And robustness to ensure adequate execution in diverse conditions [16].

Because of this feature, the present work proposes using a multiple parallel converter topology of HESS with battery and ultracapacitor and a fuzzy controller for power management between the systems. Section 2 describes the hybrid energy storage system: the bidirectional converter created and the values chosen for battery, ultracapacitor, and inverter. Section 3 presents the fuzzy controller, section 4 shows the results and the analysis, and finally, section 5 relates the conclusions and the contributions of this work.

2 Hybrid Energy Storage System

According to Li et al. [5], batteries and Ultracapacitors (UCs) fall under the same category of electrochemical devices. However, the use of these devices is different, making their characteristics very different.

Batteries have a high energy density ranging from 30-200 Wh/kg; values vary according to the chemical compound and the applied power density. UCs, on the other hand, have a low energy density but a significantly high power density.

It has a lifetime of over one million cycles, a much higher value than the battery, and a better low-temperature performance when compared to the battery. Combining these characteristics makes it possible to obtain a satisfactory hybrid system.

The set of batteries and ultracapacitors can be arranged in different ways according to the most viable topology for the vehicle, as Cao and Emadi [10] cites in their work: the basic parallel topology, the UC/Battery configuration, the Battery/UC configuration, the cascaded configuration, the multiple input configuration, and the multiple converter configuration, were chosen for this work.

This topology, with multiple converters, as the name implies, has two converters, one for the battery system and another for the ultracapacitor system. The connection of these converters is made directly to the dc link and in parallel. The output voltage of these converters is the same. For this article, the output voltage is 400V. Figure 1 below illustrates the multiple converter topology.

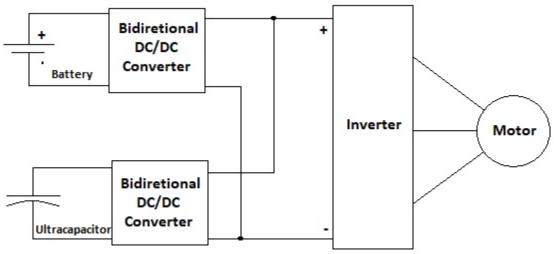

Figure 1. Multiple Converter Configuration

2.1 Electronics Converters

In the present topology, both the battery and the ultracapacitors will supply and receive energy from the bus. Thus, the converters need to have this bidirectional energy flow, sometimes lowering, sometimes increasing the voltage. For this purpose, the buck-boost converter was chosen [17] and [18].

The buck-boost converter is a non-isolated system, sometimes called a dip-boost, with a voltage-inverting topology. They are usually chosen in projects because they can generate an output voltage lower than the Buck converter or higher than the Boost. Its operation is divided into two parts when operating in continuous conditions.The converter has the most common applications in photovoltaic panel systems precisely because it encompasses all points of the power system, that is, regardless of the temperature or radiation of the panel.

The output voltage is opposite to the input voltage when the switch is turned on, transferring energy from the source to the inductor. On the other hand, the diode does not conduct, as it is reverse biased, and the capacitor is feeding the load. When the switch turns off, the inductor current is given by the conduction of the diode, since the energy stored in the inductor is delivered to the capacitor and the load. The output current and the input current are discontinuous, and the voltage supported by the transistor and the diode is the sum of the input and output voltages. Figure 2 illustrates the buck-boost converter.

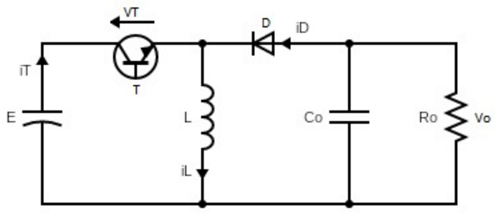

Figure 2. Bidirectional Converter Buck Boost

In this work, the entire HESS system will be simulated. Thus, the converters will be built according to the chosen parameters, the power of 11kW, to keep the efficiency constant. Table 1 below shows the values used for current, inductance, and capacitance calculations, both for the battery converter and the ultracapacitors converter.

With these values, it was possible to build the buck-boost converter block, in the Figure 3, for the simulation.

Table 1. Converter Parameters

Parameter	Value
Potency	11000W
Current Max Battery	63.65A
Current Max SC	29.33A
Capacitancy Battery	0.000920F
Capacitancy SC	0.0001955F
Indutancy Battery	0.0031H
Indutancy SC	0.0016H

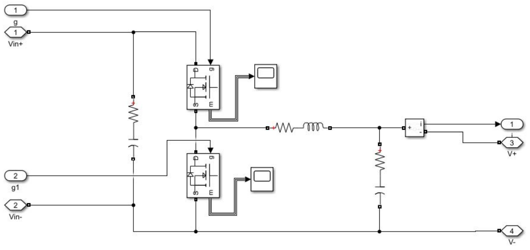

Figure 3. Converter Block

2.2 Battery

For the battery pack, 172.8V were added, totaling 180Ah Ni-MH, where 144 1.2V 90Ah cells were used in series and two more in parallel. In simulation, these parameters are registered in the block representing the battery, which belongs to the Simscape library from Simulink.

2.3 Ultracapacitors

A bank of 16.67 F ultracapacitors was used as a simulation parameter, totaling 375V. To reach such values, 150 PC2500 2.5V 2500F ultracapacitors were used. In simulation, these parameters are registered in the block representing the ultracapacitors, which belong to the Simscape library from Simulink.

3 Fuzzy Control

A fuzzy control was developed to manage the energy demanded by the HESS. Using the following inputs: the power required (Preq) by the system, the derivative of the power required (dPreq), in order to evaluate the trend, the state of charge of the battery (SOCb), and the state of charge of the supercapacitors (SOCsc). And the outputs are battery activation (BPreq) and ultracapacitors activation (SCPreq), which are the signals that activate the pulse width modulation block linked to the operation of the converters. Unlike [19], who used fuzzy Sugeno; in the present work, we chose to use the Mamdani-type control, because that have widespread acceptance and be more intuitive and interpretable rule based.

The membership functions for the inputs were created with triangular waves, equally spaced within limits stipulated for each input, according to the table 2.

Table 2. Membership Function Parameters

Name	Type	Limits	Technical Features
Preq	Input	-11000 to 11000	Extremely Low, Very Low, Low, Little Low, Medium, Little Positive, Positive, Very Positive, Extremely Low
dPreq	Input	-2500 to 2500	Low, Medium, High
SOCb	Input	0 to 100	Very Low, Little Low, Medium, Little High, Very High
SOCsc	Input	0 to 100	Very Low, Little Low, Medium, Little High, Very High
BPreq	Output	-11000 to 11000	Extremely Low, Very Low, Low, Positive, Extremely Positive
SCPreq	Output	-11000 to 11000	Extremely Low, Very Low, Low, Little Low, Medium, Little Positive, Positive, Very Positive, Extremely Positive

It was possible to condition the behavior of the energy flow of the HESS with 102 rules. It is important to mention that in the elaboration of the fuzzy rules, restrictions are characterized, such as the minimum state of charge of the battery and the state of charge of the capacitors. It is even possible to take advantage of the regenerative energy from the vehicle's braking. The Simulink model with the fuzzy controller is shown in Figure 4. The interactions between inputs and outputs of the fuzzy control can be seen in Figure 5 and the surface graph of input-output relationship is shown in Figure 6.

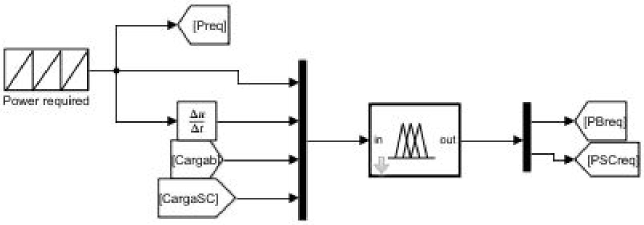

Figure 4. Simulink Controller Model

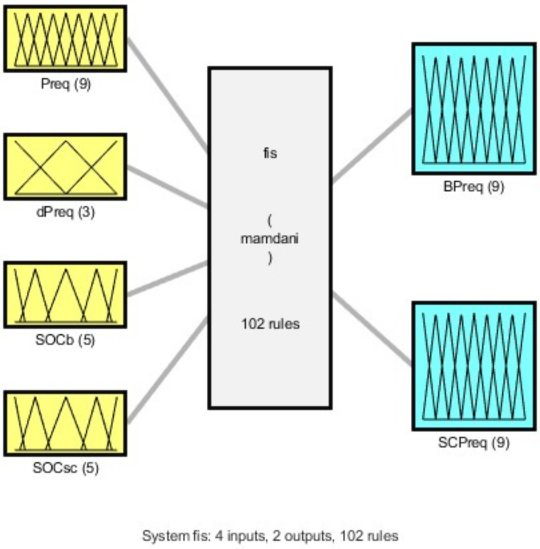

Figure 5. Fuzzy Model

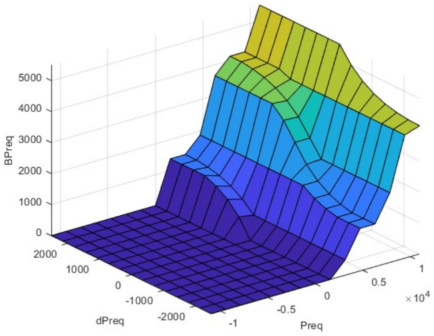

Figure 6. Surface Graph of Input-Output Relationship

4 Results and Analysis

A cycle of random values for the required power input was used to test the control. It is possible to see, in the Figure 7, that the generated power follows the required power, with a slight delay in the negative values.

However, fuzzy control aims to achieve performance and minimize battery usage in urban driving cycles. For this, a vector with values of power versus time, as preset values, called FTP75, was used to validate the control.Another works like [19], [20], [18] and [21] use other conduction cycles such as climbs, the HWFET, the US06, and the FTP-75. The FTP75 simulate an urban route of 12.07 km with frequent stops. This vector has 120 seconds of simulation, but we chose to use the first 60 seconds for practical purposes. The Figure 8 shows the generated power following the required power's behavior, and Figure 9 shows the power fluctuations, harmful to the battery, were handled for the ultracapacitors, components that are more appropriate for the behavior.

And the Figure 10 shows the SOC of battery and the ultracapacitors. It is possible to verify that, the charge of the battery remains at 50% while the state of charge of the ultracapacitors decreases according to the path. This is positive, considering that one of the project's goals was to increase battery life.

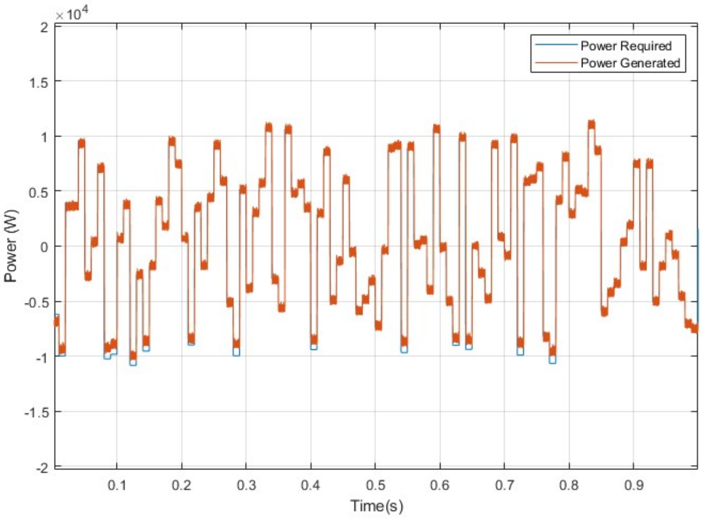

Figure 7. Random Power Required x Power Generated

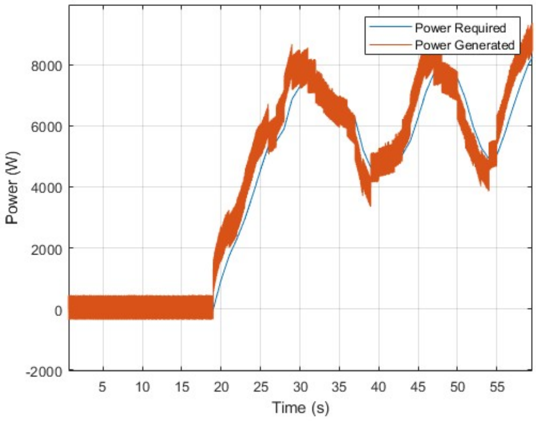

Figure 8. FTP75 Power Required x Power Generated

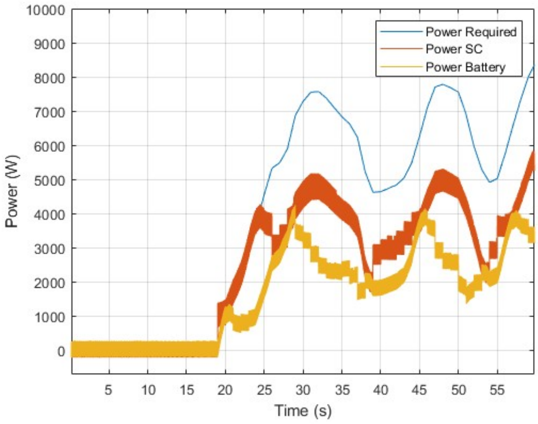

Figure 9. FTP75 Power Required x Battery Power x SC Power

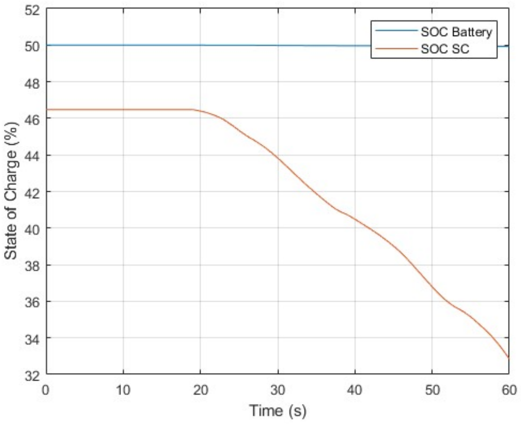

Figure 10. Battery and SC SOC

5 Conclusions

In this article, a controller for a HESS system was created. As far as the simulations took place, the control proved capable of adapting the power demands according to the state of charge of both the battery and the ultracapacitors. With the control created, it was possible to obtain an adequate battery performance, which can operate more smoothly, working together with the capacitors.

It is essential to highlight that the fuzzy control developed applies to a typical vehicle that has a HESS system with a topology of multiple converters in parallel. This parallelism is ideal for working with components that have different voltage levels. All these benefits using the regenerative brake to recharge the batteries and extend the vehicle's autonomy.

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