Artículo de Investigación (evaluado por pares)

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Topologías para la interconexión de baterías y supercondensadores en microrredes de tipo residencial con generación intermitente

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Abstract

Context: This paper presents a comparison study of the performance of three topologies for the interconnection of Lithium ion batteries and supercapacitors in a Hybrid Energy Storage System for the application in electric residential microgrids with inttermitent generation. The main goal of the Hybrid System is the prolongation of lifetime of batteries, using the supercapacitor for dealing with the dynamic component of the current from a pulsed current load. The paper is the extension of a preliminary simulation based study of topologies comparison, in which two semi-active topologies were evaluated. Here, an active topology is added to the study and the operational benefits of each topology are documented.

Method: For every topology in this study, a non-isolated Half-Bridge Bidirectional DC converter was used and a PI double loop linear ACC control algorithm was designed for the control of converters. In the active topology an additional optimization-based real-time frequency-decoupling control strategy was selected.

Results: A parallel active topology allows to manage better the stored energy in the SC due to the possibility of varying the voltage in the terminals of SC with a DC converter as interface to the DC bus.

Conclusions: Semi-active topologies are easier to design and control, however, the operational benefits of supercapacitors require voltage variations in the terminals. This variation is possible to make in an active topology.

Keywords: Lithium-ion battery; supercapacitor; DC/DC bidirectional converter, Energy Storage System (ESS); power density; energy density

Resumen

Contexto: Este artículo presenta un estudio mediante simulación del comportamiento de tres topologías para la interconexión de baterías y supercondensadores en un sistema híbrido de almacenamiento de energía con potencial aplicación a microrredes eléctricas residenciales. El estudio se basa en una comparación preliminar de dos topologías semi-activas hecha por los autores. En este artículo se añade una topología activa al estudio comparativo.

Método: En cada una de las topologías del presente estudio se ha usado un convertidor DC bidireccional de medio puente y como estrategia de control básica se usó un control de corriente promedio de doble lazo. Para la topología activa se utilizó una estrategia de control adicional para el desacople de las componentes dinámicas y promedio de la carga o generación pulsante.

Resultados: La topología activa permite utilizar mejor la energía almacenada en el condensador, gracias a la posibilidad de variar la tensión en sus terminales

Conclusiones: El diseño y control de las topologías semi-activas resulta mucho más sencillo que el de la topología activa en paralelo. No obstante, para aprovechar la capacidad de almacenamiento del supercondensador, la tensión entre sus terminales debe tener una variación importante, lo que se puede conseguir con la topología activa.

Palabras clave: Sistema Híbrido de almacenamiento de energía; batería de ion-litio; supercondensador; Convertidor DC/DC bidireccional, Densidad de potencia; Densidad de Energía.

1. Introduction

The evolution of electric systems has lead us to the conception of electric microgrids, defined as a collection of distributed generators and loads, placed within a demarcated border. This microgrid can operate in either grid-connected or islanded mode [1], [2]. In a lower power scale some authors have introduced the concept of residential microgrids or nanogrids, conceived as microgrids connected at a single Point of Common Coupling (PCC), located in the low voltage distribution grid. A residential microgrid can come up by limiting its electric boundary to a single house with a capacity range of 2 – 20 kW [1], [3], [4].

The use of wind turbines or solar panels in residential applications, makes convenient the use of Energy Storage Systems (ESS) to solve the problems related to the intermittency of the power generation. Battery Energy Storage Systems (BESS) have been commonly used for this kind of applications [5]. However, it has been demonstrated that storing intermittent energy from renewable sources could reduce the battery lifetime [6]. In order to solve this problem, combinations of different storage technologies have been studied.

A Hybrid Energy Storage System (HESS) is an Energy Storage System using two or more energy storage technologies. The use HESSs results convenient because of the potential use of every operational attribute of the storage technologies [7]. However, the feasibility for the implementation of a HESS depends on several technical and economic factors.

Since the late 90s, one of the most used and studied HESS configurations is the combination of batteries and supercapacitors (SC) [8], [9]. Most of them have taken place in electric vehicles [10], although there have been HESS applications for wind turbines [7], [11], for solar generation systems [6], and UPS, [12], [13]. Here, some advantages of the combination of batteries and supercapacitors: the extension of the battery lifetime, the capability for fast energy storing, it is a suitable ESS for intermittent sources of energy, and it has a reduced environmental impact.

In the specific application of microgrids, HESSs have to be designed taking into account many operational factors of the Microgrid, for example: the energy supply nature, the microgrid operation mode (interconnected- islanded), the voltage conversion ratio, the energy and power ratings, the chosen power electronics topologies, among others [5].

There are different topologies for the interconnection of Batteries and Supercapacitors in a HESS. A classification of topologies divides them in passive, active and semi-active. The difference between an active topology and a passive one is that in the active connection the storage elements are connected via DC converters while in the passive connection the storage technologies are directly interconnected [14]. In a semi-active topology, it is used that only one of the storage devices is connected through a DC converter, or a single converter is used to connect the pre-connected storage mediums to the load.

This paper presents a study of the performance of three topologies for the interconnection of batteries and supercapacitors in a HESS. The paper is based on a preliminary study of topologies made by the authors, in which two semi-active topologies were evaluated [15]. Here, an active topology is added to the study and the operational benefits of each topology are documented. The paper is organized as follows: a detailed system description and the transfer functions of the system and controllers are described in section 2. Section 3 presents the simulation results. Finally, some conclusions are presented in section 4.

2. System Description

In this study, a HESS, composed by Li-ion batteries and a SC, is designed for a 5kW rated capacity residential microgrid. Three topologies for the interconnection of batteries and SCs, two semi-active and an active one, are simulated. The storage system has a rated energy of 5 kWh and a rated power of 5 kW. The DC bus has a rated voltage of 360 V.

A non-isolated bidirectional half-bridge DC converter topology has been chosen for the integration of the storage mediums in an active or semi-active topology. Figure 1 shows the topology of the mentioned converter and its control architecture with a battery as single storage unit. This converter and its control architecture, works as a buck converter, when the battery is in charging mode, and as boost converter when it is discharging. An ACC double-loop control strategy, commonly used in methods of charging and discharging batteries [16], has been used for this purpose.

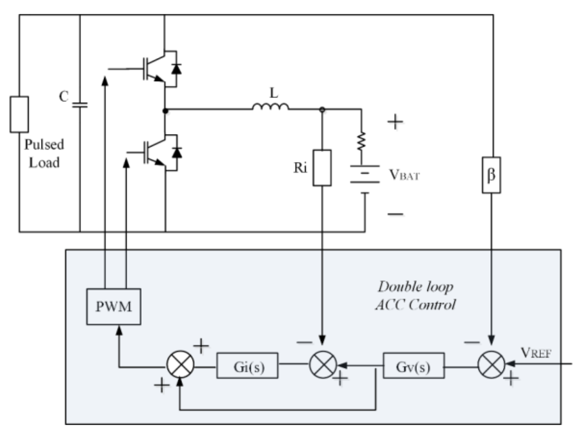

Figure 1. Half-Bridge DC/DC converter with an ACC double loop control strategy

For the simulations of the HESS topologies, a square shaped load with frequency of 10 Hz is connected. The main purpose for the combination of batteries and supercapacitors in a HESS in this study, is to extend the battery lifetime while the short-term storage medium (supercapacitor) deals with the dynamic component of the current load. Some studies have demonstrated that this combination can extend the lifetime of batteries reducing the electric stress in the battery caused for the sudden changes in load or generation. These type of systems are economically justified whenever battery reaches a lifetime extension of 50% or more [17].

SISOTOOL of MATLAB was the main computational tool, used for the calculations of the elements of the converter and for the design of the controllers. For the simulation of the entire system, the software Power SIM 11.0.1 was used.

Two semi-active topologies and an active one are analyzed. The parallel semi-active hybrid topology (Figure 2) the Battery semi-active hybrid topology (Figure 3) and the parallel active topology (Figure 4). The battery converter is designed and sized for the battery capacity and used for the two semi-active topologies. For the case of the parallel active hybrid topology, a new converter is designed and sized for the supercapacitor.

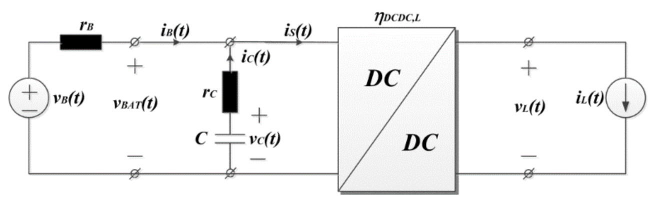

Figure 2. Parallel semi-active hybrid topology [23]

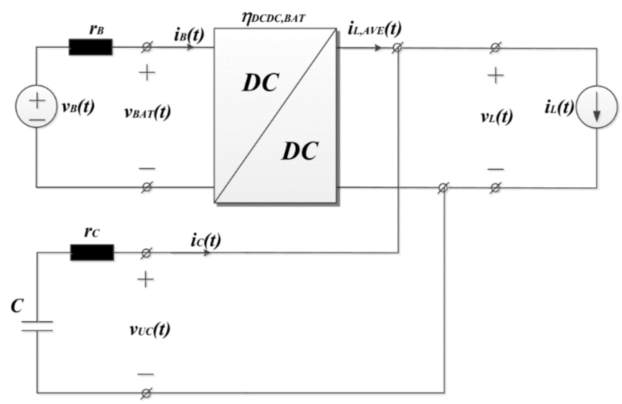

Figure 3. Battery Semi-active Hybrid topology [23]

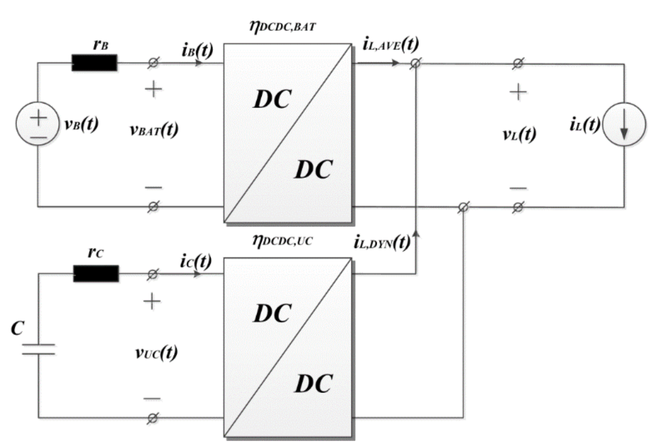

Figure 4. Parallel Active Hybrid Topology [23]

Table I shows a summary of the elements used in the converters. The main transfer functions of the system under study and the used controllers are shown in Table II.

Table I. DC/DC converter parameters for the Battery and for the Supercapacitor

Variable name	Variable	Battery Converter	SC Converter
Rated Power	Pn	5 kW	7 kW
Rated Voltage	Vout	360 V	360 V
Rated input Voltage	Vbat	144 V	120-240 V
Nominal current	In	13,9 A	19,44 A
Δ IL_max	ΔIL_max	3,5 A	5,8 A
Switching freq	fs	4 kHz	12 kHz
Filter Inductance	L	6 mH	3 mH
Filter capacitor	C	1 mF	180 μF

Table II. Basic Transfer Functions for the control of DC converter

Function	Transfer Function
Duty cycle to inductor current	$Gid(s)=\left.\frac{\hat{\imath}_L(s)}{\hat{d}(s)}\right\rvert_{\hat{v}_i=\hat{\imath}_o=0}=\frac{V_{DC}+(1-D)\,Z_{DC}\,I_{Lbat}}{sL+(1+D)^2\,Z_{DC}}$
PWM Modulator Gain	$F_M=1$
Current loop gain	$T_i(s)=Gid(s)\,R_i\,G_{ix}(s)\,F_M$
Control voltage to inductor current	$ILC(s)=\left.\frac{\hat{\imath}_L(s)}{\hat{v}_c(s)}\right\rvert_{\hat{v}_i=\hat{\imath}_o=0}=(1+G_{ix}(s))\frac{F_M\,Gid(s)}{1+T_i(s)}$
Inductor Current to Output Voltage	$G_{vi}(s)=\left.\frac{\hat{v}_{DC}(s)}{\hat{\imath}_L(s)}\right\rvert_{\hat{v}_i=\hat{\imath}_o=0}=\frac{V_{DC}\,Z_{DC}\,(1-D)-\,Z_{DC}\,sL\,I_{Lbat}}{V_{DC}+(1-D)\,Z_{DC}\,I_{Lbat}}$
Control Voltage to output voltage	$V_{oc}(s)=\left.\frac{\hat{v}_{DC}(s)}{\hat{v}_c(s)}\right\rvert_{\hat{v}_i=\hat{\imath}_o=0}=ILC(s)G_{vi}(s)$
Voltage loop gain	$T_V(s)=\beta\,V_{oc}(s)\,G_{vx}(s)$
Current Controller *Battery, x=1* *SC, x=2*	$G_{ix}(s)=\frac{w_{ix}\left(1+\frac{s}{w_{zx}}\right)}{s\left(1+\frac{s}{w_{px}}\right)}$
Voltage Controller	$G_{vx}(s)=\frac{w_{vx}}{s}$

Variables and transfer functions of Table II are used in the DC converter control loops as shown in Figure 5. In order to ensure the system stability the current control loop controller (Ti(s)), the minimum phase margin is 50 degrees with a cutting frequency much lower than the switching frequency, $10\%\,fs < fc < 5\%\,fs$. Something similar is applied for design of the voltage control loop controller (Tv(s)), with its cutting frequency much lower than the cutting frequency of the current loop, $10\%\,fs < fcut\_current < 5\%\,fs$. Additionally, for an effective separation of the average and dynamic components of the load current, it is recommended that the bandwidth of the battery voltage control loop be much smaller than the bandwidth of the SC voltage loop. This is to make sure that only SC compensates for rapid fluctuations and the battery responds to slow dynamic power [18], [19]. Based on the above, on the design topics of the controllers, the authors of the present paper consider convenient to use a higher switching frequency for the converter of the supercapacitor. A table resume of some control parameters is presented in Table III.

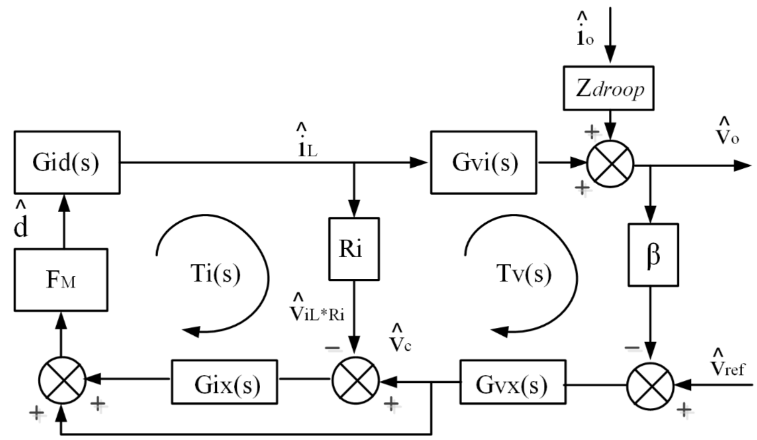

Figure 5. DC/DC bidirectional converter control loops.

Table III. Control parameters for DC converters

	Battery Converter	**Supercapacitor Converter**
Voltage sensor gain (β)	1	1
Current sensor gain (*Ri*)	1	1
Current control loop bandwidth	625 Hz	1.660 Hz
Voltage control loop bandwidth	34,3 Hz	155 Hz
Current Controller Phase Margin	65,8°	70,1°
Voltage Controller Phase Margin	77,9°	60,1°
R_{DROOP} / C_{DROOP}	2 Ω	0,1 F
Current controller	$G_{i1}(s) = \frac{4.741\ (s + 1.456)}{s\ (s + 81.990)}$	$G_{v1}(s) = \frac{25{,}7}{s}$
Voltage controller	$G_{i2}(s) = \frac{33.377\ (s + 3.163)}{s\ (s + 416.800)}$	$G_{v2}(s) = \frac{87{,}3}{s}$

3. Simulation results and comparative analysis of the studied topologies

This section presents the simulation results of the three mentioned topologies using the software Power SIM 11.0.1. These plots were obtained from the system and the related topologies described in section 2. First, the DC converter has been designed and analyzed with li-ion batteries as a single storage medium. The schematic circuit is the one described in Figure 1.

As Figure 6 a) shows the load current fluctuates between 50% and 100% of the nominal current, with a switching frequency of 10 Hz. Figure 6 b) shows the output voltage with a small variation over the 360 V due to the implemented double loop control strategy. Figure 6 c) shows how the battery has to deal with large current variations as a consequence of the referred load current. For an effective ripple reduction, a 50µF capacitor is connected between the terminals of the battery.

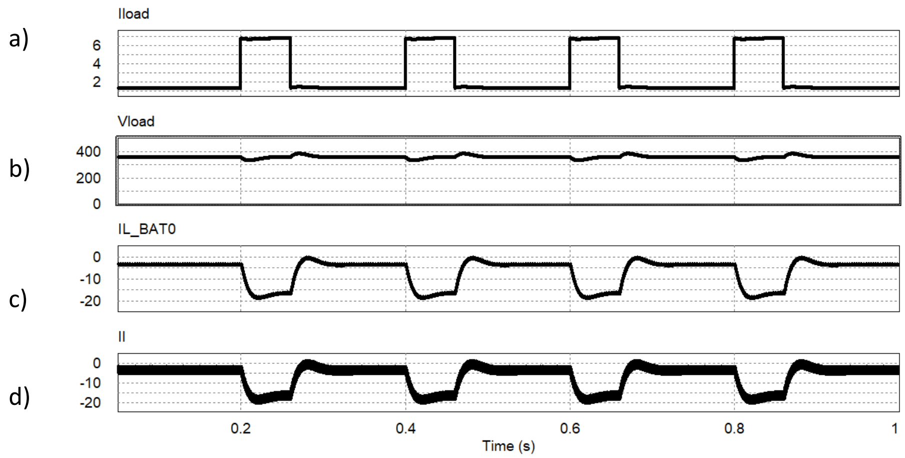

Figure 6. Simulation plots of DC converter with batteries as a single storage unit. a) Current Load [A]. b) Output voltage [V]. c) Battery current [A]. d) Inductor current [A]

3.1. Simulation results of the hybrid Parallel semi-active topology

Based on the previous storage system based on batteries, now, a supercapacitor is connected in terminals of the battery creating a semi-active Hybrid parallel topology. It is expected that the SC supply the dynamic component of the pulsed current load. The time constant of SC is chosen to be much longer than the period of the pulsed load, e.g. T_{load}=0,2s. Taking into account that this time constant depends strongly on the internal resistances of the battery and the supercapacitor, an inaccurate estimation of these electric parameters may result in a bad representation of the behavior of the real system.

When the supercapacitor is included, it is necessary to use a bigger filter capacitor in order to reduce an overvoltage in the DC bus. Once this new filter is connected, the transfer functions and the controllers are updated. Figure 7 shows the time plots of the parallel semi-active topology. Figure 7 b) and c), shows how the SC current follows closely the dynamic component of the inductor current with an approximate variation of 16 A. The result is that the ripple of the battery current is reduced to less than 2 A, as shown in Figure 7 d). The main advantages on this system behavior are the potential reduction on the battery current capacity, and an increase in the battery lifetime due to the diminution on its electric stresses.

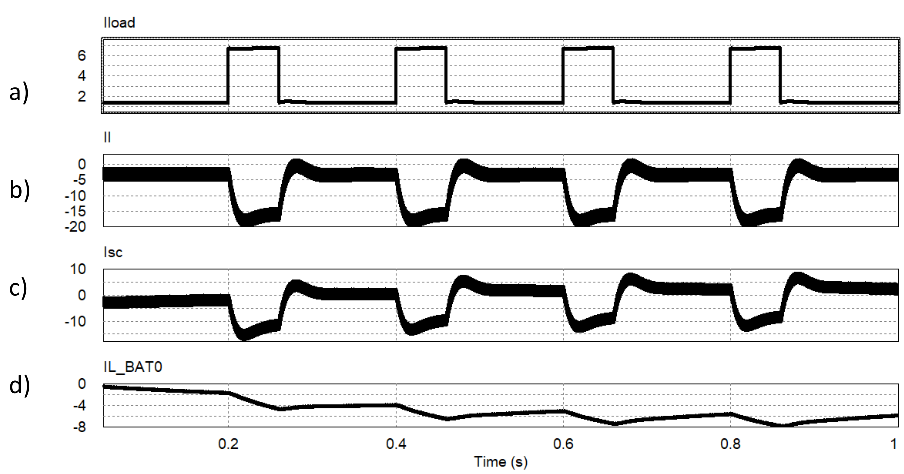

Figure 7. Simulation plots of a semi-active parallel topology. a) Current Load [A]. b) Output voltage [V]. c) Supercapacitor current [A]. d) Battery current [A].

3.2. Simulation results of the hybrid Battery semi-active topology

Now, from the previous ESS based on batteries, a SC is connected in terminals of the DC bus, and a battery semi-active hybrid topology is obtained. The simulation results of this topology are shown in Figure 8. The method for the SC selection is similar to the previous topology. Consequently, an effective power management and a well predicted behavior relies strongly on an accurate estimation of the electric model parameters of the storage devices. The big capacitance connected to the load terminals improves the voltage regulation in the DC bus. However, the system dynamics and their controllability are heavily affected. Figure 8 b) shows the battery current and an important low frequency variation. As Figure 8 c) shows the SC behaves as a high pass filter of the converter high-frequency current component.

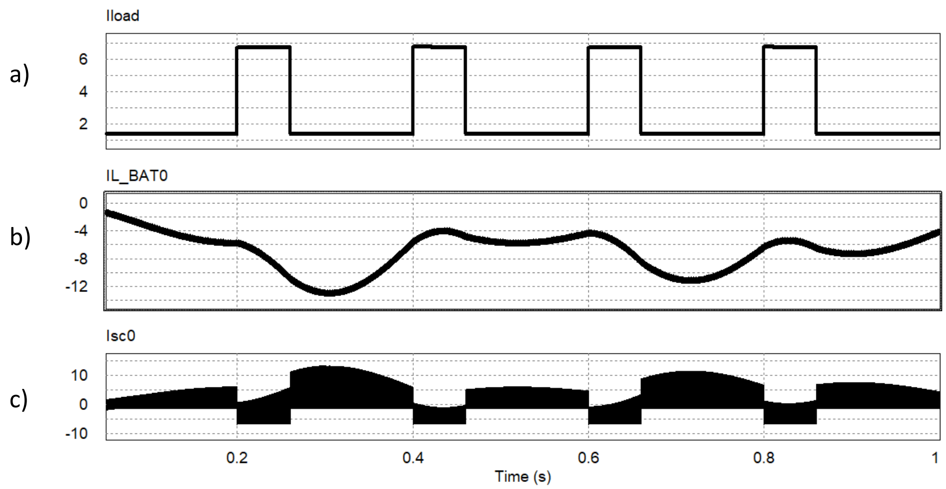

Figure 8. Simulation plots of a battery semi-active topology. a) Load current [A] b) Battery current [A]. C) Supercapacitor current [A].

3.3. Simulation results of the hybrid Parallel active topology

The energy management for a HESS in an active topology demands a more complex control strategy [20], because of the need of disaggregating the average and dynamic components of a pulsed current. For this purpose, an optimization-based real-time frequency-decoupling control strategy has been selected for the present study. A real-time control strategy allows the controllers to operate independently, without the need of using central controllers and communications. It provides better reliability of the entire system [21]. An extended explanation of this control strategy is presented in [18], [19]. As a general description a virtual Low Pass Filter (LPF) and a High Pass Filter (HPF) are included in a third control loop of each DC converter, one converter for every storage technology used. An specific application for residential microgrids with an emulated solar generator is presented in [22].

The complete schematic circuit of a parallel active hybrid topology is shown in Figure 9. The pulsed current load is connected to the DC bus and is represented by the element marked as LOAD. The output voltage remains nearly constant over the 360V. The switching frequency in the SC converter is chosen to be higher than the used in the battery converter. The differences in the switching frequencies allows to adjust better the bandwidth of the voltage controllers and provide the SC converter with a faster dynamics. In addition, the rated power of the SC converter should be also higher because of the current variation in the supercapacitor. An overview list of the SC converter parameters and the controller bandwidths of the entire system in a parallel active hybrid is presented in Table I and Table II.

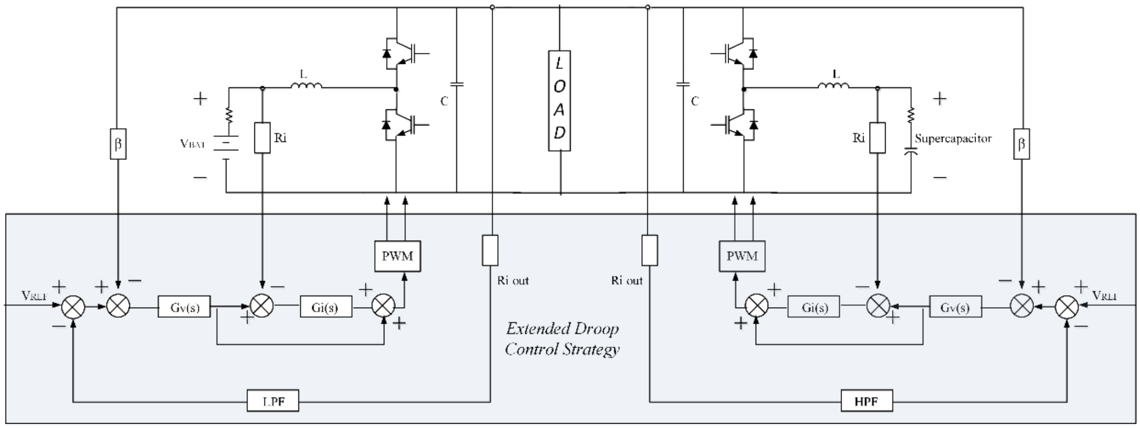

Figure 9. System Schematic with the implemented control strategy

Figure 10 shows the simulation plots of the parallel active topology. The injected load current, shown in Figure 10 a), is divided into the converters in parallel as expected. The dynamic component of the load current is assigned to the SC and the average component to the battery. These current components referred to the side of each storage medium are shown in Figure 10 b) and Figure 10 c). Sudden changes in load current do not change the battery current immediately, therefore the electrical stress in the battery is considerably reduced.

As mentioned in section 2, the use of a converter for the SC makes possible to better manage its stored energy. Figure 10 d) shows the voltage in terminals of the supercapacitor. This plot shows a SC voltage variation in a range of 5V. The voltage variation in terminals of the SC depends on the energy associated to the oscillations in the load current as well as the SC value. It is important to notice that in the semi active topologies, the variation of voltage in SC terminals is not possible because the direct parallel connection in terminals of the battery or DC bus, both with defined voltage levels.

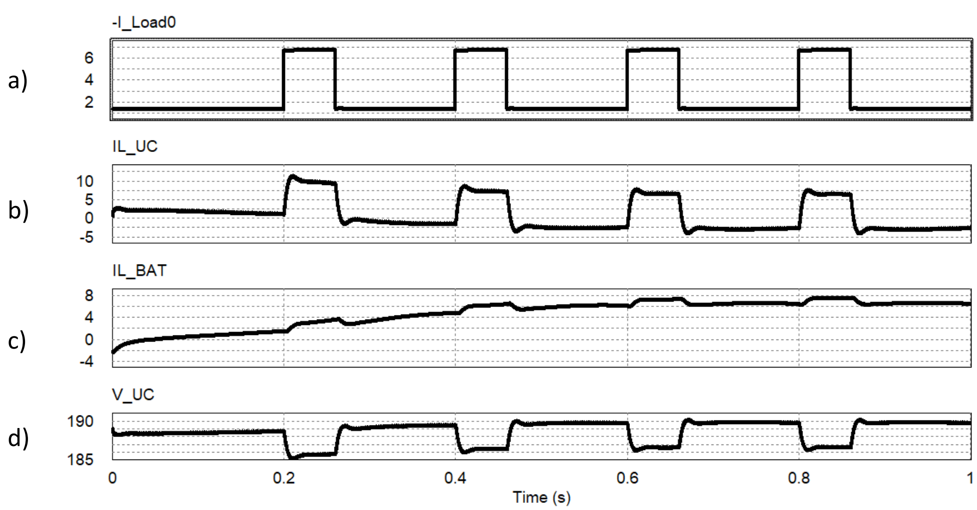

Figure 10. Simulation Plots of a HESS in an active topology. a) Injected Load Current [A]. b) Battery current plot [A]. c) SC current plot [A] d) Voltage variations in SC terminals [V]

4. Conclusions

A comparison of three topologies of HESS composed of lithium- ion batteries and supercapacitors with potential application to residential microgrids has been made. A PI double loop linear ACC control algorithm and an extended droop control strategy were designed for the energy management of the three studied topologies.

In an active parallel topology, an effective separation of the dynamic and the average components of the injected current depends on the parameters of the virtual filters included in the third control loop of the implemented control strategy.

In an active parallel topology, it is important to take into account that the dynamics of the SC converter should be higher than the converter dynamics used for the battery. Larger bandwidths for voltage and current controllers of SC normally imply the convenience of using a higher switching frequency for the SC converter.

Semi- Active topologies result to be simpler and cheaper than the parallel active topology, however, they present a lack of controllability and have limited operation performance. In contrast, the active topology allows to manage better the stored energy in the SC because of the voltage variations in terminals. These variations are possible because of the use of a DC converter for the connection of the supercapacitor that allows to remain nearly constant the voltage in the DC bus.

A suitable value of SC will depend on two main factors: first, the energy associated to the intermittences of the injected current, and second, the ratio conversion of the used DC converter. In addition, with a chosen value of capacitance, it is possible to manage de dynamics into the supercapacitor, varying the parameters of Rdroop and Cdroop.

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