Mestrado em Engenharia Eletrotécnica

Energetic Macroscopic Representation of an Hybrid Energy Storage System for an Electrical Vehicle

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RESUMO

A sociedade hoje em dia é maioritariamente dependente do petróleo, esta dependência é verificada sobretudo em setores industriais. Esta dependência é ainda mais acentuada na indústria automóvel, onde a maioria dos combustíveis provêm do petróleo. O fato de só alguns países possuírem reservas de petróleo faz com que se crie uma dependência destes países a esse produto. Esta dependência é prejudicial a nível económico e ambiental. A produção de CO_2 e de outros gases para a atmosfera durante o processo de queima do petróleo tem causado fenómenos, como por exemplo, efeito de estufa, alterações climáticas, chuvas ácidas, buraco de ozono etc., o que tem levantado algumas preocupações em reduzir essas emissões de gases. Estas preocupações têm feito desenvolver novas tecnologias em diversos setores industriais visando sempre um desenvolvimento sustentável e processos mais eficientes.

Um dos maiores setores consumidores de petróleo é o automobilista. Por isso, nesse setor tem-se verificado uma grande mudança no tipo de veículos fabricados. O setor tem evoluído no sentido de criar uma nova geração de veículos menos poluentes. Tem-se revisto por completo o conceito automóvel. Hoje um automóvel já não é visto como sendo um veículo térmico dependente do petróleo e altamente poluente. Agora tem-se focado em veículos independentes dessa matéria-prima tornando-os menos poluentes, de forma a diminuir o impacto no planeta terra. Ao longo destes últimos anos tem-se realizado enúmeres estudos para veículos mais eficientes e menos poluentes e isso tem-se notado no mercado com o aumento de veículos híbridos e elétricos. Um veículo híbrido nesse contexto é visto como um veículo que possui mais que uma fonte de energia para alimentar o seu sistema de tração, estas fontes de energia podem ser do mesmo tipo ou diferente. Um veículo elétrico é um veículo que possui somente uma fonte de energia que neste caso será elétrica para alimentar o seu sistema de tração. Na maioria dos casos essa fonte serão baterias. Também existirão veículos híbridos elétricos, ou seja, veículos com mais que uma fonte de energia mas neste caso as duas ou mais fontes serão elétricas. Contudo o desenvolvimento deste tipo de veículo pode não ser a solução mais eficiente. Isto porque, um veículo elétrico necessita de energia elétrica para recarregar as suas fontes de energia. O problema coloca-se na forma como é obtida essa energia. Estudos indicam que é mais rentável utilizar veículos térmicos do que elétricos, dependendo do modo de produção da energia elétrica. Centrais a gás natural mas sobretudo a carvão libertam grandes quantidades de CO_2 no processo de produção de energia tornando esta solução tão ou mais poluente que os veículos térmicos. A solução ideal seria a utilização de fontes renováveis tais como, eólicas, fotovoltaica, biomassa etc.. Por isso, a implementação do uso de veículos elétricos no nosso quotidiano tem que ser um compromisso entre diversos setores da sociedade. Um dos setores influêntes é o setor politico.Esse setor terá de porpocinonar formas e condições para a implementação deste tipo de veículos na sociedade. Outros setores serão os de marketing para realçar as vantagens de o uso desse tipo de transporte. Por fim, o ultimo setor será o setor automóvel, esse setor tem como tarefa apresentar produtos atrativos e a preços acessíveis.

Este estudo foi realizado com a colaboração do *"Laboratoire d'Electrotechnique et d'Electronique de Puissance de Lille, L2EP".* Este laboratório é especializado em controlo de sistema electromecânicos como por exemplo, metros, carros elétricos, tendo também experiência em sistemas de produção de energia como sistemas eólicos e painéis fotovoltaicos.

O trabalho consiste no desenvolvimento de um sistema de armazenamento de energia híbrido elétrico para veículos elétrico e da sua estratégia de gestão de energia. Este sistema é constituído por baterias e supercondensadores. Para a representação deste sistema foi utilizado um formalismo desenvolvido pelo L2EP, *"Energetic Macroscopic Representation"* utilizando a ferramenta do Matlab Simulink. Este formalismo é desenvolvido pelo *"Laboratoire d'Electrotechnique et d'Electronique de Puissanse de Lille, L2EP"*e baseia-se no efeito de causalidade. Para definir a cadeia de controlo é necessário inverter diretamente cada um dos elementos. Com esta forma de deduzir o controlo encontramos diretamente onde serão necessários colocar controladores. Assim sendo, o controlo do sistema é conseguido de forma sistemática. De forma a distinguir cada um dos elementos, consoante as suas características, utilizam-se cincos diferentes pictogramas. Estes são:

Fontes de energia;

Elementos de acumulação;

Elementos de conversão mono físicos Elementos de conversão multi físicos;

Elementos de acoplamento;

O sistema estudado é um veículo elétrico *"TAZZARI".* Este veículo pertence ao L2EP e é utilizado para desenvolver projetos académicos ou projetos de doutoramentos. O seu sistema de tração é constituído por um motor de indução trifásica, inversor, um diferencial, rodas e o seu chassis. O sistema de armazenamento de energia estudado é um híbrido elétrico constituído por baterias, supercondensadores e um conversor de eletrónica de potência.

Este tipo de veículos possui custos ainda muito elevados e autonomias relativamente baixas quando comparadas com veículos térmicos. Isto deve-se ao seu sistema de armazenamento de energia possuir uma densidade energética inferior à dos combustíveis utilizados nos veículos térmicos. Estas fontes de energia são tipicamente baterias devido à sua grande densidade de energia elétrica. É essa densidade energética que permite obter a sua autonomia. Em contra partida uma bateria possui baixa densidade de potência, e esta característica torna-se prejudicial quando o sistema de tração requer grandes quantidades de potência, em momentos de grandes acelerações por exemplo. Nestes momentos de alta potência as baterias poderão fornecer essa potência mas degradando o seu tempo de vida. O fato de o sistema ser constituído por baterias, trás desvantagens em relação aos seus custos. De fato este componente é dos mais caros neste tipo de veículos. Baterias têm um tempo de vida em modos de utilização aconselháveis de aproximadamente 5 anos. Como foi explicado, uma bateria não é o mais adequado para alimentar este tipo de tração. Neste momento no mercado não existe nenhuma fonte de energia que seja capaz de satisfazer plenamente o sistema em termos de potência e energia. Existe então uma necessidade de encontrar soluções para aumentar o seu tempo de vida de forma a baixar os custos associados à manutenção. Esta solução tem passado por criar sistemas de armazenamento de energia híbridos. Diversos estudos têm sido desenvolvidos sobre este tipo de sistemas. Tem-se estudado diversas topologias, existindo duas grandes categorias, passiva e ativa, sendo estas possuidoras de características distintas:

- Passiva: nesta topologia as duas fontes encontram-se conectadas diretamente em paralelo;
- Ativa, esta topologia possui diversas sub-topologias:

“Cascade converters”

“Paralell Multi-inputs converter”

“Multiple converters”

Supercondensadores/Baterias

Baterias/Supercondensadores

Para o controlo deste tipo de sistemas é necessário aplicar uma estratégia de gestão de energia de forma a conseguir gerir da melhor forma possível os fluxos de energia entre as duas fontes. Algumas das estratégias já estudadas são:

- Filtragem
- Corrente de saturação
- *“Switch”*
- Aceleração

Neste trabalho é estudada a topologia ativa, supercondensadores/baterias. Esta topologia possui duas grandes vantagens. Possui um DC-Bus praticamente constante, dado ter a bateria a garantir o nível tensão e utilizar os supercondensadores com alto rendimento para conseguir-se aproveitar grande parte da potência armazenada. A estratégia utilizada é a estratégia de filtragem. Esta estratégia permite filtrar a potência de tração necessária em altas e baixas frequências. A potência de tração possui altas frequências, que corresponde a níveis de potência elevados e baixas frequências que corresponde a níveis de energia elevados. Como foi dito anteriormente as baterias conseguem alimentar um sistema com muita energia mas não conseguem, sem degradar o seu tempo de vida, fornecer altas potências. Com esta estratégia é possível separar isso e fazer com que as baixas frequências sejam alimentadas pelas baterias e as altas pelos supercondensadores. Contudo a estratégia é definida por um conjunto de regras definidas de forma a assegurar a segurança do utilizador e dos componentes. Nessa estratégia existe a particularidade de poder recuperar alguma da energia reenviada pelo sub sistema de tração durantes as fases de travagem. Esta característica permite-nos recarregar as baterias e os supercondensadores. Tendo isto como objetivo os supercondensadores serão dimensionados consoante a potência necessária para o sistema de tração e as baterias serão dimensionadas para a necessidade energética .

Na representação do sistema foram expostos todos os elementos constituintes do sistema. Foram considerados para cada um dos modelos os fenómenos mais relevantes para a análise final do sistema. A parte do controlo é obtida através da inversão direta de todos os elementos à exceção dos elementos de acumulação, onde essa inversão direta não é possível. Nesse elemento o controlo é feito com a ajuda de controladores do tipo IP, integral proporcional. Foi feita a escolha desses controladores para evitar *"overshoots"* e em certos casos para resolver problemas de *"algebric loops"*. De forma a simular o comportamento de um condutor, foi utilizado um "cycle drive" para veículos elétricos, *"World-Wide Harmonized Light"* "WLTC". Este tipo de ciclo possui diversas classes conforme o rácio entre a massa do veículo e a potência da máquina elétrica.

Os resultados obtidos não foram integralmente os esperados. Verifica-se, em alguns momentos, que os supercondensadores não fornecem a parte de altas frequências devido a limitações impostas pela estratégia de energia.

Como trabalho futuro propõe-se desenvolver outro tipo de estratégia de forma a obter resultados mais eficientes aplicando outra tipo de fonte como auxílio às baterias.

Palavras chave: Energetic Macroscopic Representation, sistemas de armazenamento de energia, sistemas de armazenamento híbridos de energia, veículos elétricos, gestão de energia.

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Simbology

a- Acceleration

f_{losses} - Friction losses

A- Area

C- Capacitance

c_{aero}- Aerodynamic coefficient

E- Energy

F- Faradays

F- Linear force

F_{acc}- Acceleration Forces

F_{break}- Break forces

F_{drag}- Drag forces

f-Frequency

f_r- Coeficient of losses by friction

F_{res}- Resistives forces

F_{slop}- Slop forces

F_{tract}- Traction forces

g- Gravity

I-Current

i_{ma}- Currant machine

i_{trac}- Currant traction

J- Inertia

K_{diff}-Transformation ratio

kg- Kilogram

kW- Kilowat

kW/h/L- Kilowat hour per liter

K_{wheels}- Wheel radius

L- Inductance

m-Mass

N_{scp}- Supercapacitors in paralele

N_{scs}- Supercapacitors in serie

N_{sctot}- Total quantity of supercapacitors

P- Electric Power

p- Weight

P_{acc}- Power acceleration

P_{losses}- Electrical power losses

P_{res}- Power resistive

P_{sc}- Supercapacitors power

P_{tract}- Power traction

R- Resistance

r_d- *Radius*

r_{wheels}– Radius wheels

T- Torque

T_{mach}- Torque machine

T_{wheels}- Torque wheels

u_{dc}- DC voltage

u_{sc}- Supercapacitos voltage

v- Linear velocity

V- Voltage

W/kg- Watt per kilogram

Wh/kg- Watt hour per killogram

τ- Constant time

Ω- Angular velocity

Ω_{diff}- Angular velocity of the differential

Ω_{mach}- Angular velocity machine

Ω_{shaft}- Angular velocity shaft

Ω_{wheels}- Angular velocity of wheels

$\boldsymbol{\rho}$- Density of the air

Abbreviations

CO_2 - Dioxide Carbone

EMR-Energetic Macroscopic Representation

ESS-Energy Storage System

EV- Electrical Vehicle

H-ESS- Hybrid Energy Storage System

HV- hybrid Vehicle

IM-Induction Machine

L2EP- Laboratoire d'Electrotechique et d'Electronique de Puissance

Li-Ion-Lithium Ion

OCV- Open Circuit Voltage

PSA- Peugeot Citroen

RC- Resistance Capacity

SC-Supercapacitors

SNCF- Sociéte Nationale de chemins de fer Français

UC-Ultracapacitors

WLTC-World Light Test Cycle

Abstract

Nowadays the environmental preoccupations are increasing due to climate changes, the ozone hole and other effects. These consequences are mainly produced by the automobile industry, due to the thermal engines used for vehicles. This sector one of the most pollutants, 23% of emissions are caused by this sector. Therefore, it is necessary to find solutions in order to reduce these impacts. One solution is to develop electrical vehicles (EVs). These vehicles possess 0% of local pollutant emissions. However, these kind of vehicles have large costs associated to batteries and reduced autonomy in comparison with thermal vehicles. Another characteristic is that the batteries' lifetime is limited in traction applications. So, different hybrid solutions should be studied in terms of topology and strategy.

The topology studied in his work, is composed of batteries and supercapacitors. The strategy used is a filtering strategy. The choice of this topology was due to its characteristics, constant DC-bus, high efficiency utilization of supercapacitors and simple control. The strategy possesses the advantages of dividing the power traction in high frequency and low frequency. It is advantageous because high frequencies damage the lifetime of batteries due to their low power density. Thus, the installation of supercapacitors that possess high power density will supply the high frequency part.

This work is realized with the Matlab tool Energetic Macroscopic Represnetation, EMR.

Key words: Electrical Vehicles, Energetic Macroscopic Representation, Energy Storage System, Hybrid Energy Storage System

1 Introduction

1.1 Context

Our society is more and more concerned with environmental issues and the impact of our behaviour in the ambient (Chan and Wong 2004). These worries appear due to the climatic change and the increase of the population. The idea of sustainable development is continuously discussed and present in our quotidian. Some authors considered it as one of the major challenges of our century. One of the possible definitions for sustainable development is the capacity to consume natural resources without putting at risk future generations (Bruntland 1988). However, it is possible to observe in Figure 1 that the reality is different. Taking into account this definition, the consumption and the productivity must be equilibrate. Observing Figure 1it is possible to see that the global consumption of oil increases faster than the discovery of new wells. If this rhythm continues, it is predicted that in 2040 there will not be enough oil for the global necessities.

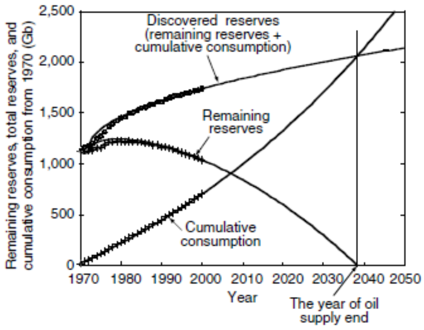


Figure 1-Evolution of the consumption and discovery of oil resources (Ehsani et al. 2005)

One of the causes of this consumption is the emission of greenhouse gases. These emissions cause global warming and climatic changes. Dioxide Carbone (CO_2) is the main cause responsible for this effect. By dividing the levels of emissions per sector, it is possible to verify in Figure 2, that the transportation sector is one of the largest sector responsible for the emission of these gases. In Figure 2 it is also possible to observe that the road transport is the largest responsible for the emission of CO_2.

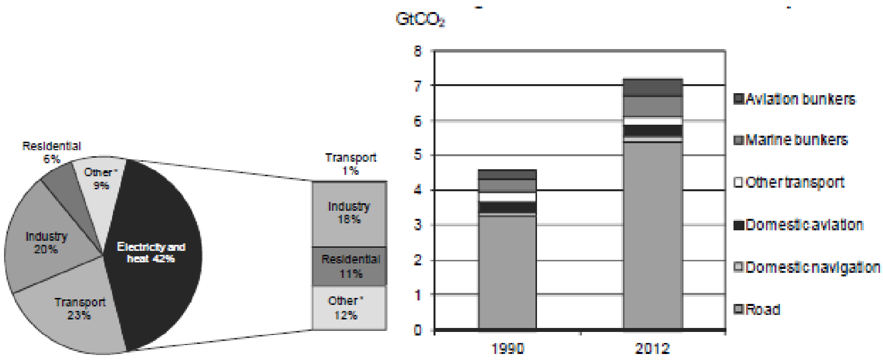


Figure 2-Emission of CO_2 in transportation per sector (International Energy Agency 2014)

Thus, the road transport is a sector where changings can allow important results in the final emissions levels of CO_2 (Eurelectric 2007). One solution to solve this problem is the utilization of a new generation of vehicles. For example, electrical vehicles (EV) (Messagie, Macharis, and Van Mierlo 2013) (Eurelectric 2007) or hybrid electric vehicles (HEV). These types of vehicles have been in development in recent years due to the possibility of decreasing the impact in the environment for this sector.

However, this solution can have some drawbacks. The concept that an EV does not emit CO_2 is not always true. It depends on what is considered in the study. If we consider the consumption of energy of the well of oil to the tank of the car, this emission can be different from zero. The supply of EV's demands an important quantity of electric energy in order to recharge the battery. This energy can be produced using different methods. Depending on the plant used for the production of electricity, the emission of CO_2 can be very different (Messagie, Macharis, and Van Mierlo 2013). In some cases the production of CO_2 can be more important in the EV circumstance, than in a conventional car (Messagie, Macharis, and Van Mierlo 2013). The optimal solution would be the utilization of renewable energy plants. This solution bring us to levels of emission practically null.

Another drawback of EVs is the cost of some components. The main source of energy for a EV is the battery (Karangia et al. 2013) due to their high energy density, compact size and reliability (Khaligh and Li 2010). However, this choice brings some drawbacks. The expensive cost of batteries and their short lifetime are a real problem. This has been the motivation for the development of other types of storage systems in order to improve these drawbacks.

Even batteries that have a high energy density, this value is small compared with the energy density of the fuel used in thermal vehicles. A thermal engine has a quantity of energy per litre equal to 6 kW/h/L. These engines have a maximal efficiency of 30% for gasoline and 40% for diesel (Eurelectric 2007). Even with these low values of efficiency, it is enough to obtain higher range levels than in EVs. So the main disadvantages of EVs are the range and charging time (Chan and Wong 2004).

Thus, to face these drawbacks, one solution has been developed. This solution consists of creating a Hybrid Energy Storage System (H-ESS). These systems consist in joining more than one source of energy for the storage system. The main advantage is the possibility of splitting the power flow between the sources and optimize each one (Khaligh and Li 2010). There are several works regarding the application of association of different energy sources; batteries associated with thermal engine, batteries with fuel cells (Depature, Bouscayrol, and Boulon 2013) and supercapacitors (Castaings et al. 2014b)(Karangia et al. 2013) (Trovao et al. 2013) .

1.2 Subject

This study consists on elaborating the control of an on board H-ESS for an EV represented in Figure 3. The selected topology is shown in Figure 3.1 and is composed of batteries and supercapacitors. This subsystem is constituted by a bi-directional DC/DC converter. This converter has to be bi-directional for the recovery of energy during the deceleration or breaking moments. The storage system feeds a traction system of 15 kW, composed by an inverter, an electrical machine, a differential and wheels as shown in Figure 3.2.

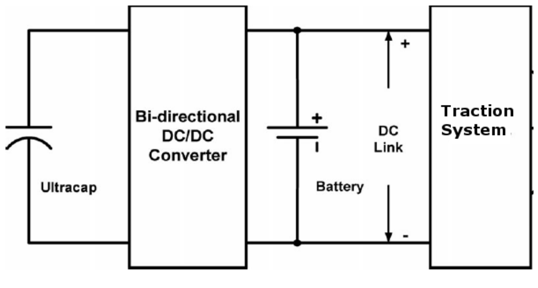


Figure 3.1-H-ESS

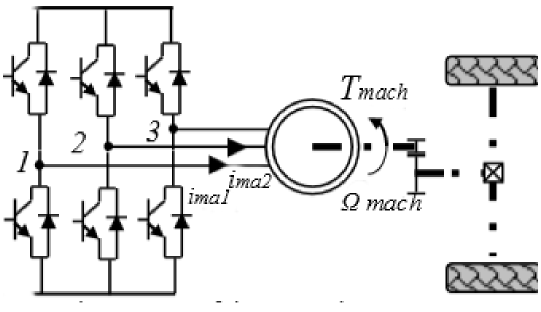


Figure 3.2-Traction System

Figure 3-Subsystems

To represent these two subsystems, a description tool is used, which was created by professors and researchers of *“Laboratory of Electrical Engineering and Power Electronics, L2EP”*. This tool allows to decide the model that is used, to represent it and to finally perform the simulations. This tool is a formalism that represents complex systems, Energetic Macroscopic

Representation, EMR (Roboam 2012) (EMRwebsite - Home n.d.). This formalism is based on the principle of causality. The main goal of this tool is to systematically deduce the control structure of the system.

The main goal of this study is to create a current strategy to control the battery current. The strategy used for this task is a frequency strategy. This strategy divides the current in high frequency and low frequency components with a low pass filter (Allegre, Bouscayrol, and Trigui 2009). The current is constituted by two components, the high frequency and the low frequency component. The high frequency part has a high level of power and the low frequency a high level of energy. Batteries have a high energy density, so they will supply this part, and supercapacitors have a high power density, so they will supply the high frequency part.

For these kinds of systems different topologies exist, passive and active topologies. The different topologies depends on the way that they are connected. This topic will be better explained in the next section.

For this study, the topology is an active one, a converter cascade topology. This topology (Figure 3.1) was chosen due to its different advantages. The advantages of this topology are:

- To be able to control the power flow between the two sources;
- To have a constant DC Link, due to the constant battery voltage;
- More efficient utilization of supercapacitors;

The drawback of this topology is the necessity to design the converter in order to support the high peak current of supercapacitors (Cao and Emadi 2012).

1.3 State of art

In order to evaluate the EVs, there are some aspects to take into account. These aspects are mainly related with the Energy Storage System (ESS), and they are (Khaligh and Li 2010):

- Energy density
- Power density
- Lifetime
- Costs
- Maintenance

At this moment, there is not a unique source with high power density, high energy density and with a long lifetime. Therefore, the hybridization of the battery is useful. **Erro! Fonte de**

referência não encontrada. shows the results of this hybridization. Another advantage of the hybridization technique is the performance improvement of the vehicle in terms of (Karangia et al. 2013) (Xiaoliang, Tosiyoki, and Yoichi 2014a):

- Acceleration
- Increasing the range of the EV's
- Reducing the life cycle costs by extending the life of the batteries
- Reducing the costs associated to the batteries

To follow a specific drive cycle, a high quantity of energy is necessary. This energy is supplied by the batteries. However, during the cycle there are moments where the current values reach important peaks, for example during accelerations or braking moments. These peaks are very prejudicial to the lifetime of batteries (Cao and Emadi 2012) (Cao, Schofield, and Emadi 2008) (Hung, Hopkins, and Mosling 1993), so, to save their lifetime, the installation of the Supercapacitors is very important. Supercapacitors possess a high power. This characteristic allows to recover the power during the braking moments and to supply peak power during the acceleration, without damaging batteries (Behjati and Davoudi 2012). **Erro! Fonte de referência não encontrada.**4 shows the different values of power density and energy density between the two sources. Another advantage of the supercapacitors is the fast recharging time. This hybridization allows to supply the vehicle in energy and power demand and recover for recharging the source of energy during the braking moments (Khaligh and Li 2010)(Karangia et al. 2013) (Xiaoliang, Tosiyoki, and Yoichi 2014b) **Erro! Fonte de referência não encontrada.** shows the results of the junction of the aspects referred before.

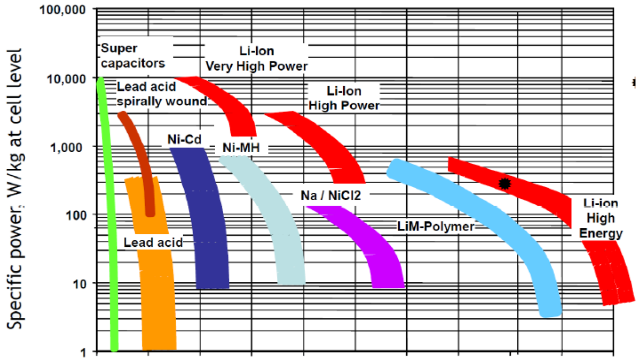


Figure 4- Comparison of Energetic density and Power density between Batteries and SC (Guibert and (Saft Groupe SA) 2009)

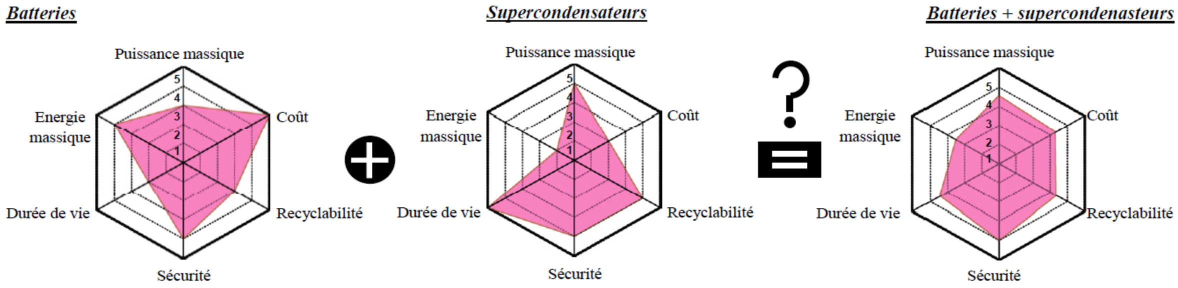


Figure 5- Results of association between batteries and SC (ALLEGRE 2010)

With this system, it will be possible to supply the vehicle with power and energy without damaging the sources.

1.3.1 Hybrid Storage System (H-ESS)

There are two different topologies of H-ESS, passive and active. The difference between these topologies is the way that the different sources are connected. The differences between the different topologies are represented in Table 1. This table demonstrates the differences of the sources connections, some details regarding the control and explains also some advantages and drawbacks of each topology.

Table 1-Topologies of H-ESS

Type	Topology	Characteristics
Active	Cascade	Complex control. Expensive costs. Bigger efficiency of sources.
	Batteries/Supercapacitors	Variable DC Link. Decrease of the costs associate with batteries.
	Supercapacitors/Batteries	Constant DC link. Converters must support the high currents of supercapacitors.
	Multi Input converter	Decrease of costs associate to converters in comparison to the Multi converter.
	Multi converter	Two converters for each source. Control more complex. More expensive.
Passive	Parallel	Directly linked without converters. Low efficiency of the supercapacitors.

Passive system

Figure 6 demonstrates a passive system. It has the two sources directly connected in parallel (Cao and Emadi 2012) (Lukic et al. 2006).

This topology has the advantage of being simple of implementation, due to the absence of power electronics converters (Cao and Emadi 2012) (Behjati and Davoudi 2012). Its drawback is the impossibility to control the power flow between the two sources. In these topologies, the supercapacitors do not deliver all the stored energy. This is due to the fact that the batteries voltage is higher than the supercapacitors voltage. The capacitors in this topology have a low efficiency. The efficiency of supercapacitors is related with the quantity of energy they can deliver. In this topology, this quantity is never the total stored. This happens because supercapacitors are connected directly with the battery.

The energy delivered by supercapacitors is given by equation (1):

$$\mathrm{E} = \frac{1}{2} c\, v_{sc}^{2} \tag{1}$$

Where c is the capacitance of the supercapacitor This value, given in Faraday (F), is the difference between the final voltage and the initial voltage. Since these two sources are directly connected in parallel, the voltage is the same. Consequently, the energy delivered by supercapacitors will never be the nominal. In these topologies, the supercapacitor is used as a low pass filter (Blanes et al. 2013). This application is not usually used for industrial applications (Behjati and Davoudi 2012).

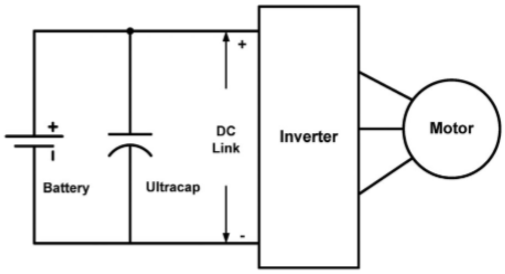


Figure 6-Passive system (Cao and Emadi 2012)

Active systems

An active system is an improvement of the passive system. That improvement is accomplished with the placement of a power electronic converter. This converter will enable the control of the power flux between the sources. With the addition of this converter, the following advantages are obtained (Gao, Dougal, and Liu 2005):

- Higher flexibility in the capacity of the batteries and the supercapacitors;
- More power capacity;
- DC link more constant;
- The weight of the power source can be smaller ;
- The converter can also serve as a regulator for the charging of the batteries.

There are different topologies of active systems. The different topologies are chosen depending on the strategies used, the voltage or on the application that will be used.

The active systems can have different topologies:

- One converter:
    - Battery/Supercapacitors;
    - Supercapacitors/Batteries;
- Multiple converter configuration;
- Multiple input-converter configuration;
- Cascaded converter configuration;

One converter topology Batteries/Ultracapacitors

With this topology, it is possible to have a smaller battery voltage. It is used for batteries where the battery capacity is smaller. With this topology it is possible to decrease the weight of batteries and associated costs. The supercapacitor will be used as a low pass filter and will supply the DC Bus voltage between voltage values that the supercapacitors allow (Cao and Emadi 2012). In Figure 7 it is possible to verify the connection between the batteries and supercapacitors.

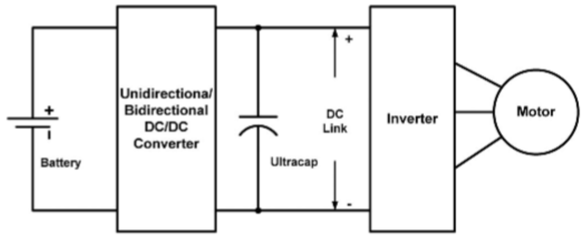


Figure 7-Batteries/Supercapacitors (Cao and Emadi 2012)

Cascaded configuration

This topology is the same as the previous one, however, for a better control of the supercapacitors, a second converter is added, as Figure 8 demonstrates, (Cao and Emadi 2012). With this topology it is possible to control separately the state of charge of the sources and to control the DC bus with the second converter (Behjati and Davoudi 2012).

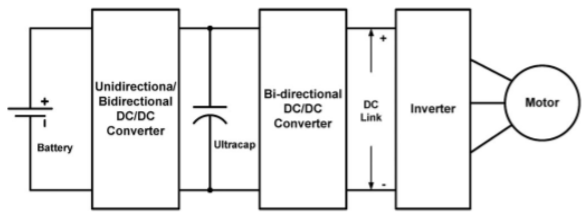


Figure 8-Cascaded configuration (Cao and Emadi 2012)

Multiple converter configuration

In this topology represented by Figure 9, the output of the two converters are linked to the DC link. In this way, the voltage of the two sources can be lower than the DC Bus. The drawbacks of this topology is the necessity of having two full size converters, this will add costs (Behjati and Davoudi 2012)(Cao and Emadi 2012).

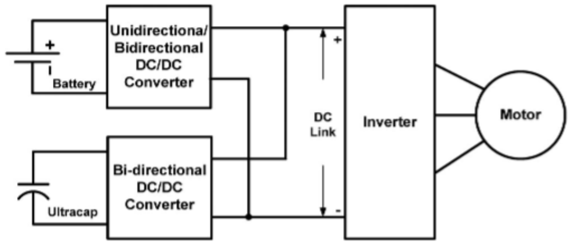


Figure 9-Multiple converter configuration (Cao and Emadi 2012)

Multiple input converter configuration

With the configuration of Figure 9 one of the drawbacks is the cost associated to the two converters. In order to reduce these costs the topology of Figure 10 is proposed (Cao and Emadi 2012). Other advantages are the reduction of the complexity and the size of the H-ESS (Behjati and Davoudi 2012).

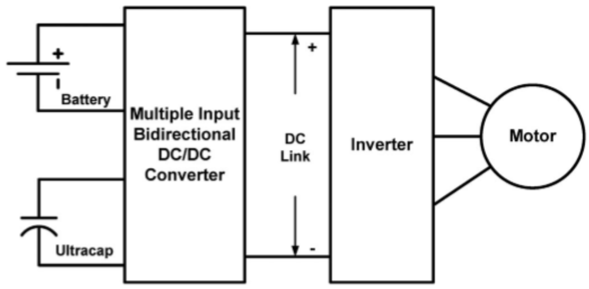


Figure 10-Multiple input converter configuration

1.3.2 Strategies of Energy Managment

For optimizing the distribution of power flow between the sources, a strategy management is created to decide the quantity of power that each source will supply in function of the subsystem traction demands. These strategies can be more or less complex depending of the concerning HESS. The strategy is an important factor in the efficiency of the H-ESS, so it is important to define it correctly.

It is possible to divide the strategies in two large categories, strategies based on rules and strategies based on optimization. The strategies based on rules can be deterministic or non deterministic. The deterministic rules impose a previous knowledge of the system. The non deterministic are for example, the Fuzzy or Neural. These kind of strategies do not need prior knowledge of the sytem.

These strategies are easy to implement and the computation time is smaller in comparison with the optimization strategies, however they do not ensure the optimal result.

The strategies based on optimization can be divided in two different sub categories, global optimization or real-time sub-optimal solutions. These strategies based on optimization are defined by the physical limitations of the system and allow an optimal solution.

Other strategies are based in rule strategies. The choice of this kind of strategies was made by the simplicty of the implementation and due to the smaller calculation time. Some of these strategies are presented below:

Resistance Strategy

Some works developed a strategy based in the internal resistance of the energy sources (ALLEGRE 2010). The aim of this strategy is to reduce losses of the ESS. As we know, the losses are equal to $P_{losses} = R\, I^2$ so, to decrease these losses, the source that will provide the demand of current will be the source with the smaller resistance. In this case, between supercapacitors and batteries the supercapacitors contain a smaller resistance.

Switching Strategy

These strategies consist on the utilization, at the same time, of just one source to supply the traction system. The choice is made in function of the State of Charge (SOC) and of the power losses of each of them. As the supercapacitors possess a higher efficiency than batteries, the supercapacitors are more used. However, when the supercapacitors voltage becomes too small it makes a smooth transition to batteries, the smooth transition is realized to avoid peak current (Allègre, Bouscayrol, and Trigui 2013).

Frequency strategy

This kind of strategy is already tested in (ALLEGRE 2010) (Xiaoliang, Hiramatsu, and Yoichi 2013)(Carreira, Domingos Marques, and Sousa 2014a). This strategy consists in dividing the current between the two sources of energy trying to reach the best efficiency of each of them.

The current traction contains two different components, the high frequency and the low frequency part. The high frequency is characterized to have a high level of power. As it was referred before, the batteries have a low level of power density as opposed to the supercapacitors. For this reason, the high frequency will be supplied by the supercapacitors. Another characteristic of high frequency current is the effect it causes on the batteries This current damages the electrochemical characteristics of batteries. (Xiaoliang, Hiramatsu, and Yoichi 2013) (Carreira, Domingos Marques, and Sousa 2014a). So, because of these two reasons, the high frequency is supplied by supercapacitors and the low frequency by batteries (Xiaoliang, Hiramatsu, and Yoichi 2013). Therefore, battery stress will be lower due to the peak power necessary for the traction subsystem been supplied by supercapacitors. In consequence, it is expected that the batteries lifetime increase.

Variable saturation strategy (ALLEGRE 2010)

The goal of this strategy is to limit the power received and supplied by the batteries. The batteries supply the system until this value is equal or smaller than their saturation current. If the current is higher, the supercapacitors will supply the rest of the current necessary.

Acceleration strategy

This strategy was tested in some studies as shown in (ALLEGRE 2010).

For the movement of the vehicle it is necessary to apply a force to the vehicle. This force, F_{tract} can be decomposed in in two different forces, acceleration forces F_{acc} , and the resistive forces to the movement, F_{res} . In the acceleration moments more power is necessary, so it will be supplied by the supercapacitors.

$$F_{tract} = F_{acc} + F_{res} \quad (2)$$

$$F_{acc} = Ma \quad (3)$$

$$P_{tract} = P_{acc} + P_{res} \quad (4)$$

Equation (4) results from equation (2) expressed in power where P_{acc} is acceleration power and P_{res} is resistive power. Normally the demand of power is higher in the P_{acc} than in P_{res} so the supercapacitors supply the acceleration and batteries supply the constant power.

1.4 Laboratory of Electrical Engineering and Power Electronics (L2EP)

This work was developed in collaboration with the control team of the *"Laboratory of Electrical Engineering and Power Electronics of Lille"*. The control team of L2EP is specialized in the control of electromechanical systems (Bouscayrol et al. 2009). They are specialized in new generation transports (Letrouve et al. 2012) (Verhille et al. 2006), like subways, hybrid trains (Mayet et al. 2013), marine propulsion (Zahr, Semail, and Scuiller 2014) and energy system storage for electrical and hybrid vehicles. They work with industrial partners like Alstom, PSA Peugeot Citroën, Siemens, SNCF, Valeo. They also have collaborations with laboratories around the world for example, Canada, Argentina, China and Switzerland. These collaborations allow the realization of common projects.

1.5 Outline of the work

The structure of this work is divided in three essential parts.

1. Presentation of EMR formalism.

In this part, the goal is to present the tool which was used in order to understand all the construction processes for the representation of the system. For the correct use of the tool, it is necessary to know how to work with it. For this, rules and principles of good uses will be presented. In addition, this tool contains some techniques to solve conflicts that can appear during the construction of the representation system. All these characteristics are present in chapter 2 section.

2. Modelling part.

All models used for the realization of the system will be presented in chapter 2. An accurate model is important in order to obtain good results and a good accuracy for the global system. These models can be different depending of the phenomena to be studied. The modelled subsystems are the traction subsystem and the Hybrid Energy Storage System, “H-EES”. The traction subsystem is modelled based on the vehicle “Tazzari” (commercial EV of “L2EP”). The mass of the vehicle is 542 kg and it is constituted by an induction machine of 15 kW, a gear box, a differential and mechanical braking. Batteries, supercapacitors, and a bi-directional converter constitute the H-ESS system. The batteries pack impose a voltage of 78 V and the supercapacitors bank, 60V.

During the construction of a system, it is possible to find some conflicts of association. For these conflicts there are EMR rules to solve them. These conflicts will be identified.

3. Control part and results.

After the representation of system is done, it is necessary to build its control scheme. This control aims to achieve the defined objective and to insure the safety of the person who will use it. This realization is accomplished following different steps. The first step is the definition of the tuning path. This path defines the variables that will be necessary to control, and its connections to the tuning variable. For the traction subsystem, the tuning path aims to control the velocity of the vehicle and for the ESS, the tuning path aims to control the supercapacitors current. For the control, it is necessary to implement some controllers. These controllers will permit to maintain the stability of the system while achieving the requested performances. However, we need to know where to install them. Another fundamental aspect in the realization of the control is the physical limitation of the system, it is important to respect it to achieve a safe and accurate control.

2 Energetic Macroscopic Representation (EMR)

As it was previously referred, to represent the studied system the tool used is EMR. In this chapter, this tool will be presented and all the characteristics will be explained.

EMR is a graphic tool that allows the representation of complex system for control purpose. The principle used by EMR is the principle of a interaction between the different connected systems (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012). It is put in evidence the energetic characteristics of each subsystem. These different subsystems can be source, accumulation, distribution and conversion of energy. These four subsystems are represented by four different pictogram shown in ANNEX A. EMR can be described as follows:

Energetic- exchange of energy between subsystems considering to the causality principle related to energy;

Macroscopic- exchange of energy between subsystems considering to the interaction principle without focusing on internal relations;

Representation- allowing the organization of the mathematic models or other kind of models;

2.1 Representation of pictograms

2.1.1 Source element

The source element is the subsystem that describes the external environment of the system. These pictograms are always in the extremities of the system. They represent the environment where systems are localized. They can be a generator or a receptor and have an input vector and output vector. In EMR the sources are represented by oval green pictograms (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012). One example can be the traction system of the studied system which will be explained in the next section shown in (Figure 11).

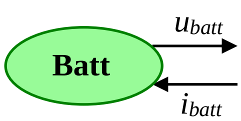


Figure 11- Source element

2.1.2 Accumulation element

This element exhibits an accumulation of energy. Its inputs and outputs are already defined because of the causality. This pictogram is described by a crossed orange rectangle. The oblique bar imposes a delay between the input and output. This subsystem has one input and output in the downstream and one input and output in the upstream. These outputs and inputs can be vector or scalar (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012). One example of an accumulation element is shown in Figure 12.

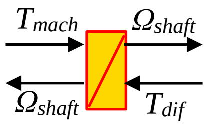


Figure 12- Accumulation element

2.1.3 Mono-Physical/Multi-Physical Conversion Element-

The mono-physical conversion element allows the transformation without changing the domain Figure 13(a). The multi-physical conversion element allows the transformation of energy between different domains Figure 13(b). These elements do not have energy storage. They can have losses or not. For the conversion of energy, it is possible to use a third input. It possess two pairs of inputs and outputs, one in the upstream and other in the downstream. It can also have a tuning input; this input can be a vector or a scalar. This allows the management and the conversion of the energy (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012)

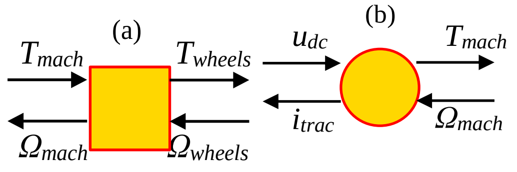


Figure 13- Figure (a) Mono-Physical Figure (b) Multi-Physical

2.1.4 Coupling element

This pictogram is represented by overlapped squares when it represents mono-physical coupling, for example the distribution of forces in Figure 24, or by overlapped squares when the coupling is multi-physical. This coupling does not have accumulation of energy and can or not have losses. It can have *m* inputs and outputs in the downstream and *n* inputs and outputs vector in the upstream. There are three possibilities for characterizing this element (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012):

- **Downstream**, when *m>n*, the function is to collect energy
- **Upstream**, when *n>m*, the function is to divide the energy and to provide more flows
- **Neutral**, *m=n*, the function is to reorganize the energy flow

(23)

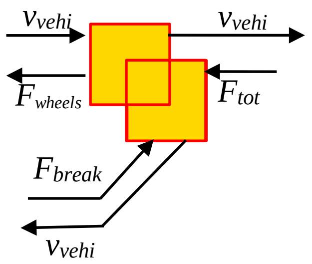


Figure 14- Coupling element

2.2 Associations rules

2.2.1 Merging rule

When, in a system, there are two or more accumulation elements that deliver the same state variable it is possible to merge them into an equivalent one. The mathematical models are combined in order to obtain the correct equivalent model. This rule avoids to describe one system with the integral causality and the other with derived causality (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012). Figure 15 demonstrates an example of a possible case of merging rule. Figure 15 gives an example of a case of association rule of two capacitors in parallel.

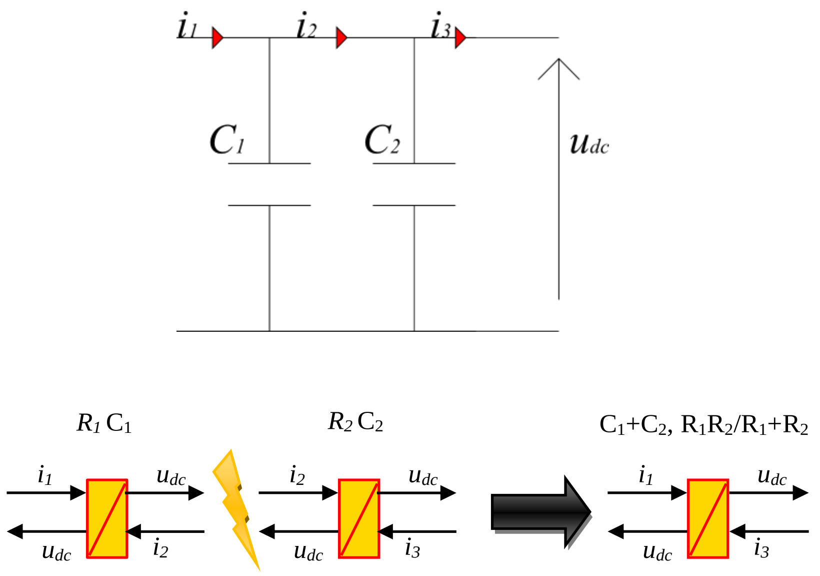


Figure 15- Merging Rule

2.2.2 Permutation rule

The permutation rule consists in doing the permutation of two elements maintaining the same global input and output. This allows verifying the virtual subsystem necessary to obtain the same output. Figure 12 demonstrated a case of permutation. This happens because the shaft imposes that the output must be the angular velocity, and the input of the chassis must be the force that will be applied. This happens due to the characteristics of these elements that will be explained further on.

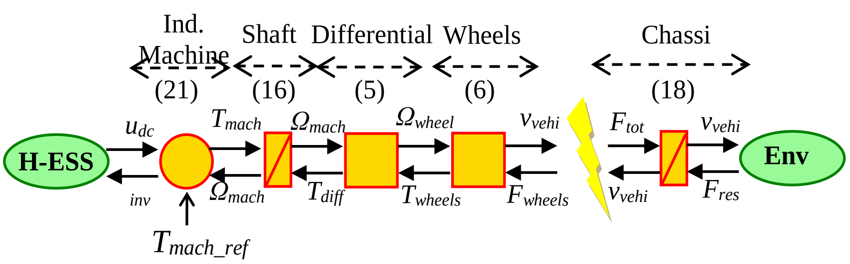


Figure 16- Conflict of association

To solve this problem the differential and the wheels are merged in one unique element creating a new factor conversion. For the calculus of the new relation, it is necessary to find the relation between the rotation speed of the shaft Ω_{mach} and the velocity of the vehicle v_{vehi} and also to find the relation of forces applied in the wheels F_{wheels} and the torque of the induction machine

T_{diff}. Equation (5) and (6) represent the differential and the wheels. These elements are represented by two equations:

$$\begin{cases} \Omega_{wheel} = K_{diff}\,\Omega_{mach} \\ T_{diff} = K_{diff}\,T_{wheels} \end{cases} \quad (5)$$

$$\begin{cases} v_{vehi} = \dfrac{1}{K_{wheels}}\Omega_{wheels} \\ T_{wheels} = \dfrac{1}{K_{wheels}}F_{wheels} \end{cases} \quad (6)$$

The new relation between T_{mach} and F' is equal to:

$$\begin{cases} F' = K'\,T_{mach} \\ \Omega_{mach} = K'\,v_{vehi} \end{cases} \quad (7)$$

With:

$$K' = \frac{K_{wheels}}{K_{diff}} \quad (8)$$

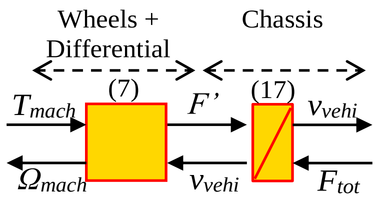


Figure 17- Equivalent virtual element

After implementing the permutation it is possible to merge the two accumulation elements in just one because they have the same output variable.

With these two rules, it is possible to solve every kind of conflict of association.

2.3 Traction subsystem

In this section the EMR and the control of the traction subsystem is represented. All the subsystems by which it is composed are also explained. For the development of the H-ESS, it is necessary to understand the behaviour of the vehicle and all of these subsystems and it is fundamental to know which model to use for each subsystem.

For the traction subsystem the parameters of the electrical vehicle, "Tazzari" were used. This vehicle belongs to L2EP and it is usually used in the laboratory for the development of projects and research.

Figure 18-Tazzari EV

The EV has a mass of 542 kg and its traction subsystem is constituted of one gearbox ratio, one differential and an electrical induction machine of 15 kW supplied by a voltage source inverter (Depature et al. 2014).

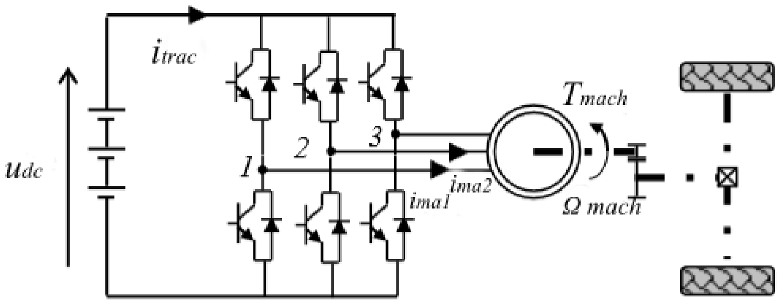


Figure 19- Traction subsystem (Depature et al. 2014)

Table 2- Dynamics parameters

Name	*Symbol*	*Value*	*Units*
Mass	M	542	kg
Gravity force	g	9.8	m/s^2
Rolling coefficient	f_r	0.02	-
Aerodynamic coefficient	c_{aero}	0.7	-
Air density	ρ	1.2223	kg/m^2
Surface contact	A	2	m

2.3.1 Traction subsystem model

Environment

The environment is a source of force, $F_{res,}$, as represented in Figure 21. This source is composed by all the resistive forces to the vehicle movement. Three different forces are considered, the rolling resistance, aerodynamic forces and the grading resistance (Ehsani et al. 2005). The input is the velocity of the vehicle and consequently the output is the resistive force. The EMR pictogram of this subsystem is described in Figure 21.

$$F_{res}(t) = F_{rol}(t) + F_{drag}(t) + F_{slop}(t) \tag{9}$$

$$\begin{cases} F_{rol}(t) = P\, f_r \\ F_{drag}(t) = \dfrac{1}{2}\rho(v + v_{wind})^2\, v_{vehi} c_{aero} A \\ F_{slop}(t) = M_{vehi}\, gp \sin\alpha \cong M_{vehi}\, gp \end{cases} \tag{10}$$

Rolling Resistance

F_{rol} represents the forces between the road and the wheels. These forces are influenced by the characteristics of the tire. The torque produced by this interaction , T_r , is equal to:

$$T_r = pa \quad (11)$$

Where p is the weight and a is the acceleration.

To pass this torque in horizontal force it is necessary to divide equation (11) by the radius of the tire resulting in:

$$F = \frac{T_r}{r_d} = \frac{pa}{r_d} = p\, f_r \quad (12)$$

The interaction between the tire and the road can be translated by a horizontal force in the center of the tire in opposition to the movement, where p is the normal force and f_r the rolling resistance coefficient. This coefficient depends on the temperatures, material, structure, tire inflation geometry, road roughness, road material, and the presence or not of liquid in the road (Ehsani et al. 2005).

The studied system possesses a rolling resistance of 0.02.

Aerodynamic forces

With a certain speed, the forces caused by the air start to have an important impact in the effort made by the traction system. These forces result of two aspects, the shape of the vehicle and skin friction. This force is equal to:

$$F_{drag}(t) = \frac{1}{2}\rho\left(v + v_{wind}\right)^2 v_{vehi}\, c_{aero}\, A \quad (13)$$

In order to simplify the calculus and problem of form, the v_{wind} was considered equal to zero. The surface in contact with the air is represented by the variable A, and the density of the air by the variable $\boldsymbol{\rho}$. The c_{aero} represents the impact of the shape in this force. The smaller this coefficient is the better the aerodynamics behaviour will be. In ANNEX B it is possible to observe the different coefficients and the aspect of the vehicle.

Slope forces

During the climbing of a slope, the vehicle is submitted to natural forces caused by the inclination of this slope.as represented in Figure 20:

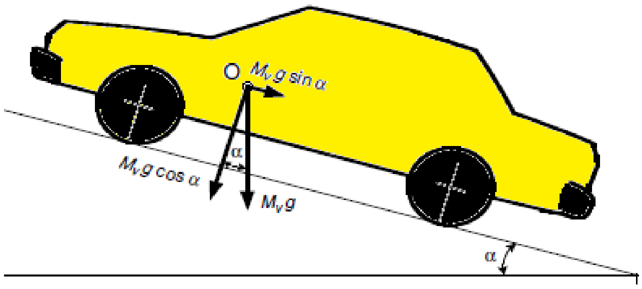


Figure 20-Climb forces

The slope force represents the force in opposite to the movement during the climbing. This force is influenced by the mass of the vehicle, M_{vehi}, and the angle of the inclination, α. The equation is equal to:

$$F_{slop}(t) = M_{vehi}\, gp \sin \alpha \cong M_{vehi}\, gp \qquad (14)$$

(9)

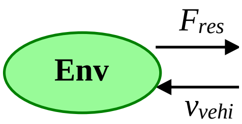


Figure 21- Environment pictogram

Mechanical brake- The mechanical brake is represented by a source of force as shown in Figure 22. The effect of this is just the application of an opposite force to the movement. The force reference is delivered by the control. In the next chapter, it will be explained, what is considered in the calculus of that force and how it is calculated.

$$F_{breake\_ref} = F_{break} \tag{15}$$

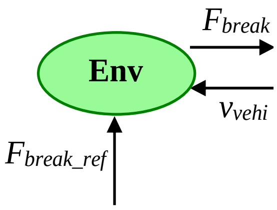


Figure 22- Mechanical Break pictogram

Machine shaft- The shaft is represented by an accumulation element as shown in Figure 23. This part allows the connection of the electrical machine to the wheels and consequently causes the movement of the vehicle. The output is the torque due to the principle of causality. Equation (16) represents the shaft equation with J equal to the inertia of the shaft and f_{losses} equal to the losses by friction. T_{rr} is the torque applied in the shaft, this torque is the same that T_{mach}.

$$T_{mach}(t) - T_{rr}(t) = J\frac{d}{dt}\Omega_{shaft}(t) + f_{losses}\,\Omega_{shaft}(t) \tag{16}$$

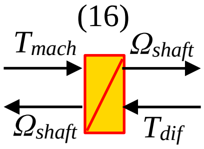


Figure 23-Shaft pictogram

Applying the Laplace transformation to (16) result in:

$$\Omega_{shaft}(t) = \frac{T_{mach}(s) - T_{dif}(s)}{Js + f_{losses}} \tag{17}$$

Chassis of the vehicle- The chassis represents all the rigid components of the vehicle. In EMR, it is represented by an accumulation element, where the output is the velocity and the input, the force that will be actuating in the vehicle. In this subsystem all the inertias are represented (Bouscayrol 2003). The subsystem is represented in Figure 24.

$$F_{tot}(t) - F_{res}(t) = m\frac{d}{dt}v_{vehi}(t) \tag{18}$$

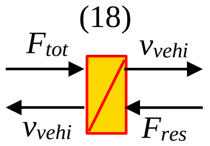


Figure 24- Chassis pictogram

Applying the Laplace transformation to (18) result in:

$$v_{vehi}(s) = \frac{F_{tot}(s) - F_{res}(s)}{ms} \tag{19}$$

Differential: The differential splits the torque produced by the Electrical Machine between the two wheels. T_{diff} has to be always higher than T_{mach}. For this study, it is considered that the two traction wheels of the vehicle are in the same type of surface and always in strength trajectory, therefore, the torque is equally divided between the two wheels. The equations (20) and Figure 25 describe this subsystem.

$$\begin{cases} T_{wheels}(t) = K_{diff}\,T_{mach}(t) \\ \Omega_{mach}(t) = K_{diff}\,\Omega_{wheels}(t) \end{cases} \tag{20}$$

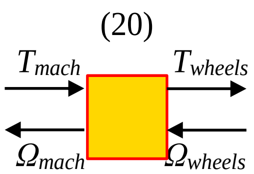


Figure 25 - Differential Pictogram

Wheels: the effect of wheels in the system is to transform the torque into a linear force and the radius speed into a linear speed. For this, it is just necessary to introduce a gain. This gain, in fact, is the radius of the wheel. These relations are demonstrated in equation (21) and the pictogram is demonstrated in Figure 26.

$$\begin{cases} F_{wheel} = T_{wheels} \dfrac{1}{r_{wheel}} \\ \Omega_{wheels} = v_{vehi} \dfrac{1}{r_{wheel}} \end{cases} \quad (21)$$

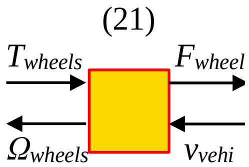


Figure 26- Wheel pictogram

Asynchronous Machine- It is represented by a multi-domain converter as shown in Figure 27. The electric power received by the storage subsystem is transformed into a mechanical power T_{mach}.

The model given by the L2EP is a static-model. The efficiency map was obtained with dynamic simulations. The efficiency map is expressed in function of the velocity and the torque. The model represents the inverter of the electrical machine and the Induction Machine, (IM).

The torque reference is given in order to know the traction current, which will be necessary to supply. This current, $i_{trac,}$ is obtained with the equation (22).

Table 3 shows the advantages and drawbacks of the utilization of this type of model.

Table 3- Characteristics of Static Model (Letrouvé et al. 2010)

Advantages	Drawbacks	Used
-Simulation time	-No dynamic is taken into account - Modelling simplicity, - Needs a high precision losses table	Study of power and energy during steady states

$$\begin{cases} T_{mach}(t) = T_{mach\_ref} \\ i_{trac} = \dfrac{T_{mach}(t)\,\Omega_{mach}(t) + P_{losses}}{u_{dc}(t)} \end{cases} \tag{22}$$

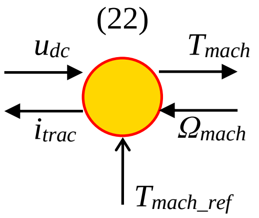


Figure 27- Asynchronous Machine

Brake system- This subsystem is represented by a coupling element. In this subsystem there are two different forces actuating. One is the force caused by the electrical machine and the other is the mechanical brake.

$$\begin{cases} F_{tot} = F_{wheels} + F_{break} \\ v_{vehi} = v_{vehi} = v_{vehi} \end{cases} \tag{23}$$

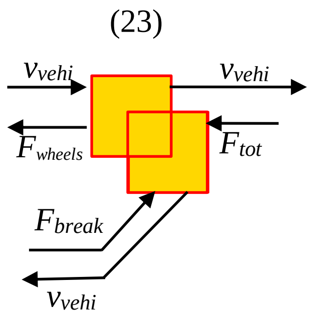


Figure 28- Chassis pictogram

2.3.2 Conflict of associations

During the construction of the EMR it is possible to observe that there is a conflict of association between the wheels and the chassis. This conflict can be observed in Figure 29. The wheels have the velocity, v_{vehi} as output but the chassis requires the force as input, F_{tot} . This happens due to the principle of causality used in the accumulation elements. These elements impose their outputs and inputs. So, it is necessary to respect them. To solve this problem it will be necessary to apply some rules.

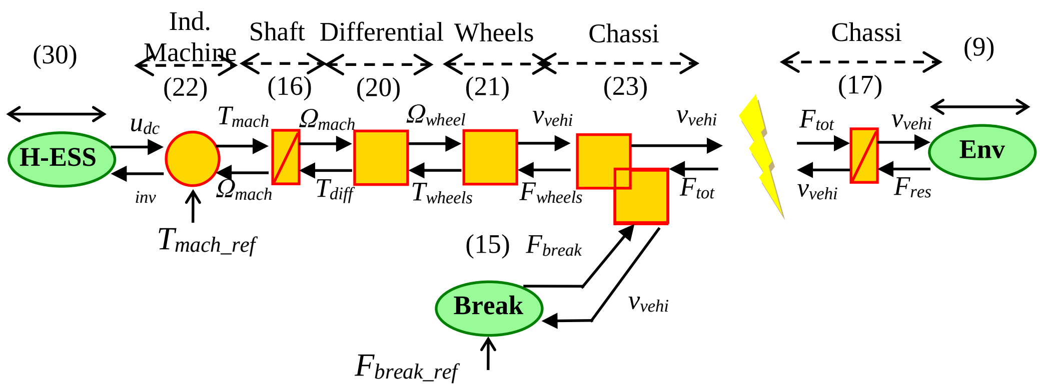


Figure 29-Conflict of association

Permutation rules:

The shaft is permutated with the differential and the wheels. However, it is necessary that the final inputs and outputs of the resulting system remain the same.

The equation of the shaft is:

$$T_{mach}(t) - T_{dif}(t) = J\frac{d}{dt}\Omega_{mach}(t) + f_{losses}\,\Omega_{mach}(t) \quad (24)$$

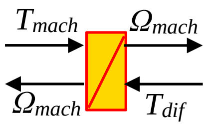


Figure 30- Shaft pictogram

For the simplification of the resolution of the problem, the differential and the wheels are considered as a gain *K'* as shown in Figure 31.

$$\begin{cases} v_{vehi}(t) = K'\,\Omega_{mach}(t) \\ T_{dif}(t) = K' F_{tot}(t) \end{cases} \quad (25)$$

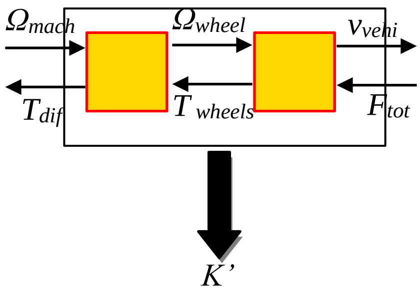


Figure 31- Association of the two blocks

The result of the permutation of the equation (24) is given by the equation (25). By changing the variable on the equation (24) the new relation is:

$$\begin{cases} F'(t) = K'\,T_{mach}(t) \\ \Omega_{mach}(t) = K' v_{vehi}(t) \end{cases} \quad (26)$$

The result of the junction of this two components result in the equation (25). The permutation of this new block K' with the shaft results in Figure 28. This permutation result in the. equation shaft (26).

$$F'_{tot}(t) - F_{tot}(t) = J\frac{d}{dt}v_{vehi}(t)\frac{1}{K^2} \quad (27)$$

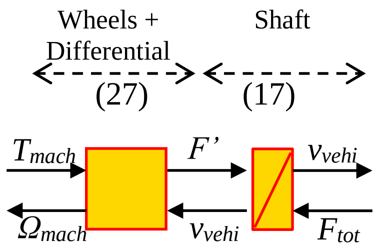


Figure 32- Permutation

Merging rules:

After the permutation, the shaft and the chassis possess the same state variable so it is possible to merge these two elements in just an equivalent one. Therefore, the new values of the friction losses and the new mass are given by the equation (28):

$$m_{equ} = \frac{J}{K^2} + m_{vehi}$$
$$f_{losses-equi} = \frac{f_{losses}}{K^2} \quad (28)$$

$$F'_{tot}(t) - F_{tot}(t) = m_{equ}\frac{d}{dt}v_{vehi}(t)\frac{1}{K'^2} + f_{losses-equi}K'v_{vehi}(t) \quad (29)$$

The changes effectuated leadto the EMR model represented in Figure 33.

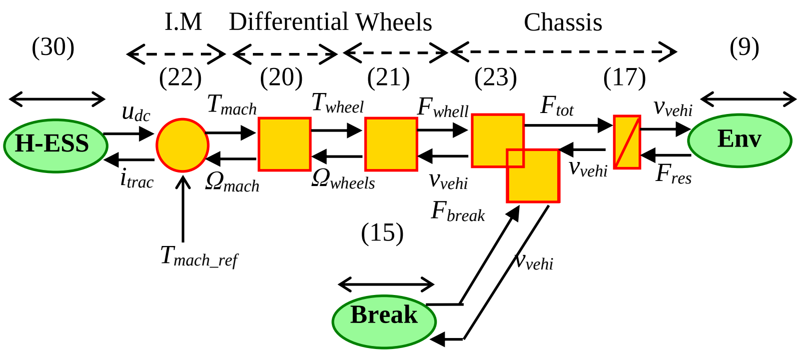


Figure 33-EMR of Traction Subsystem

2.4 Hybrid Energy Storage System (H-ESS)

In this chapter, the EMR and the model used for each parts of the H-ESS will be presented. Figure 30 represents the topology used. This subsystem is already referred as being composed by batteries, supercapacitors and a bidirectional DC/DC Converter.

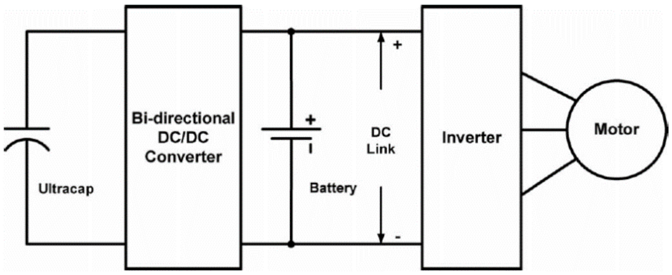
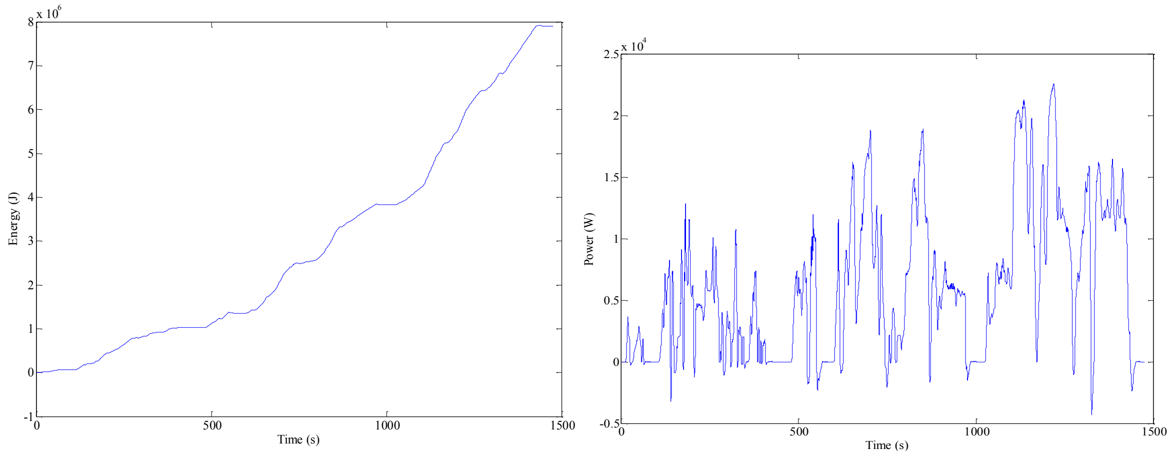


Figure 34- Schematic of H-ESS

2.4.1 Model of H-ESS

Sources of energy

For this part of the work the model of the sources is very important for the behaviour of the system and for the final conclusions. In fact, one of the goals is to observe the impact on batteries of the implementation of supercapacitors. As previously mentioned the supercapacitors will supply the power demands. For this, it is necessary to know the power behaviour of the system in order to size this source correctly. It is also necessary to know the quantity of energy that the system needs to size the batteries. This fact was not taken so much into consideration, in this work, since a model of batteries already existed for the *"Tazzari"* vehicle. It was only verified if the batteries had enough energy for the drive cycle. In order to know how to size the energy source it is necessary to know the energy and power profile, Figure 35 shows these profiles.



(a)- Energy (b)- Power

Figure 35- Energy and Power demand

Batteries- This battery bank is the battery bank of the Tazzari vehicle.

The battery bank is considered as a voltage source, imposing the DC voltage. The batteries model used is a static-model. This model was developed by L2EP. It is an OCV with a series resistance as shown in Figure 36. The map was obtained with dynamical simulations. In ANNEX C the characteristics of the type of batteries are given. The EMR pictogram represented in Figure 33 is a source of voltage. Equation (30) represents the equation of the voltage in function of the current battery, with τ the constant time.

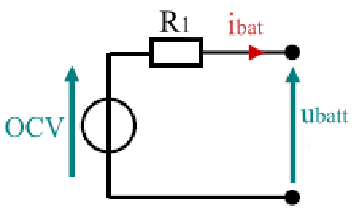


Figure 36- Schematic of the Battery model

$$u_{batt} = i_{batt} \frac{1}{1+\tau s} \tag{30}$$

(30)

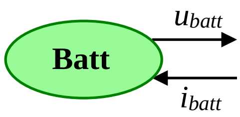


Figure 37- Pictogram of batteries

Sizing of battery bank

As it was already explained, the batteries possess a high energy density, so, it is that source that will insure the energy necessary for the vehicle during the trajectory. For this, it is necessary to size the bank battery in energy. However the bank used in this study is the bank of the *"Tazzari"* vehicle. This model was realize by the *"L2EP"*. The characteristics are presented in Table 4 and ANNEX D.

Table 4- Characteristics of the battery

Battery used	Energy density (Wh/kg)	Capacity (Ah)
Li-On	80	160

Supercapacitors

The model used for the supercapacitors is a RC series model. The value of the series resistance is given by the manufacturer. The convention considered is the generator convention, represented in equation (31), with u_{sc} the supercapacitors voltage, R_s the internal resistance, i_{sc} the supercapacitos current and C the capacity . In ANNEX D the information about the chosen superacapacitors are presented. The voltage of the supercapacitors voltage is 60 V.

$$u_{sc} = i_{sc}\left(-R_s - \frac{1}{2\pi f\, C_{dc}}\right) \tag{31}$$

Applying the Laplace transformation to equation (31) result in:

$$u_{sc} = i_{sc}\left(-R_s - \frac{1}{C_{dc}\, s}\right) \tag{32}$$

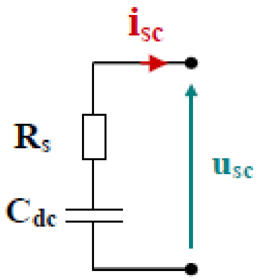


Figure 38- Supercapacitors model

(32)

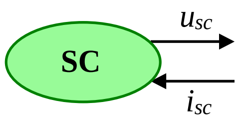


Figure 39- Pictogram Supercapacitors

Sizing of Supercapacitors

The design of the supercapacitors was done considering power. The equation used for calculating the power of one supercapacitors given by, P_{sc} , is demonstrated in equation (33).

$$P_{sc} = \frac{0.12 u^2_{sc}}{R_s} \tag{33}$$

With u_{sc} the nominal voltage of the supercapacitors, R_s is the resistance series. In order to know the quantity of supercapacitors, N_{sctot} , necessary to supply the demand of power of the traction system, $P_{tractot}$,the next equation must be done:

$$N_{sctot} = \frac{P_{tractot}}{P_{sc}} \tag{34}$$

After calculating the power of each supercapacitors, it is necessary to decide the voltage of the supercapacitors bank, u_{scbank}, depending on the voltage of one supercapacitor, u_{sc}. This voltage will decide the number of supercapacitors in series, N_{scs}.

$$N_{scs} = \frac{u_{scbank}}{u_{sc}} \tag{35}$$

To reach the necessary power it is necessary to increase the capacity, for this it is also necessary to calculate the quantity of supercapacitors to put in parallel, this value is given N_{scp}, and the equation is equal to equation (36):

$$N_{scp} = \frac{N_{sctot}}{N_{scs}} \tag{36}$$

Sizing of supercapacitors for the studied case

The power of supercapacitors was calculated with a security margin of 10%. This value reaches 24 kW. Therefore, the supercapacitors must be sized in a way to be able to supply the system demand. For this it is necessary to apply the equations previously explained.

For calculating the power of supercapacitors equation (33) is used. With u_{sc} and R_s, equal to three miliohms

$$P_{sc} = \frac{0.122 \cdot 5^2}{3.2.10^{-3}} = 234W \tag{37}$$

Afterwards, to calculate the power of each supercapacitor, it is necessary to calculate the quantity that will be necessary. For this, the following equation (35) is used

$$N_{sctot} = \frac{2,4.10^3}{234} = 102.5 \tag{38}$$

To have an exact value, 103 are selected. After knowing the quantity necessary, it is necessary to decide the voltage of the supercapacitors bank to calculate the number of supercapacitors that to have to be put in series.

Inductance-The inductance imposes an accumulation of energy. This accumulation will cause a delay between the input and the output. So this element is used to represent an accumulation element. The equation of this subsystem is given by equation (39). This inductance is used to smooth the current of the supercapacitor.

$$u_{sc}(t) - u_{chop}(t) = L\,\frac{d}{dt}\,i_{sc}(t) + R\,i_{sc}(t) \qquad (39)$$

Applying the Laplace transformation to equation (39) result in:

$$i_{sc}(s) = \frac{u_{sc}(s) - u_{chop}(s)}{Ls + R} \qquad (40)$$

(40)

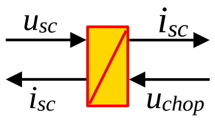


Figure 40- Pictogram of inductance

Chopper- The chopper is a bidirectional DC/DC converter. For this type of application, it has to be a buck/boost converter. In this case, this subsystem allows controlling the power flux between the two sources. As explained previously, it has the capacity to recover energy during braking. Thus, the converter has to be able to receive this energy and to transfer it to the supercapacitors. It also must be able to control the power flux when this flux has the direction of supercapacitors to the traction system.

Depending on the signal power traction the converter will work in different ways. When the system works in traction mode, positive power, the converter will work in boost mode. However, when the system is in regenerative mode, negative power, it will work in buck mode (Wangsupphaphol et al. 2014).

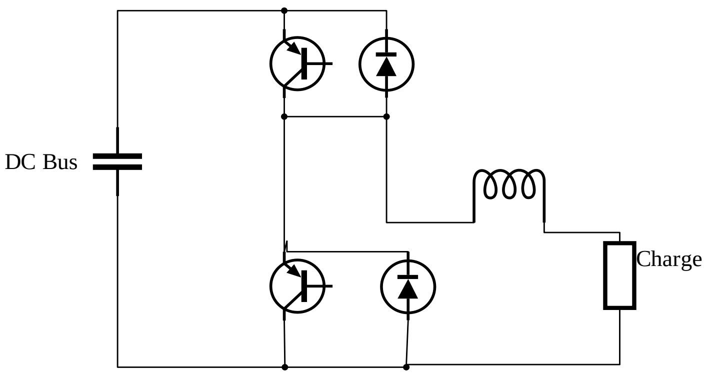


Figure 41- Configuration of the DC-DC converter

Equations of the chopper are given in equation (41)

$$\begin{cases} i_{chop}(t) = m_{chop}\,\eta\, i_{sc}(t) \\ u_{chop}(t) = m_{chop}(t)\, u_{batt}(t) \end{cases} \tag{41}$$

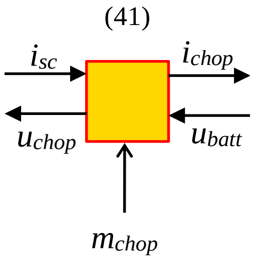


Figure 42- Pictogram of DC/DC Converter

Coupling The coupling element is the junction of two different currents. The equation of this subsystem is given by equation (42).

$$\begin{cases} i_{batt}(t) = i_{trac}(t) - i_{chop}(t) \\ u_{batt}(t) = u_{batt}(t) = u_{batt}(t) \end{cases} \tag{42}$$

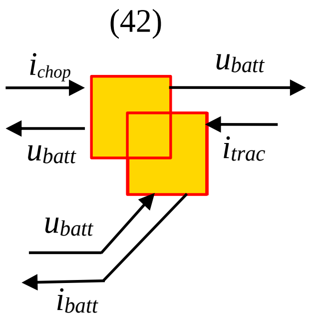


Figure 43- Coupling of the current

After presenting all subsystems, the EMR of the H-ESS subsystem is given by Figure 44.

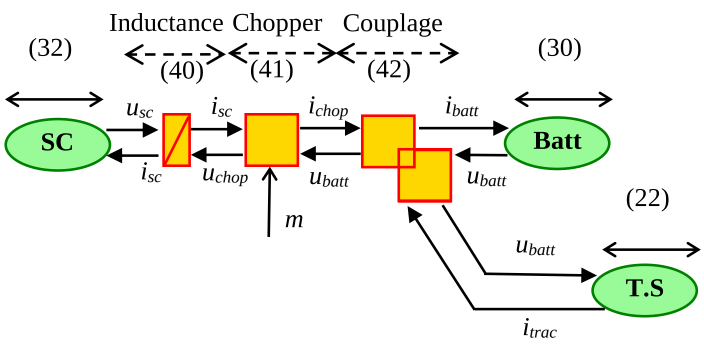


Figure 44- H-ESS EMR

In Table 5 the characteristics of the main components of the system are demonstrated.

After defining all the models of each components of the system, it necessary to know how the control will be organized, where will the controllers be installed and which variables are necessary to control.

Table 5- Main characteristics of the system

Batteries voltage	78 Volts
Bank Supercapacitors	52 Faradays and 60 Volts
Induction Machine	15 kW
Vehicle	542 kg
Converter	Bi-directional

3 Control structure

An energetic system is organized in order to achieve a determined goal. In this case, the studied system has the objective to supply the traction system and impose a current reference for the battery. This task is accomplished with the exchange of energy between the different subsystems. However, some physical constraints such as the state-of-charge (SoC) of sources or traction current need to be considered. It is necessary to control the (SoC) in order not to reach a maximal or minimal value that may damage the sources. The traction current. Value must be maintained between the values accepted by the induction machine. Many possibilities of energy exchange between the different subsystems need to be considered; for example, the H-ESS subsystem for the traction subsystem, when the power is positive, or the traction subsystem for the H-ESS when the power is negative. Therefore, control is fundamental in order to obtain an efficient and secure system.

To implement the control it is necessary to take some measurements and impose a reference. This reference can come from a subsystem output or can be delivered by the strategy. Therefore, the system must be able to do the task which it is designed for. Figure 42 represents how the control is achieved.

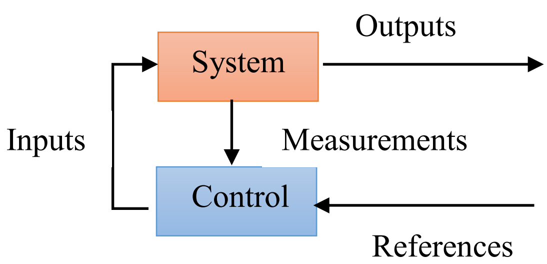


Figure 45- Schema for control

The control has to ensure two different aspects; one is to ensure the dynamics of each subsystem and the other is the safety of users and components. The second is to ensure the best possible efficiency.

The control is implemented in a local and global manner. The local aproach consists in the individual control of each subsystem and the global one coordinates all the system in order to achieve the global goal (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012). To define the control of the system from EMR, it is necessary to follow the next steps (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012) (Letrouve, Delarue, and Bouscayrol 2009):

1. Define the EMR model of the system
2. Identify the tuning path
3. Invert the different subsystems
4. Simplify if necessary
5. Estimate the non-measured variables
6. Design the controllers
7. Implement the control and test

3.1 Control of traction subsystem

This section shows how the control of the traction subsystem is implemented. The goal of this subsystem is to insure that the system follows the velocity reference imposed by the driver.

3.1.1 Tuning paths

As previously described, to deduce the control of a system it is necessary to find the tuning path. This tuning path gives the inputs and output of each subsystem necessary to the control. Figure 46 gives the tuning paths of the traction subsystem.

This path links the objective variable to the tuning variable. In this case, the tuning variable T_{mach_ref} of the induction machine and F_{brake_ref}, and the objective is the velocity v_{vehi}.

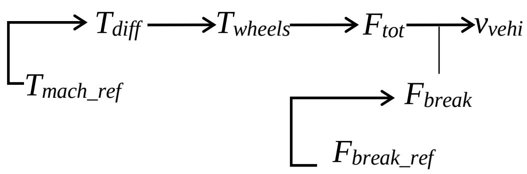


Figure 46-Tuning paths of traction system

3.1.2 Element inversion

Inversion of elements of accumulation

The output of an accumulation element is a state variable and it is the result of one integral function due to the principle of causality used in EMR. Thus, the direct inversion is not possible. Consequently the control of this type of element needs a closed-loop control (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012).

Chassis- With the tuning paths it is possible to verify that the $F_{tot\text{-}ref}$ will be the output of the system. Equations (17) allows deducing the equation for the control. Figure 47 demonstrates the control pictogram for the chassis.

For the control of the velocity the controller used is a IP The tuning of the control is presented in the ANNEX C.

$$F_{totref}(s) = \left(v_{vehi-ref}(s) - v_{vehi-meas}(s)\right)C_{cont}(s) + F_{res-meas}(s) \tag{43}$$

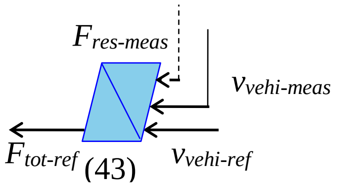


Figure 47- Inversion Pictogram of the chassis

Inversion of mono-domain converter/multi-domain converter

These elements do not possess acumulation of energy and therefore it is possible to implement directly the inversion. In some cases, it is posssible to have only one tuning variable and in these cases one of the input turns into a perturbation (BOUSCAYROL, HAUTIER, and LEMAIRE-SEMAIL 2012).

Differential and Wheels- These two elements are mono-domain conversion elements, so, their inversions are direct and the equation is given by equation (45) for the wheels and (44) for the differential. These two equations are deduced taking into acount equation (21) for wheels and equation (20) for the differential.

$$T_{mach-ref}(t) = \frac{T_{diff-ref}(t)}{K_{diff}} \tag{44}$$

$$T_{diff-ref} = K_{wheels} F_{wheels-ref} \tag{45}$$

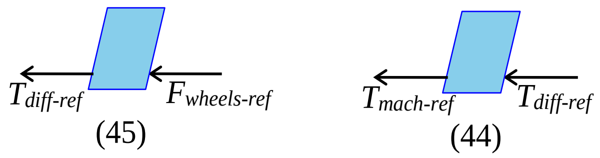


Figure 48- Pictogram control of the differential and wheels

Inversion of coupling element

The inversion of these elements can be very different depending on the kind of coupling we posses. In the studied case the coupling element is an upstream type, with three elements connected. Therefore the distribution variable will be just one.

Chassis- In the chassis two forces are applied. These two forces,Fwheels and Fbreak, result in one force, Ftot, that causes the movement of the vehicle. So, for the control, it is necessary to decide the contibuition of each force. For this, a distribution variable Kd.is created. This variable can take the value 0 or 1. This value changes depending on some conditions. This variable decides if the braking is mechanical or electrical.

$$\begin{cases} T_{diff-ref} = (1-K_d)F_{tot-ref} \\ F_{break-ref} = K_d F_{tot-ref} \end{cases}, K_d = 1 or\ K_d = 0 \quad (46)$$

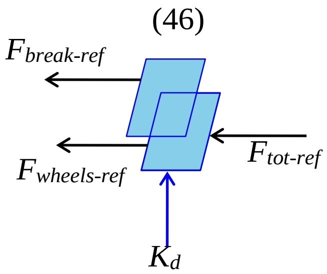


Figure 49- Pictogram control of wheels

Braking strategy

With an EV it is possible to brake in two different ways, mechanically and electrically. To decide the braking that will be used it is necessary to define a strategy. This strategy will measure some variables, and, depending on their values it will deliver the output in order to decide the braking method.

The more conventional braking mode is the mechanical brake, this dissipates the energy in heat (Letrouve, Delarue, and Bouscayrol 2009) the second method is the electrical, which is called regenerative brake. This brake allows the recovering of energy. The creation of a negative torque during the braking phases by the electrical machine creates a negative current that allows recharging the energy sources. However, it is necessary to control this quantity of energy due to the physical limitation of components. In this studied case, it is necessary to control it because of the energy sources. The sources do not have an infinite capacity of storage, so, it is not possible to recover all the energy generated by the braking.

To decide in which way the subsystem will brake, the strategies deliver a distribution coefficient K_d . This coefficient attributes the percentage of the F_{tot} that will go to F_{break} and F_{wheel}. This coefficient is determined given the state of charge of the two sources and the $F_{tot\text{-}ref}$. As (Figure 50) demonstrates K_d is 0 when the brake is done electrically and 1 when it is mechanical.

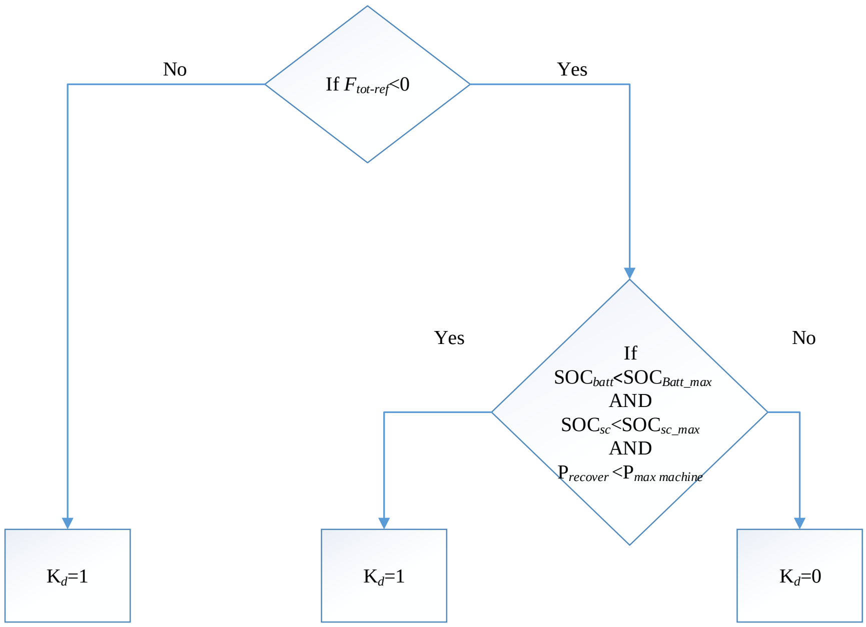


Figure 50. Braking Strategy

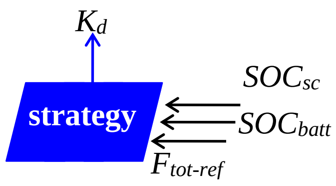


Figure 51- EMR Strategy block

Finaly, after defining the tuning path and the control of all the subsystems it is possible to represent the final EMR as shown in o Figure 49.

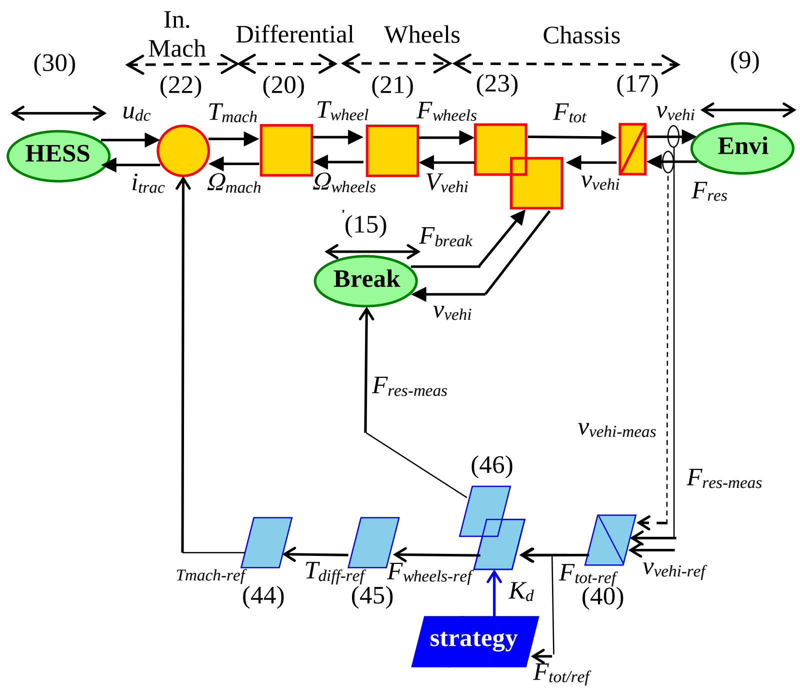


Figure 52- Final EMR of the traction subsystem

3.2 Control of H-ESS

The control of the H-ESS splits the power between the two sources. This occurs by imposing the battery current. This battery current reference is obtained using a filter strategy. This strategy filters the current traction in low frequencies and high frequencies.

The tuning path starts in the tuning input of the DC/DC converter. This choice is made because it is the only variable where it is possible to actuate.

$$m_{chop\_ref} \longrightarrow u_{chop} \longrightarrow i_{chop} \longrightarrow i_{trac}$$

Figure 53- Tuning path for control of H-ESS

3.2.1 Element inversion

Inductance

In this element it is necessary to install a controller because of the delay between the current and the voltage. This control will decide the current, which passes by the inductance. The output is the voltage reference of the DC-DC converter, $u_{chop\text{-}ref}$. For this control, it is necessary to measure the supercapacitors voltage response to a perturbation input. Equation (40) allows the deduction of the control equation (47)

The current measure, i_{sc_meas} is the current that will be supplied by the suppercapacitors. The DC-DC converter gives the current reference, i_{sc_ref}.

In this particular control, the determination of $m_{chop\text{-}ref}$ is problematic. To determinate, this variable it is also necessary to measure it. In other words the $m_{chop\text{-}ref}$ depends on itself. In real time this is not possible due to the PWM (Castaings et al. 2014a). That is called algebraic loop. This algebraic loop cannot be solved by Matlab. To solve that problem an IP controller is used.

The reason for that is because of the existence of an algebraic loop between the relation of the current and the voltage of the inductance and the DC-DC converter. It is necessary to create a delay between the current and the voltage. This delay allows determinanin the $m_{chop\_ref.}$

$$u_{chop-ref}(s) = \left(i_{sc\_meas}(s) - i_{sc\_ref}(s)\right)C_{cont}(s) + u_{sc\_meas}(s) \qquad (47)$$

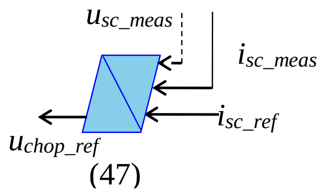
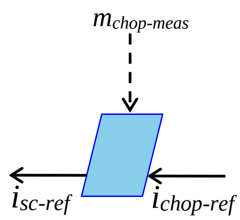


Figure 54- Pictogram control of inductance

Chopper-The control of the chopper is obtained inverting directly the EMR model. For this study, it is necessary to control it two times. The first time requires to obtaining the current reference of the supercapacitors and the second time is to obtain the duty cycle of the converter. This is demonstrated in Figure 55 for the current control and Figure 56 for the duty cycle.

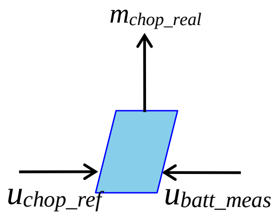
$$i_{sc-ref}(t) = \frac{1}{m_{chop-meas}} i_{chop-ref}(t) \tag{48}$$



(48)

Figure 55-Pictogram control of chopper

$$m_{chop\_real} = \frac{u_{chop\_ref}}{u_{batt\_meas}} \tag{49}$$



(49)

Figure 56- Inversion

Coupling

The control of this element is obtained by direct inversion without distribution input. This occurs because the i_{bat_ref} depends of $i_{trac\text{-}ref}$. The current traction is imposed by the traction subsystem so it is not possible to control it. Given the relation (50), it is possible to verify that if the batteries current is delivered by the current strategy and the traction current is imposed by the traction subsystem, the current of the converter, i_{chop_ref} is automatically calculated. The battery current, $i_{bat-ref}$, is the output of the strategy.

$$i_{chop\_ref}(t) = i_{trac\_meas}(t) - i_{bat\_ref}(t) \tag{50}$$

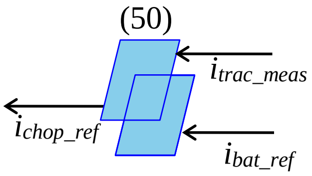


Figure 57- Pictogram control of coupling element

Battery Current Strategy

As it was already mentioned, batteries are one of the most expensive components of an EV. That is why, it is important to find a way to increase their lifetime. Batteries possess a chemical characteristic that if the discharge current has high frequencies, losses will increase and their lifetime decrease. These losses are caused by current stress. Thus, it is important to apply an adequate strategy in order to accomplish the main goal, which aims to increase their lifetime.

The strategy must receive inputs in order to be able to decide which will be the value of the current reference. In this study, inputs are the state of charge of the two source of energy and the traction current, $i_{trac\text{-}meas}$.

However, it is necessary to establish the strategy to decide what will be the value of $i_{batt\text{-}ref}$.. This strategy, in this study, uses basic rules to decide. These rules arise from previous knowledge of the system. They are related with the safety of the users and physical limitation of the components, for example, the state of charge of the voltage sources.

The strategy must deliver a current with the lower frequency possible depending on the condition imposed by the user. In Figure 58 all the strategies are described.

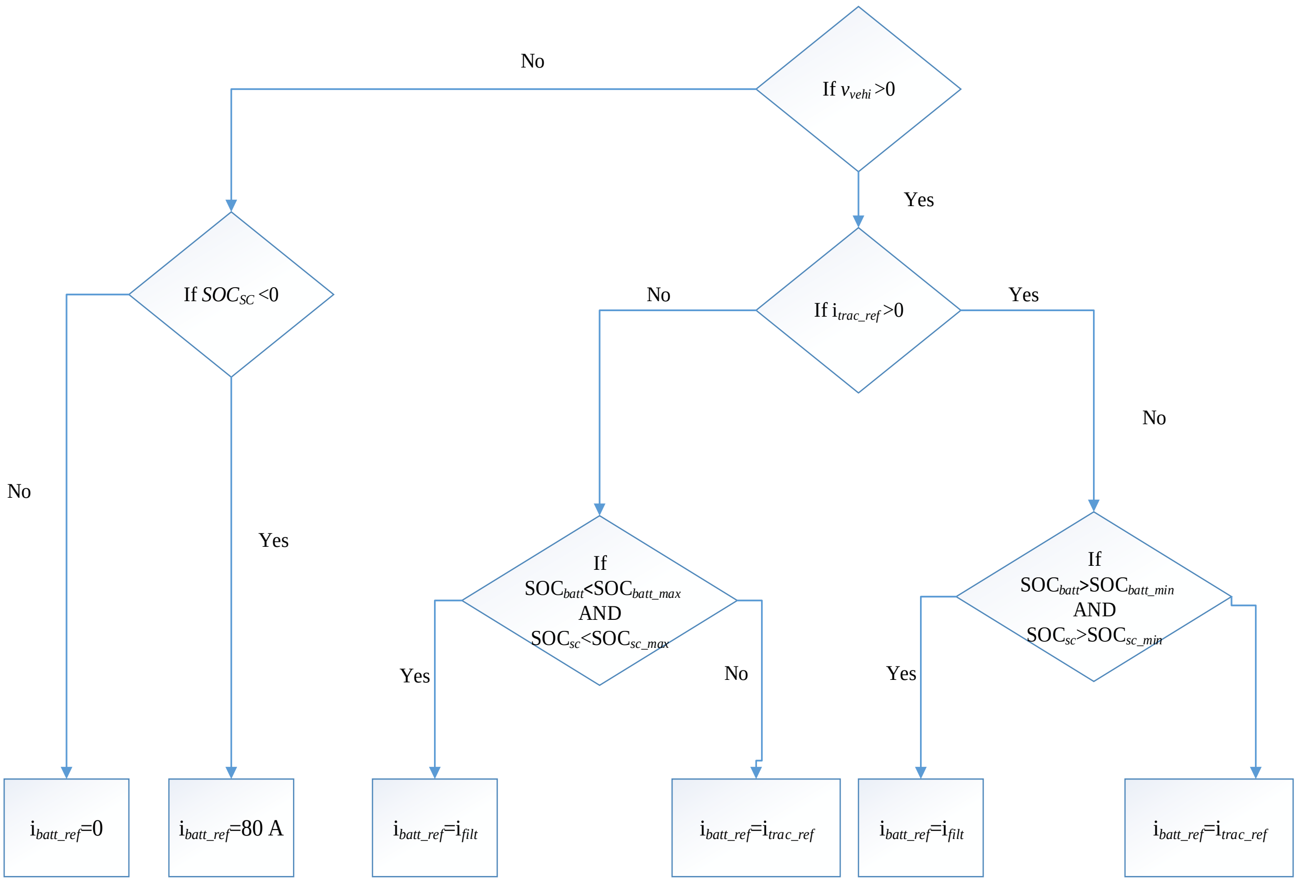


Figure 58- First Current strategy

In EMR the representation of the strategy block is represented by a blue rectangle like Figure 59.

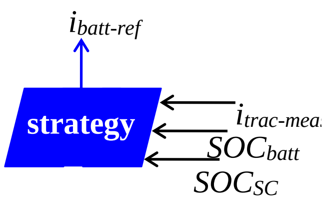


Figure 59-Strategy block for batteries current

Finally, the final EMR of the ESS is represented in Figure 60. In this figure, it is possible to observe all the EMR and the control of each element.

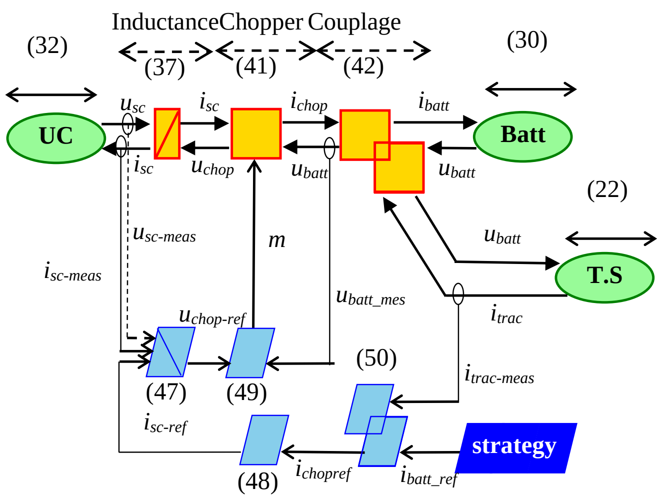


Figure 60- Final EMR and MCS of H-ESS

3.3 Simulations

3.3.1 Cycle Drive

To simulate the behaviour of the vehicle it is also necessary to simulate the driver's behaviour when the driver accelerates or brakes. In order to analyse this, cycle drives are used. There are differents cycles depending on the caractheristis of the vehicle and the type of the vehicle.

Thus, as the studied vehicle is a car, the choosen cycle is the World-Wide Harmonized Light test cycle WLTC of classe 2. This cycle posses diferent classes. These dclasses depend on the ratio between the power of the electrical machine and the mass of the vehicle;Table 6 demonstrates the three different classes that exist. As it is known from the second chapter the wheight of the vehicle is 542 kg and the power of the electrical machine is 15kW, making a ratio of 27.6. With this ratio it is possible to identify from Table 6 that the class for this vehicle is the second class.

This cycle has a duration of 1477 seconds and a distance of 14 664 m. The maximum speed is 85 km/h and the average velocity is 57,8 km/h. To simulate the effect of a climbing it is added during seven seconds a climbing with an inclination of 5%. In Figure 61 it is possible to observe the behaviour of the velocity.

Table 6- Classes of WLTC cycle

Classes	Rated
Class 1	Ratio of rated power in W /kerb mass in kg <= 22
Class 2	Ratio of rated power in W / kerb mass in kg > 22 but <= 34
Class 3	Ratio of rated power in W / kerb mass in kg > 34

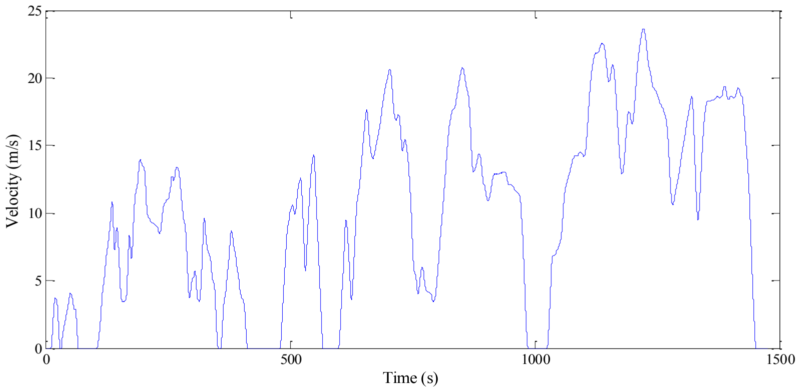


Figure 61- Drive cycle curve

3.3.2 Simulation results

Traction subsystem

The control velocity is wel acomplish the real velocity follow the reference. As Figure 62 shows, the real velocity follows the reference. It is possible to observe a little diference due to the errors.

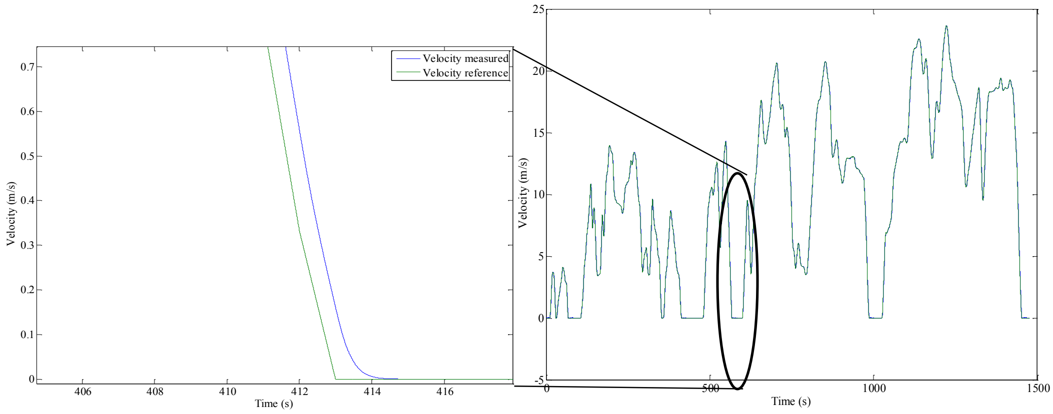


Figure 62- Result of velocity control

This drive cycle with this vehicle causes the current profile demonstrated in Figure 63. One important aspect is to verify if the current stays between the values accepted by the induction machine (IM). As it is possible to see, this condition is respected. The existent current peaks are caused by accelerations for the positive and braking phases or desacelerations for the negatives one. These negative values will be used to recharge the supercapacitors and batteries.

These peaks of current are caused by the necessity of more power for the traction subsystem in big accelerations. If we verify the equation (9) it is possible to see that, the higher is the velocity, the higher will be the force applied in the vehicle. Consequently, if it is necessary more force for the movement of the vehicle more torque the IM must produce. This is translated into an increasing of the current, as demonstrated in equation (22).

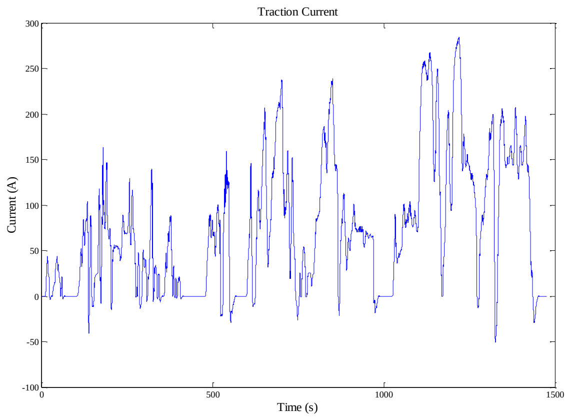


Figure 63- Current traction

Battery results

As the strategy defines, batteries must supply the system with a filtered value of the traction current, this value is constant due to the low frequency, as Figure 60 demonstrates. However, this happens until supercapacitors are able to supply the high frequency power. These results are visible in Figure 61 where the current value is practically constant du to result of the filtering of the traction current, contrarily of the supercapcitor current.

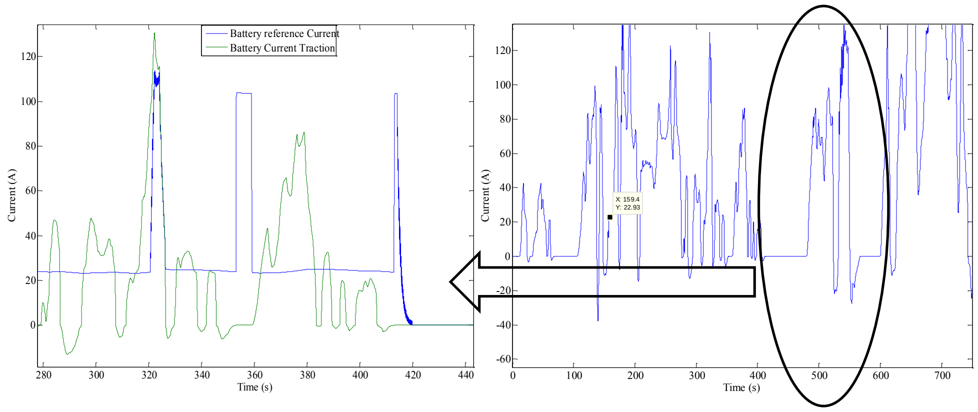
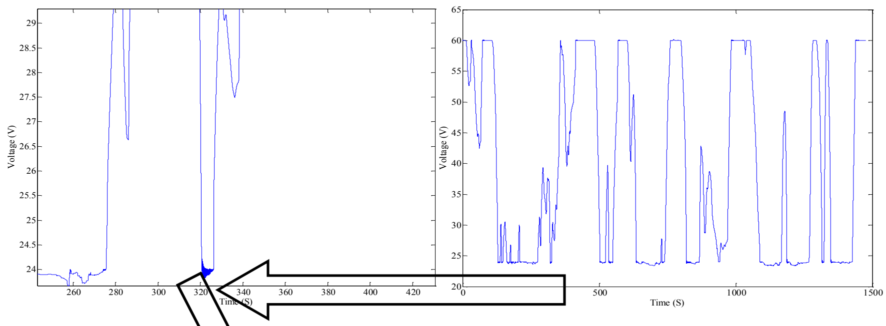
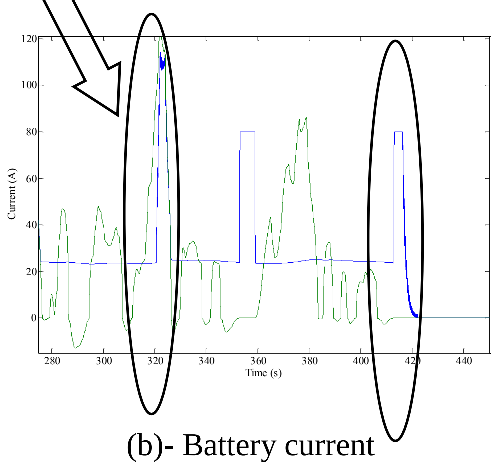


Figure 64- Filtering of low frequencies current traction

As it is expected, batteries supply the traction subsystem with a constant value of current. It represents the low frequency part of the traction current. This value is obtained by filtering it with a low pass filter. The constant time of the filter is equal to 3 mHz. This value was chosen due to results obtained in work (ALLEGRE 2010), were the best results were obtained with this value of frequency.



(a)- Supercapacitors voltage



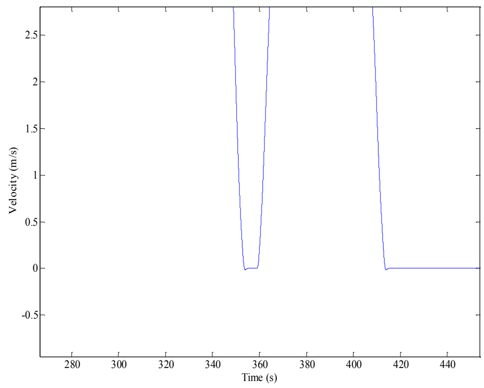
(b)- Battery current

Figure 65- Battery current

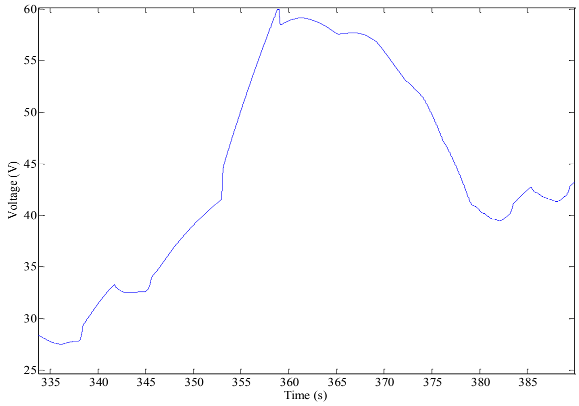
A possible situation that may occur is to consider that the supercapacitor already reached the minimal value of voltage. This results in the fact that they cannot supply the system anymore.

In these moments, batteries must replace them. Batteries will supply the high frequency demands. Figure 65 demonstrates this moment.

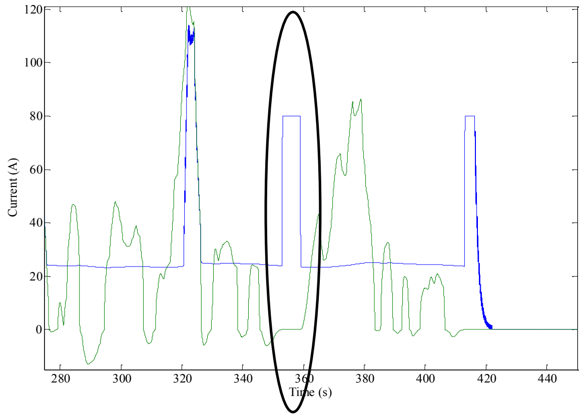
The batteries can also supply the supercapacitors when the vehicle is stopped as Figure 66 demonstrates. This values of current is 80. This value was chosen because of being the discharge value advised by the battery brand.



(a)-Velocity



(b)- SC voltage



(c)- Current result

Figure 66- Batteries recharge SC

One of the major goals is to impose the batteries current. It was already explained how it is obtained. Now, it is important to check if the current supplied by the batteries is equal to the current reference given by the current strategy. To verify this, Figure 67 demonstrates that the control is adequate for the system. However, it is possible to observe some errors due to the control and limitations.

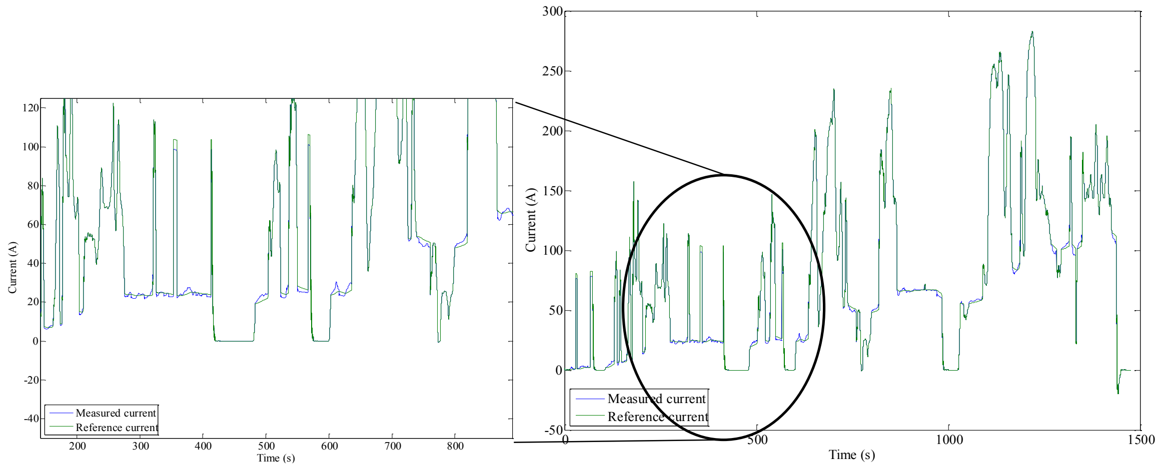


Figure 67-Result of the control current

Batteries voltage cannot vary much. This value should be the more constant possible due to their electrochemical characteristics. In this studied system, this fact is an advantage for the control of the inverter, which in this case is directly linked to the batteries. In Figure 68 it is verified that the voltage varies between normal values, wich are 79V and 72V.

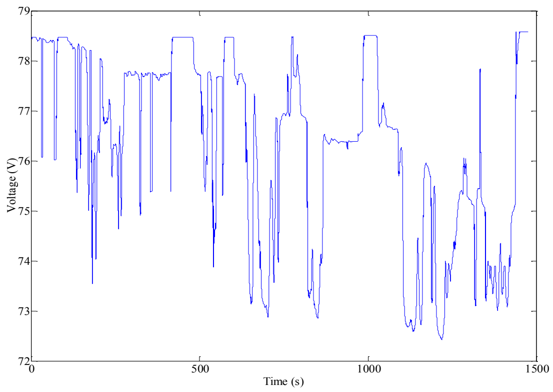


Figure 68- Battery voltage

One important value to evaluate the impact of the system in the battery is the state of charge. This value shows the quantity of energy the battery is able to supply to the system. Normally it is advisable not to pass the 80% of the SOC in order to not damage their lifetime.

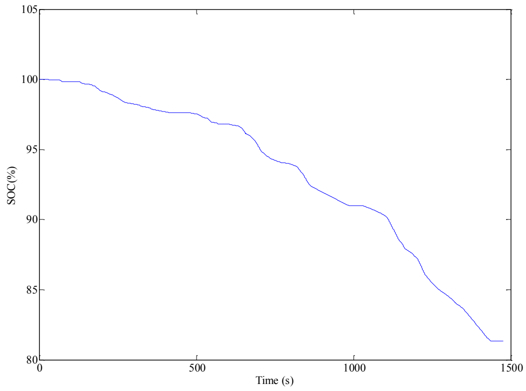


Figure 69- State of Charge of batteries

As it is possible to verify, the state of charge does not reach low values. This fact indicates that the batteries are oversized for the cycle drive of this vehicle.

For this cycle drive the battery has the capacity for a range of 97760 km and for a SOC of 20% the range decrease to 58664 km.

Supercapacitors

The instalation of supercapacitors is required to supply the traction subsystem with all the high frequency traction current, as it is refered in Chapter 2. However, with the limitations imposed by the strategy, in some moments, the supercapacitors are not able to supply the power demand. This ocurs because the voltage reaches the minimum value imposed of 24V. In Figure 70 it is possible to observe this. It is also possible to observe that all the peaks of negative power are recovered by SC's.

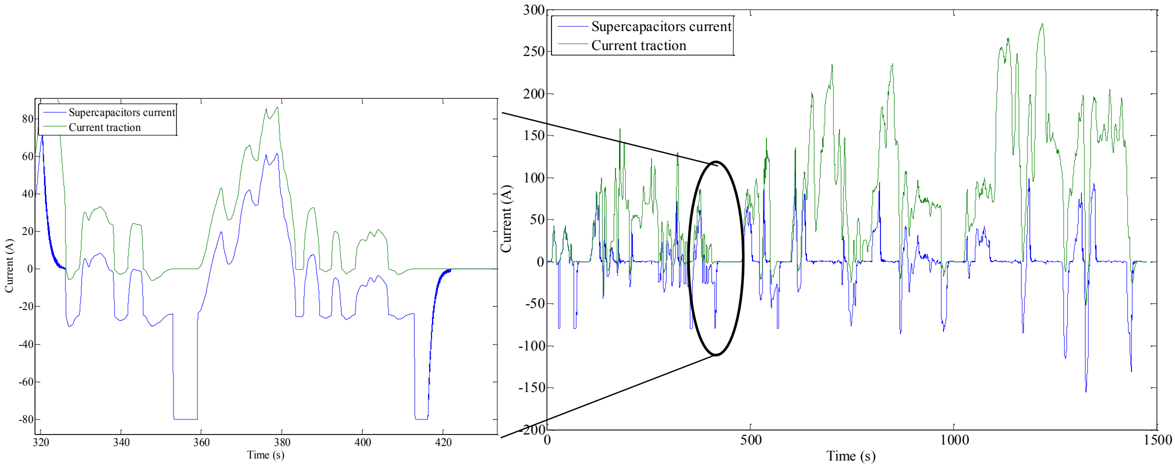


Figure 70- Supercapacitors current reference

One important aspect in the control of the supercapcitors is the control voltage. The control of supercapacitors is done in order to maintain the voltage between a maximal and minimal value. The maximal voltage is related with physical limitations. These limitations do not allow supercapacitors to recover all the power that is sent by the traction subsystem during breaking fases, having the risk of destroying the SC's.Therefore, this maximum value is established. The power delivered by supercapacitors is proportional with the square of the voltage. So for delivereing 80% of the power stored inside it, the voltage just needs to drop 40% to 50% of the nominal value.

The result of the control voltage is represented in Figure 67. The voltage is sustained between a maximum and minimum value. The maximum value is stablish as the nominal value and the minimum as 40% of the nominal value.

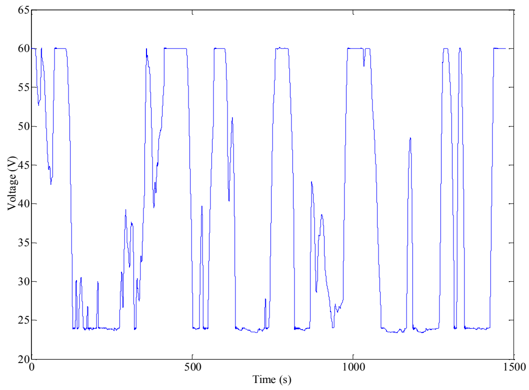


Figure 71- SC voltage

Converter results

For each control system, it is important to verify if they are physically possible to implement. One way is to verify if the duty cycle of the DC-DC converter stays between 0 and 1, like it is represented in Figure 68. There are other possible values, however, for this study case, the voltage of the converter and supercapacitors will never be negative. If this value does not respect this rule, the system is physically impossible due to the characteristics of DC-DC converters.

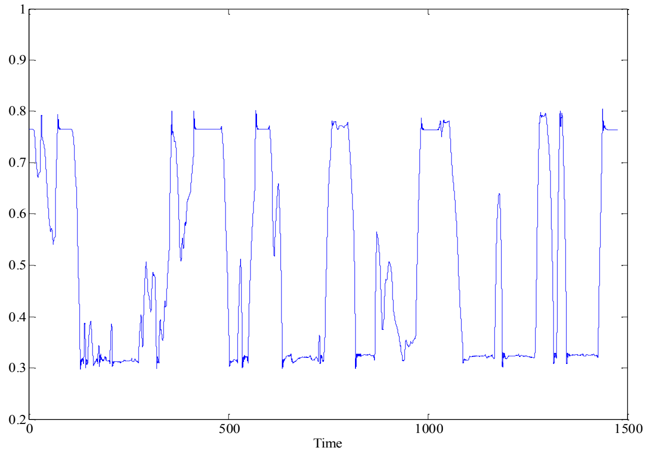


Figure 72- Duty Cycle

4 Conclusion

After the development of this study, it is possible to obtain two conclusions. The first one is the scientific part of the study. It is related with the results and the state of art of the EV. The second one is an approach more socially speaking.

Analysing the results it is possible to observe that they are not totally as expected. The goal of the energy strategy was that the supercapacitors would supply the high frequency power demand. However, this does not occurs in all situations and this fact may be a clear statement that the selected strategy is not the most accurate. Another possibility may be related with the sizing of the supercapacitors. If this is not done correctly, effected as function of the demand of power, discrepancies may exist. All of this will affect the lifetime of batteries; the fact of batteries supplying the system with the high frequency part will be prejudicial. However, the control of the supercapacitors is correctly reached. This control ensures maintaining the voltage between a maximal and minimum value. This control voltage for the supercapacitors is important for the safety of the passengers.

Analysing the state of the art of each component of the EV it is possible to verify that the main drawback is their range. This aspect is related with the type of batteries used. The evolution of batteries already reached a level of energy density very hard to pass. Thus, it is complicated to make concurrence to thermal vehicle just with ESS constituted by batteries. In conclusion was proven that a new solutions is required.

Now from the social point of view, is the society ready to receive EV’s? Personally, I do not know, maybe in a few years, but I do not think that now society is ready. In my opinion, Yes, EV’s can be very useful for the environmental impact due to the 0% of emission of pollutants gases. Decreasing the emission of prejudicial particles for the environment can help to increase the life quality. However, it is necessary to prepare the society to receive this technology. The necessity to spend a considerable quantity of money in our days is never very well accepted for political reasons. The necessity to install a considerable amount of points of charge and reinforce the electrical grid to be able to answer the demand of power when it is necessary to recharge is a problem. Another question is the relation between cost and range of EV that they currently have. EV’s are not capable to perform long travels and therefore it is necessary to have a thermal vehicle. A question remains, are people able to own two cars? If yes, I think just a few percentage of the population is ready to make this effort.

In conclusion, EV’s can be a good solution, but, it is necessary to solve all these problems. With hope and work I believe that when these problems are solved it will be possible.

References

Allegre, A.L., A. Bouscayrol, and R. Trigui 2009 Influence of Control Strategies on Battery/Supercapacitor Hybrid Energy Storage Systems for Traction Applications. *In* IEEE Vehicle Power and Propulsion Conference, 2009. VPPC '09 Pp. 213–220.

Allègre, A.-L., A. Bouscayrol, and R. Trigui 2013 Flexible Real-Time Control of a Hybrid Energy Storage System for Electric Vehicles. IET Electrical Systems in Transportation 3(3): 79–85.

ALLEGRE, Anne-Laure 2010 Méthodologies de Modélisation et de Gestion de L'énergie de Systèmes de Stockage Mixtes Pour Véhicules Électriques et Hybrides.

Behjati, H., and A. Davoudi 2012 Comparative Reliability Study of Hybrid Energy Storage Systems in Hybrid Electric Vehicles. *In* 2012 IEEE Transportation Electrification Conference and Expo (ITEC) Pp. 1–6.

Blanes, J.M., R. Gutierrez, A. Garrigos, J.L. Lizan, and J.M. Cuadrado 2013 Electric Vehicle Battery Life Extension Using Ultracapacitors and an FPGA Controlled Interleaved Buck #x2013;Boost Converter. IEEE Transactions on Power Electronics 28(12): 5940–5948.

Bouscayrol, A., X. Guillaud, P. Delarue, and B. Lemaire-Semail 2009 Energetic Macroscopic Representation and Inversion-Based Control Illustrated on a Wind-Energy-Conversion System Using Hardware-in-the-Loop Simulation. IEEE Transactions on Industrial Electronics 56(12): 4826–4835.

Bouscayrol, Alain 2003 Formalismes de Representation et de Commande Des Systemes Electromecaniques Multimachines Multiconvertisseurs. H.D.R Génie Electrique: Université des Sciences et Technologies de Lille.

BOUSCAYROL, Alain, Jean-Paul HAUTIER, and Betty LEMAIRE-SEMAIL 2012 Systemic Design Methodologies for Systems Electrical Systems. *In* .

Cao, J., and A. Emadi 2012 A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles. IEEE Transactions on Power Electronics 27(1): 122–132.

Cao, J., N. Schofield, and A. Emadi 2008 Battery Balancing Methods: A Comprehensive Review. *In* IEEE Vehicle Power and Propulsion Conference, 2008. VPPC '08 Pp. 1–6.

Carreira, D., G. Domingos Marques, and D.M. Sousa 2014a Hybrid Energy Storage System Joining Batteries and Supercapacitors. *In* 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG) Pp. 1–6. 2014b Hybrid Energy Storage System Joining Batteries and Supercapacitors. *In* 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG) Pp. 1–6.

Castaings, A., W. Lhomme, R. Trigui, and A. Bouscayrol 2014a Energy Management in EVs Using Battery and Supercapacitors: Algebraic Loop Issue. *In* 2014 16th European Conference on Power Electronics and Applications (EPE'14-ECCE Europe) Pp. 1–9. 2014b

Different Control Schemes of a Battery/Supercapacitor System in Electric Vehicle. *In* 2014 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 1–6.

Chan, C.C., and Y.S. Wong 2004 Electric Vehicles Charge Forward. IEEE Power and Energy Magazine 2(6): 24–33.

Depature, C., A. Bouscayrol, and L. Boulon 2013 Range-Extender Electric Vehicle Using a Fuel Cell. *In* 2013 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 1–6.

Depature, C., W. Lhomme, A. Bouscayrol, P. Sicard, and L. Boulon 2014 Efficiency Map of the Traction System of an Electric Vehicle from an On-Road Test Drive. *In* 2014 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 1–6.

Ehsani, Mehrdad, Yimin Gao, Sebastien E.Gay, and Ali Emadi 2005 Modern Electric, Hybrid Electric, and Fuel Cell Vehicle.

Eurelectric 2007 The Role O Electricity, a New Path to Secure Competitive Energy in a Carbonconstrained Worl.

Gao, Lijun, R.A. Dougal, and Shengyi Liu 2005 Power Enhancement of an Actively Controlled Battery/Ultracapacitor Hybrid. IEEE Transactions on Power Electronics 20(1): 236–243.

Hung, S.T., Douglas C. Hopkins, and C.R. Mosling 1993 Extension of Battery Life via Charge Equalization Control. IEEE Transactions on Industrial Electronics 40(1): 96–104.

International Energy Agency 2014 CO2 Emissions from Fuel Combustion, Highlights.

Karangia, R., M. Jadeja, C. Upadhyay, and H. Chandwani 2013 Battery-Supercapacitor Hybrid Energy Storage System Used in Electric Vehicle. *In* 2013 International Conference on Energy Efficient Technologies for Sustainability (ICEETS) Pp. 688–691.

Khaligh, A., and Zhihao Li 2010 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 Transactions on Vehicular Technology 59(6): 2806–2814.

Letrouvé, T., A. Bouscayrol, W. Lhomme, N. Dollinger, and F.M. Calvairac 2010 Different Models of a Traction Drive for an Electric Vehicle Simulation. *In* 2010 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 1–6.

Letrouve, T., A. Bouscayrol, W. Lhomme, N. Dollinger, and F.M. Calvairac 2012 Reduced-Scale Hardware-in-the-Loop Simulation of a Peugeot 3 #x221E;8 Hybrid4 Vehicle. *In* 2012 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 920–925.

Letrouve, T., P. Delarue, and A. Bouscayrol 2009 Modelling and Control of a Double Parallel Hybrid Electric Vehicle Using Energetic Macroscopic Representation. *In* 8th International Symposium on Advanced Electromechanical Motion Systems Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009 Pp. 1–6.

Lukic, S.M., S.G. Wirasingha, F. Rodriguez, J. Cao, and A. Emadi 2006 Power

Management of an Ultracapacitor/Battery Hybrid Energy Storage System in an HEV. *In* IEEE Vehicle Power and Propulsion Conference, 2006. VPPC '06 Pp. 1–6.

Mayet, C., A. Bouscayrol, J. Pouget, W. Lhomme, and T. Letrouve 2013 Different Models of an Energy Storage Subsystem for a Hybrid Locomotive. *In* 2013 15th European Conference on Power Electronics and Applications (EPE) Pp. 1–10.

Messagie, M., C. Macharis, and J. Van Mierlo 2013 Key Outcomes from Life Cycle Assessment of Vehicles, a State of the Art Literature Review. *In* Electric Vehicle Symposium and Exhibition (EVS27), 2013 World Pp. 1–9.

Roboam, Xavier, ed. 2012 Systemic Design Methodologies for Electrical Energy Systems: Analysis, Synthesis and Management. Electrical Engineering Series. London : Hoboken, NJ: ISTE ; Wiley.

Trovao, J.P., V.D.N. Santos, P.G. Pereirinha, H.M. Jorge, and C. Henggeler Antunes 2013 Comparative Study of Different Energy Management Strategies for Dual-Source Electric Vehicles. *In* Electric Vehicle Symposium and Exhibition (EVS27), 2013 World Pp. 1–9.

Verhille, J.N., A. Bouscayrol, P.-J. Barre, and J.P. Hautier 2006 Model Validation of the Whole Traction System of an Automatic Subway. *In* IEEE Vehicle Power and Propulsion Conference, 2006. VPPC '06 Pp. 1–6.

Wangsupphaphol, A., N.R.N. Idris, A. Jusoh, N.D. Muhamad, and I.M. Alsofyani 2014 Energy and Power Control Strategy for Battery Electric Vehicle with Supercapacitors. *In* 2014 IEEE Conference on Energy Conversion (CENCON) Pp. 13–18.

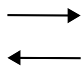
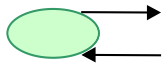
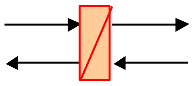
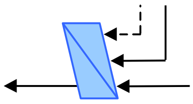
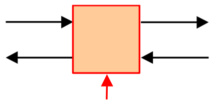
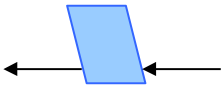
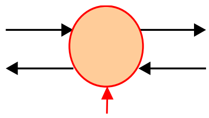
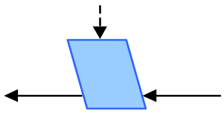
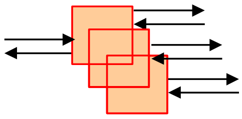
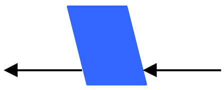
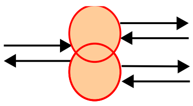
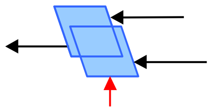
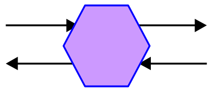
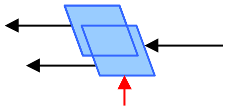
Xiaoliang, Huang, T. Hiramatsu, and H. Yoichi 2013 Energy Management Strategy Based on Frequency-Varying Filter for the Battery Supercapacitor Hybrid System of Electric Vehicles. *In* Electric Vehicle Symposium and Exhibition (EVS27), 2013 World Pp. 1–6.

Xiaoliang, Huang, H. Tosiyoki, and H. Yoichi 2014a System Design and Converter Control for Super Capacitor and Battery Hybrid Energy System of Compact Electric Vehicles. *In* 2014 16th European Conference on Power Electronics and Applications (EPE'14-ECCE Europe) Pp. 1–10. 2014b System Design and Converter Control for Super Capacitor and Battery Hybrid Energy System of Compact Electric Vehicles. *In* 2014 16th European Conference on Power Electronics and Applications (EPE'14-ECCE Europe) Pp. 1–10.

Zahr, H., E. Semail, and F. Scuiller 2014 Five-Phase Version of 12Slots/8Poles Three-Phase Synchronous Machine for Marine-Propulsion. *In* 2014 IEEE Vehicle Power and Propulsion Conference (VPPC) Pp. 1–6.

ANNEX A

Table 7-EMR Pictograms

Energetic Macroscopic Representation (EMR) [Bouscayrol 03]			
EMR is a systemic extension of COG, based on the interaction principle.			
	Action and reaction variables		Energy source (system terminals)
	Energy accumulation (energy storage		indirect inversion (closed-loop control)
	Mono-physical converter (energy conversion)		direct inversion (open-loop control)
	Multi-physical converter (energy conversion)		direct inversion using a disturbance rejection
	Mono-physical coupling (energy distribution)		Strategy (energy management)
	Multi-physical coupling (energy distribution)		Coupling inversion (weighting)
	Model or estimator (any pictogram)		Coupling inversion (distribution)

ANNEX B

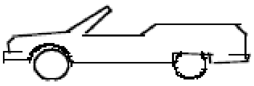
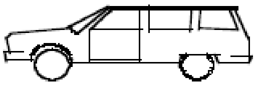
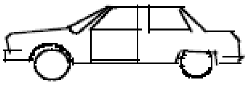
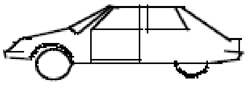
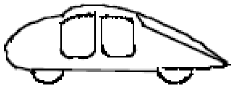
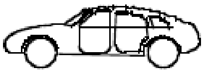
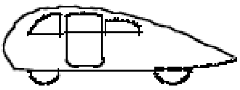
Vehicle Type	Coefficient of Aerodymanic Resistance
 Open convertible	0.5–0.7
 Van body	0.5–0.7
 Ponton body	0.4–0.55
 Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
 Headlamp and all wheels in body, covered underbody	0.2–0.25
 K-shaped (small breakway section)	0.23
 Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

Figure 73- Table o different coeficients

ANNEX C

Tuning of the controler utilized for the control of the velocity and the supercapactiros current.

Tuning of IP controler :

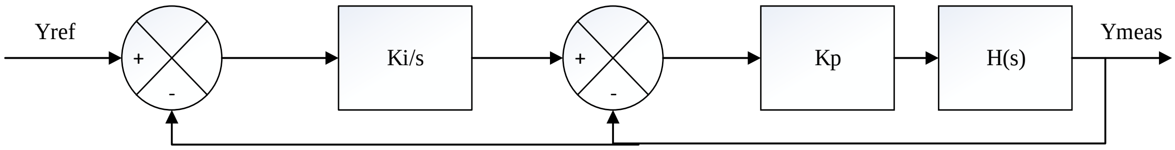


Figure 74- IP Schema block for transfer function of IP corrector

It is decide tht the system is define by an equation on the first order H(s) :

$$\frac{K}{1+\tau s} \quad (51)$$

K is the gain of the system and τ her constant time.

The equation in close loop is equal to :

$$\frac{1}{\frac{s}{K_i K_p K} + \frac{\tau s^2}{K_i K_p K} + \frac{s}{K_i} + 1} \quad (52)$$

The canonic form of second order equation is :

$$\frac{K}{s^2 + 2\xi \omega_n s + \omega_n^2} \quad (53)$$

With equation (52) and (53) it is possible calculate de gains of the controller.

$$\begin{cases} K_i = \frac{2\xi \omega_n \tau - 1}{K} \\ K_p = \omega_n^2 \frac{\tau}{K} \end{cases} \quad (54)$$

ANNEX D

Sources of energy

Batteries :

Figure 75- Battery characteristics

DATASHEET
BC ENERGY SERIES RADIAL D CELL 350F ULTRACAPACITOR

BCAP0350 E270 T11

FEATURES AND BENEFITS

- Round, radial mounting design for easy surface mount assembly
- Over 500,000 duty cycles
- 10 year life capability
- Ultra-low internal resistance

APPLICATIONS

- Industrial power back up
- Portable power tools
- Renewable energy systems
- Short term UPS (uninterruptible power supply) and telecom applications

PRODUCT SPECIFICATIONS

CAPACITANCE	
Nominal capacitance	350 F
Capacitance tolerance	+20% / -0%
VOLTAGE	
Rated voltage	2.7 V DC
Surge voltage	2.85 V DC
Maximum operating voltage	2.7 V DC
Isolation voltage	N/A
RESISTANCE	
ESR, DC	3.2mΩ
Resistance tolerance	Max.
Thermal resistance (Rth)	10.9C/W
TEMPERATURE	
Operating temperature range	-40°C to +65°C
Storage temperature range	-40°C to +70°C
Temperature characteristics	
Capacitance change % at 25°C	± 5%
Internal resistance % at 25°C	± 150%
POWER	
Pd	4,300 W/kg
ENERGY	
Emax	5.62 Wh/kg
LIFESPAN	
Endurance After 1,000 hours application of rated voltage at 65°C.	
Capacitance change	<20% decrease
Internal resistance	<25% increase
Life test At rated voltage and 25°C.	10 years
Capacitance change	≤20% decrease
Internal resistance	≤100% increase
CYCLES	
Cycles - Capacitors cycles between specified voltage and half rated voltage under constant current at 25°C (500,000 cycles)	

Capacitance change	20% decrease
Internal resistance	100% increase
CURRENT	
Leakage current After 72 hours at 25°C. Initial leakage current can be higher.	0.3 mA
Short circuit current (Isc) CAUTION: Current possible with short circuit from U_R. Do not use as an operating current.	840 A
Maximum continuous current	25 A
Maximum peak current, 1 sec	220 A
CONNECTION	
Terminal	Radial
SIZE	
Dimensions	See drawing
Volume	0.053 L
Mass	63g

MOUNTING RECOMMENDATIONS

Solder tabs to PCB. See application note for further information and slot spacing recommendations.

MARKINGS

Parts are marked with the following information: Rated capacitance, rated voltage, product number, name of manufacturer, positive and negative terminal, warning marking, serial number.

ADDITIONAL TECHNICAL INFORMATION

Capacitance and ESR, DC measured per document no. 1007239, available at www.maxwell.com.

I_c = leakage current after 72 hours at 25°C

$$Isc \text{ (short circuit current)} = \frac{V_{RATED}}{ESR}$$

R_{th} = thermal resistance

$$Emax = \frac{\frac{1}{2} CV^2}{3{,}600 \times mass}$$

$$Pmax = \frac{\frac{V^2}{4R\,(1khz)}}{mass} \qquad Pd = \frac{\frac{0.12V^2}{R\,(DC)}}{mass}$$

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Figure 76-Characteristics of SC's