Fuzzy logic-based energy management strategy on dual-source hybridization for a pure electric vehicle

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ABSTRACT

This paper presents a fuzzy logic controller (FLC) based energy management strategy (EMS), combined with power filtering for a pure electric vehicle. The electrical power supply is provided by a hybrid energy storage system (HESS), including Li-Ion battery and supercapacitors (SCs), adopting a fully active parallel topology. The vehicle model was organized and constructed using the energetic macroscopic representation (EMR). The main objective of this work is to ensure an efficient power distribution in the proposed dual source, in order to reduce the battery degradation. To evaluate the impact of the developed design and the efficiency of the developed EMS, the proposed FLC strategy is compared to a classical EMS using SCs-filtering strategy and architecture based on battery storage model. To validate the proposed topology, simulation results are provided for the new European driving cycle (NEDC) using MATLAB/Simulink environment.

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1. INTRODUCTION

In the second half of the 20th century, the requirement for urban mobility has increased considerably. According to the International Energy Agency (IEA), carbon dioxide concentration (CO_2) in 2013 was approximately 40% higher than in the mid-1,800s [1]. Indeed, battery electric vehicles (B-EVs) provide significant potential to reduce transportation emissions [2]. However, the battery has to support high power rates in specific conditions, which is harmful to its performance [3]. Therefore, it is important to work towards a solution to extend the EVs battery lifespan, in order to make them sustainable. For instance, coupling the battery with other energy sources, characterized by fast dynamic response, such as supercapacitors (SCs) [4], [5], allows to implement an efficient energy management strategy (EMS).

The EMS is a key element, able to limit the factors contributing to the battery degradation. The EMSs aim to define the appropriate reference value of the battery current. A pertinent way to limit its stress and degradation [6].

Two approaches have been reported in the literature [6]–[8], EMSs applying a rule-based approach and EMSs applying an optimization-based approach. Rule-based EMSs provide several advantages, including the possibility of not requiring prior knowledge of the driving cycle, low complexity, robustness and high reliability [6]–[8]. However, the pre-established rule-based control strategy cannot be adjusted in a real application; it induces poor performance under some system's specific conditions [6]. Silva *et al.* [9] presents a rule-based EMS using a fuzzy controller, to optimize the battery contribution, especially in the high energy demands and recoveries cycles. The initial state of charge criterion (SoCsc) of SC is taken into consideration. The previous described architecture and strategy have been implemented in [10], aiming the integration of the SCs in a three-wheeled electric vehicle, powered by battery. The proposed hybridization is based on the same architecture and the same EMS.

An adaptive fuzzy logic controller (FLC)-based EMS (AFEMS) is proposed in [11], to determine the power split among battery and SCs, aiming at the enhancement of battery lifespan. The developed strategy is based on the battery degradation model, caused by the charge/discharge cycle per time unit. The main objective of the developed strategy is to maximize the system efficiency, by optimizing the performance of the hybrid energy storage system (HESS) components (battery, SC, and converters), limiting the battery current variations, and controlling the SCs which work as an energy buffer. Wang *et al.* [12] proposes an EMS combining FLC and Markov random prediction of electrical power demand, insuring the improvement of the previous mentioned energy performances. Finally, an EMS based on genetic algorithms (GA) and FLC-based strategy, is proposed in [13]. The object of this work is to identify the optimal generation of HESS parameters, which provides maximum range for the proposed vehicle.

This paper proposes modeling, control and simulation of an EV with similar technical specifications as Kia Picanto [14]. The vehicle's power supply is provided by a HESS, composed of a battery and SC. The EV architecture is shown in Figure 1, and the performances are presented in Table 1. The model organization was conducted using the energetic macroscopic representation (EMR) approach. The development of the EMS was performed using fuzzy logic controller and designed to provide efficient energy management, which reduces the battery degradation and controls the dual energy sources.

The rest of this paper is organized as follows: in section 2, the modeling and control of the system is described. Section 3 details the proposed control strategy. Section 4 discusses the simulation results. Finally, the paper is concluded in section 5.

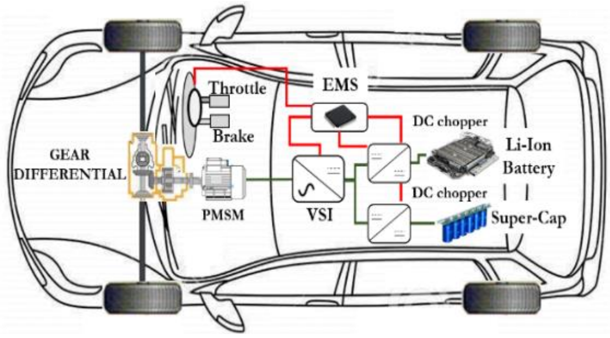

Figure 1. Synoptic scheme of the studied vehicle

Table 1. EV's technical specifications

Variables	Value
Length	3.6 m
Width	1.6 m
Height	1.49 m
Front tires size	195/45R16-D582 mm
Rear tires size	195/45R16-D582 mm
Kerb weight	1,057 kg
Max. weight	1,450kg
Traction	4×2
Maximum speed	120 km/h
Acceleration	10.3s (0 to 100 km/h)
Autonomy	150 km
Aerodynamic standard	CxS=0.7 m^2
Maximum power	74 kW

2. SYSTEM MODELING

2.1. Proposed system

The proposed vehicle is a three-door EV Figure 1. The thrust is provided by a permanent magnet synchronous machine (PMSM) and the speed is controlled by a voltage source inverter (VSI). The vehicle is powered by a HESS in fully active configuration [15], [16], equipped with a Li-Ion battery and SC. The characteristics of the Li-ion battery and SC are shown in Tables 2 and 3 respectively. Each source is controlled by a chopper in multiport mode [17].

Table 2. Characteristics of Li-ion Battery (3.7 V Lithium cells)

Variables	Symbol	Value	Unit
SoC Limits	SoC_{bat}	[30, 100]	%
Number of cells in series	N_{bat}	44	-
Energy density	ρ_{bat}	180	Wh/kg
Battery mass	M_{bat}	157	Kg
Battery energy	E_{bat}	52.3	kWh
Power limit	P_{bat_lim}	50	kW

Table 3. Characteristics of Supercapacitors (GTCAP GTSPP-2R7-508UT cells 2.7 V)

Variables	Symbol	Value	Unit
SCs pack SoC limits	SoC_{SC}	[50, 100]	%
Number of cells in series	N_{SC}	129	-
Equivalent series resistance (ESR)	R_{SC}	0.21	mΩ
SC mass	M_{SC}	102	Kg
SCs cell capacitance	C_{SC}	5000	F

2.2. EV system modeling

It is necessary to establish a model of the vehicle's mechanical and electrical components, because the implementation of the EMS depends on the mass, acceleration and speed of the studied EV. Thus, the different mechanical and electrical component models have been collected and organized by subsystems in Figure 2, referring to the modeling approaches described in the literature [10], [18]–[22]. This approach enables to establish a functional description of a multiphysics energy system and ensure the design of the control layer [23], [24]. EMR describes the energy exchange between subsystems of the studied EV, represented by personalized pictograms as shown in Figure 3, taking into consideration the interaction and causality principles [25]. The components model of the studied system has been organized using EMR as shown in Figure 4.

2.3. EV system control

The control layer was built using the inversion principle of the system's EMR model light blue part as shown in Figure 4 [26]. This operation is used to establish the maximum control structure (MCS) of the studied EV. The objective of the control is to ensure an output response that follows the input instruction. The blue crossed parallelograms correspond to the inversion of the accumulation elements using closed loop controls, these subsystems contain the proportional integral (PI) controllers for the chassis, electrical machine and battery, and integral proportional (IP) controller for SCs. The blue parallelograms correspond to the inversion of the conversion elements, using the open loop control. The superimposed blue parallelograms correspond to the inversion of the electromechanical or electrical coupling of the model layer subsystems.

The first parameter to control is the EV speed defined by the accelerator pedal (1). A PI controller (C_c) is used to define the force value F_{tr} from the new European driving cycle (NEDC) speed reference, with elimination of the disturbance represented by F_{env}.

$$F_{tr} = (v_{veh\_ref} - v_{veh\_meas}).C_c(\mathrm{t}) + F_{env\_meas}. \tag{1}$$

The second parameter is the duty cycle α_{em} defined from DC bus voltage U_{DC} and the reference voltages V_{ms}. α_{em} represents an adjustment parameter that allows the control speed of the traction machine via the VSI. The electric machine includes three model blocks (orange pictograms); therefore, the control should use three blocks as well. The first one represents an electromechanical transformation (2), the second one is a PI controller (C_s), which corresponds to the energy storage block of the machine (3), and the last one represents an electrical transformation block from dq-axis to the phase voltages V_{ms_ref} (4).

$$i_q = \frac{2C_{em}}{3p[\varphi_v + (L_q - L_d)i_d]} \tag{2}$$

$$V_{dq\_ref} = (i_{dq\_ref} - i_{dq\_meas}).C_S(\mathrm{t}) + e_{dq\_meas} \tag{3}$$

$$V_{ms\_ref} = [\mathrm{T}\ (\theta_{elect})]^{-1}\ V_{dq\_ref} \tag{4}$$

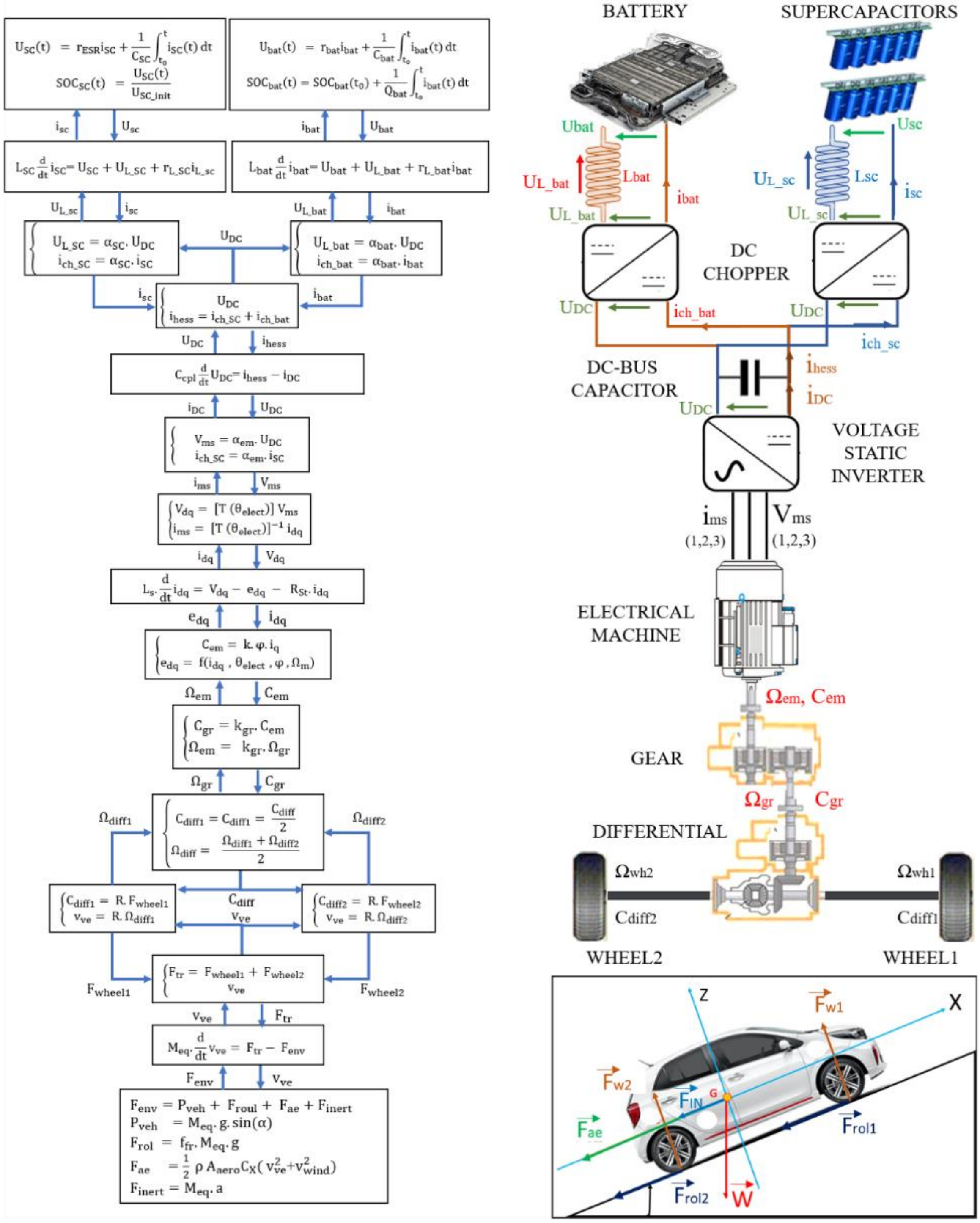

Figure 2. Synoptic scheme and mathematical models by subsystems of the studied vehicle

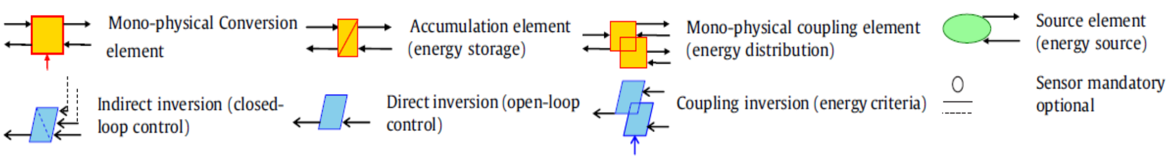

Figure 3. Pictograms of EMR

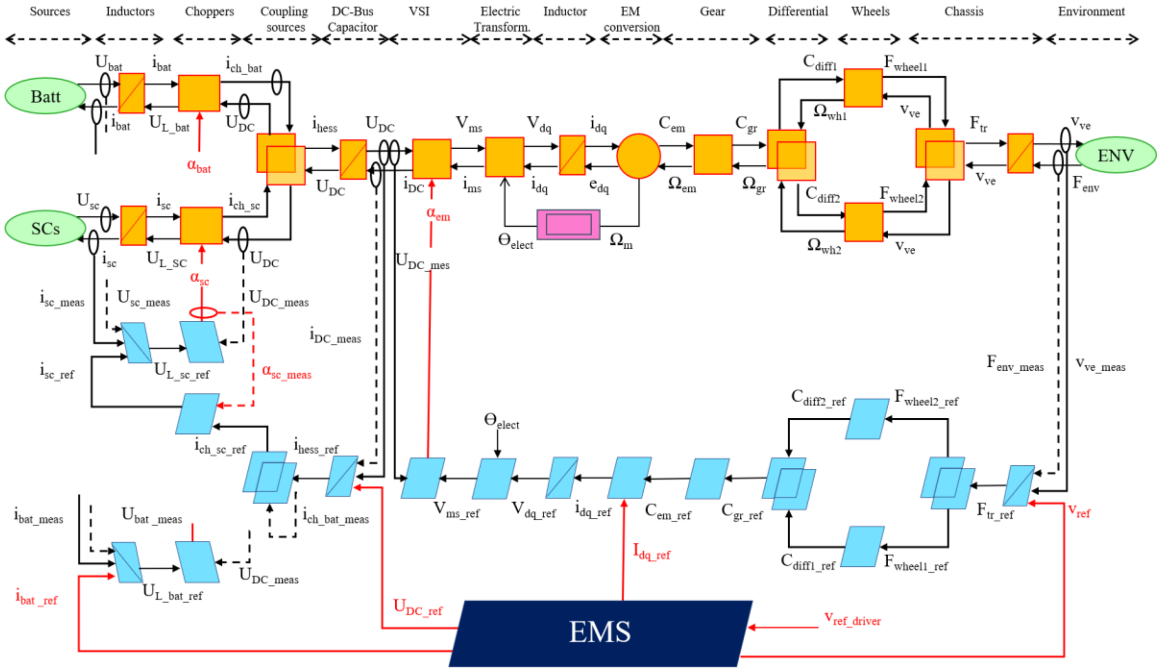

Figure 4. EMR and MCS of the studied system

The local control of the HESS ensures a battery supplied current that follows the reference fixed by EMS. This parameter is calculated by duty cycle α_{bat}, which is defined by voltage $U_{L\_bat\_ref}$ and DC bus voltage U_{DC_meas} (5). Thus, α_{bat} represents the third control parameter for the battery branch. The reference current for the primary source, should satisfy the performances criteria to minimize the battery degradation. These performances are defined in EMS.

$$U_{L\_bat\_ref} = (i_{bat\_ref} - i_{bat\_meas}).C_b(\mathrm{t}) + U_{bat\_meas} \tag{5}$$

On the other hand, the energetic properties of the studied system components are taken into consideration, in order to design the control scheme [23]. Thus, the main objective of this part is to guarantee a stable power supply to the EV powertrain from DC bus (160 V). Indeed, the reference voltage of DC bus is defined from EMS, which allows to define the total reference current that control the HESS, via C_{DC} (t) controller, used to ensure its control (6).

$$i_{hess\_ref} = (U_{DC\_ref} - U_{DC\_meas}).C_{DC}(\mathrm{t}) + i_{DC\_meas} \tag{6}$$

$$i_{ch\_sc\_ref} = i_{hess\_ref} - i_{ch\_bat\_meas} \tag{7}$$

Thus, the current reference of the SC branch, is calculated using (7) (Kirchhoff's law). Figure 4 shows a classical algebraic loop scheme, where the duty cycle α_{sc} is defined with its feedback without any delay. The measurement of α_{sc} is necessary for its determination [27]. Indeed, the resolution of the algebraic loop is conducted using a delay action. However, this operation is not possible in a real system, because of the pulse-width modulation (PWM) control. As a result, the duty cycle should be estimated.

A possible solution consists in estimating α_{sc} from the inversion-based control. It is based on the implementation of the IP corrector, which performs at first an integral action and then a proportional action, which imposes a delay in the loop [27]. Therefore, the used IP corrector scheme avoids the algebraic loop problems.

3. ENERGY MANAGEMENT STRATEGY

The main objective of the EMS design is an efficient management split of the energy flow, and an optimal use of the main source. In this case: the battery pack. Therefore, a FLC-based strategy is developed, aiming at limitation of factors affecting battery performance, and allowing optimal control of power split among sources (battery, SC). In addition, the developed EMS should guarantee the power required by powertrain, a stable power supply to the main electrical grid, and a controlled use of the SCs stored energy, keeping the SC's SoC in an accepted range.

Indeed, the EMS should take into consideration the available energy of different storage elements, and define instantaneously the contribution of each source, depending on the power profile required by powertrain. This strategy is essentially aimed at reducing the stress on the battery, which extends its lifespan. Thus, four groups of membership functions are considered, three input groups and one output group (8).

$$k_{cont} = f\left(\frac{P_{DC\_dem}}{P_{batt\_lim}}, \frac{d}{dt}\left(\frac{P_{DC\_dem}}{P_{batt\_lim}}\right), SoC_{SC}\right) \quad (8)$$

The first input group, considered in the developed EMS, is the ratio of the requested power to the battery power limit (P_{DC_dem}/P_{batt_lim}). Thus, four membership functions have been defined: under-zero, near-null, normal and high as shown in Figure 5, aiming to ensure a progressive contribution of battery energy supply, depending on the power profile requested by powertrain. This profile reflects the three driving cycles (acceleration, constant speed and deceleration/braking). Then, when the ratio is positive, the battery's power limit is taken into consideration in order to reduce its degradation. On the other hand, when the power ratio is negative, the powertrain operates in regenerative braking mode. In this case, the power generated by PMSM is recovered via the DC bus by the storage elements, depending on SoC of each source.

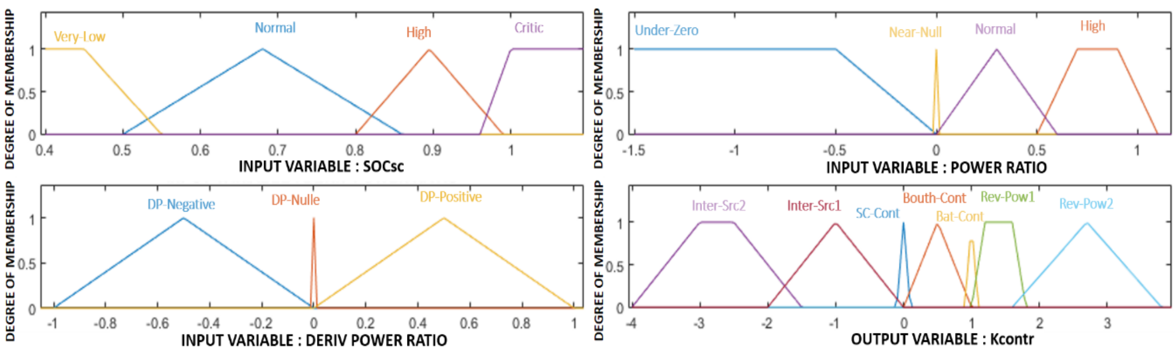

Figure 5. Developed membership functions

The second input group is the derivation of the ratio mentioned previously. Thus, three membership functions are defined: DP-Positive, DP-Null and DP-Negative as shown in Figure 5. The objective of using this input parameter, is to define the different EV's operating modes (constant speed or acceleration) when the ratio is positive. Thus, this parameter enables the EMS to determine instantaneously the contribution of SCs during start-up and acceleration, where the power demand is very high, during a very short period of time (power peaks), and the battery during speeds that are relatively constant (cruising speed), where the power demand is approximately constant.

The third input group is the SoC_{SC}. The instantaneous control of the secondary source (SC) performances by the developed EMS is important, during different EV's operating modes. Thus, during transient phases, such as: starting, acceleration and braking. This device is used to absorb power peaks and high frequency current harmonics. SCs enable efficient storage of energy for later re-use. Indeed, this operation should be performed keeping the SoC_{SC} in an optimal range: SoC_{SC} >50% [11]. For this purpose, four membership functions are defined: very_low, normal, high and critical as shown in Figure 5, which reflect the SCs performances concerning the SoC.

The last group of membership functions is the output group. The purpose of this function is to define the contribution of SCs, using the output parameter k_{cont}. The k_{cont} value determines the current distribution requested by the main bus between the HESS's sources. Indeed, seven functions are defined: Inter-Src2, Inter-Src1, SC-cont, bouth-cont, Bat-cont, Rev-Pow1, Rev-Pow2 as shown in Figure 5. The value of k_{cont} is calculated using the inference rules shown in Figure 6 and explained in Figure 7. The developed EMS system uses a low-pass filter at the output of the FLC strategy block as shown in Figure 7, to divide the required power signal into two components. The first one is the low frequency current reference, used for battery, the second one, is the high frequency current reference, provided by SCs, which supports the peaks and power fluctuations.

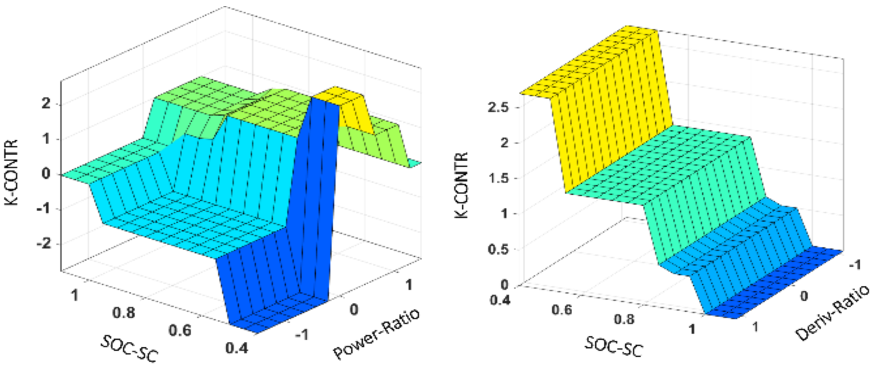

Figure 6. Proposed output SCs contribution and its membership functions

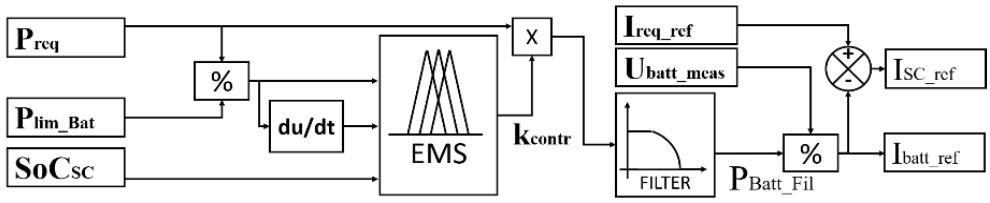

Figure 7. Fuzzy logic strategy scheme

4. RESULTS AND DISCUSSION

The simulation was conducted using MATLAB/Simulink environment under the NEDC cycle. The controller used for battery current is PI, and IP for SC. The simulation model was organized using EMR, with initial value of SoC_{SC} of 98.5%, which is considered as the optimal value for the developed EMS. The current and velocity references tracking, and the stability as shown in Figure 8 demonstrate the controller's efficiency. The results analysis in Figure 8, shows that the energy distribution is optimal, between the dual energy sources of the developed HESS model. The analysis of power demand profiles, shows that the frequency of the battery voltage demand is lower than that of the SC, which provides a low variation of the SoC_{batt} and the limitation of the battery degradation, related to this parameter [11].

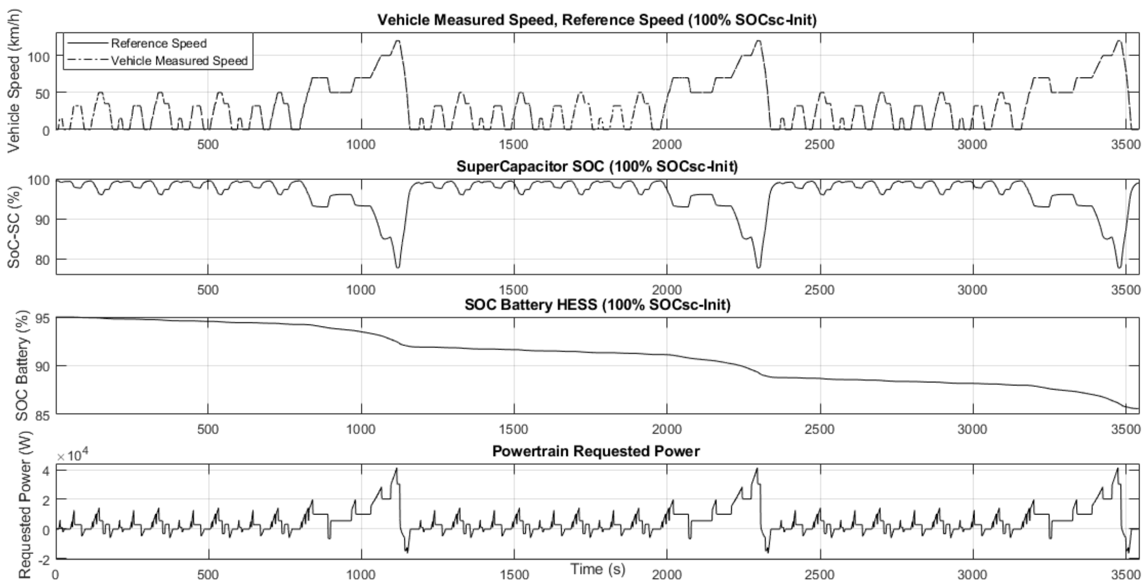

Figure 8. Simulation results of the EV HESS for NEDC driving cycle (SoC_{sc_init}=98.5%)

The performances evaluation of the developed EMS takes into consideration the three phases of driving cycle (acceleration, constant speed and braking). During the acceleration phase, the high-power demand is supported by SCs, taking into consideration the optimal SoC_{SC} range $SoC_{SC} \in [75\%, 100\%]$. The battery is activated during constant power demand phase, without exceeding the imposed battery power limit (P_{batt_lim}=50 kW), to ensure the supply of filtered current to the DC bus; while SCs support the high frequency harmonics of the current demand.

Figure 8 shows that the developed EMS enables to recover the braking energy in an optimal condition and re-inject it to supply the powertrain system during the next acceleration. In this case, the electric machine works as a generator, which enables to recover and store the generated energy. The EMS operates to ensure the recovery of the high power by SCs, to enable its recharge and limit current peaks of the battery, which are harmful to its state of health [11]. Thus, the degradation of the battery can be reduced, and the HESS energy efficiency can be enhanced.

The EMS takes into consideration the SoC_{SC} during driving cycle phases, to ensure the controlled recharge of the SCs through battery, and generated energy by PMSM. The objective of this operation is to ensure the optimal SoC_{sc} (SoC_{sc_init}=98.5%) during total stop of the EV, which demonstrates the possibility of energy exchange between sources. Thus, at the end of every cycle (total stop of the vehicle), the SCs reach a SoC of 97%. The EMS makes use of battery to ensure SCs's recharge, in order to be restored to its initial SoC (SoC_{init}=98.5%).

In Figure 9, the simulation was run with SoC_{sc_init}=50%. The objective of this operation is to evaluate the EMS's reliability of decision making. According to the results, the EMS proceeded first to recharge the SCs in order to restore them to the optimal SoC_{sc} without compromising the execution of the considered cycle. This was achieved through the progressive battery contribution, respecting the battery power limit P_{batt_lim}=50 kW, and the absorption of recovered energy via the DC bus.

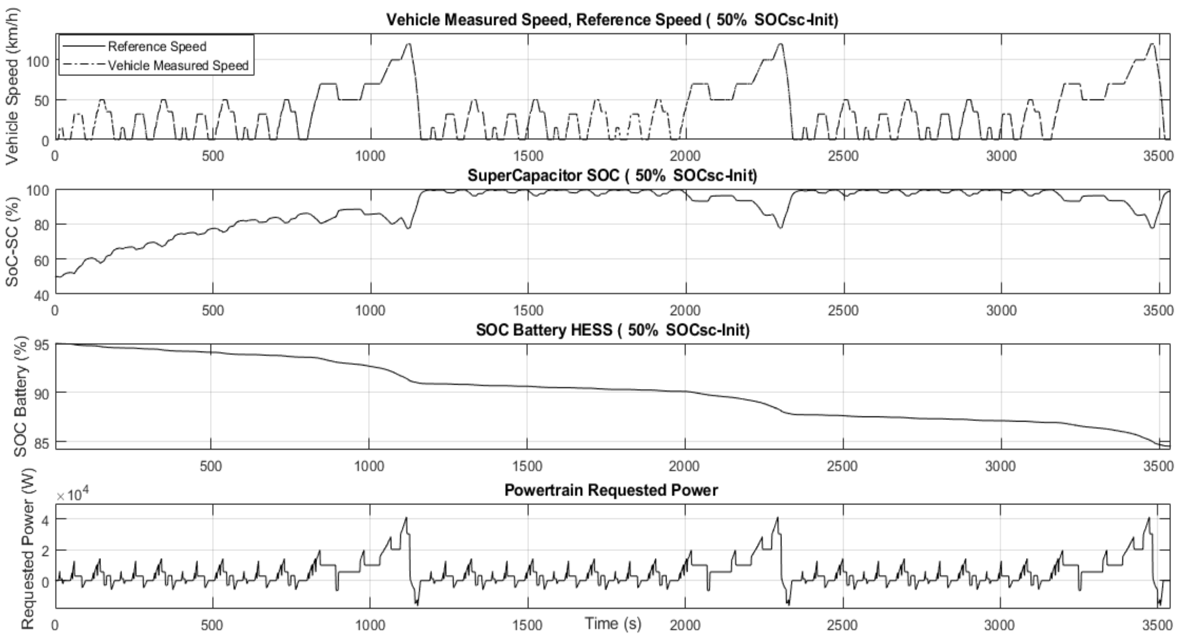

Figure 9. Simulation results of the EV HESS for NEDC driving cycle (SoC_{sc_init}=50%)

The simulation results presented in Figure 10 (SoC_{sc_init}=98.5%) and Figure 11 (SoC_{sc_init}=50%), show the evolution of the sources currents, the powertrain required power P_{DC_dem} and the DC bus voltage U_{DC} during the NEDC cycle. Referring to the literature [9], [10], one of the main EMS objectives is to ensure a constant value of the main bus voltage U_{DC}=160V, supplying VSI that controls the PMSM.

The profile of the main bus current i_{DC} follows that of the main power required by powertrain. Moreover, the curve of U_{DC} voltage is quasi-constant with minor fluctuations that does not exceed ΔU_{DC_max}=0.5 V. The DC bus voltage follows the reference defined in EMS: $U_{DC_ref=}$160 V in both cases SoC_{sc_init}=98.5% and SoC_{sc_init}=50%, which demonstrates the reliability of the designed controller and the algorithm developed in the EMS.

The difference between the states, as shown in Figure 10 and Figure 11, can be shown in the battery current at starting, which becomes more important and progressive at the beginning of the cycle in the case of SoC_{sc_init} is equal 50%. The battery current enables to recharge the SCs in order to reach the optimal SoC: SoC_{sc_opt}=98.5%. For example, at t=60s: i_{bat}=8.45A for SoC_{sc_init}=98.5% and i_{bat}=79.4A for SoC_{sc_init}=50%. On the other hand, the currents curves i_{SC} and i_{bat} allow to analyze the decisions made by the EMS algorithm. Indeed, during the transient regimes, the EMS engages the SCs to satisfy the required current demanded by powertrain on the one hand, and absorb the current recovered during the braking phases on the other hand. The battery operates in the constant and quasi-constant current demand phases to reduce its solicitations.

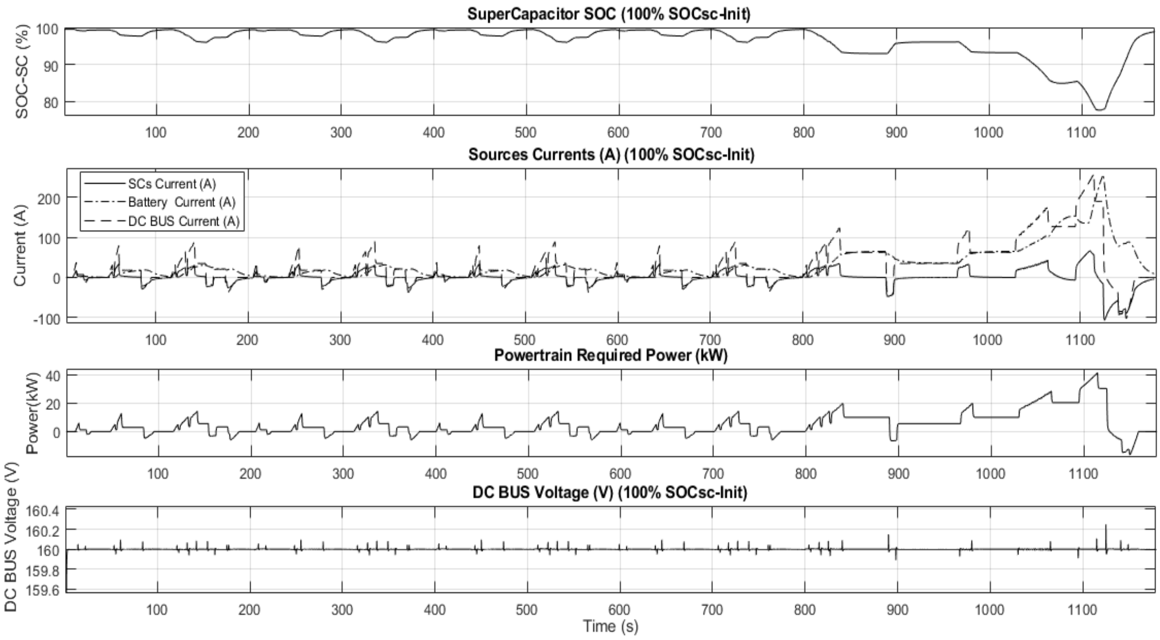

Figure 10. Sources currents, SCs currents, DC bus voltage, and powertrain required power simulation results (SoC_{sc_init}=98.5%)

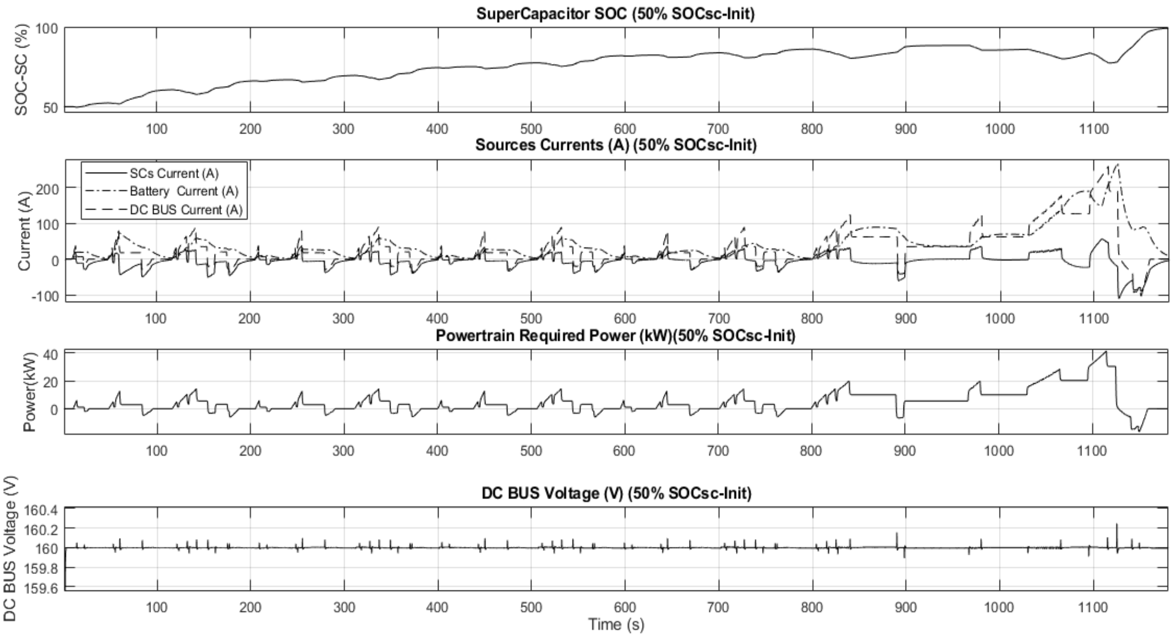

Figure 11. Sources currents, SCs currents, DC bus voltage and powertrain required power simulation results (SoC_{sc_init}=50%)

The implementation of a FLC-based EMS in the proposed system, principally aims at extending the battery's lifespan. The root mean square (RMS) value minimization of the battery current provides the limitation of the factor, impacting battery performances, which contributes to the battery degradation. Indeed, according to the strategies comparison (battery only, filtering and FLC-filtering configuration) shown in Figure 12, the battery current is globally smoothed in the developed EMS case, despite the peaks which are harmful to the battery performances, appearing during the high speeds $t \in [1110, 1130]$ s where v_{ve}>100 km/h. The results of the RMS current calculation of the three strategies show that the developed EMS is the most optimal. The FLC-filtering EMS allows a reduction of this parameter of 16.82% (I_{Bat_RMS}=50.56 A) in comparison with the strategy that uses filtering only (I_{Bat_RMS}=58.03 A), which ensures a reduction of 4.52%, compared to the architecture based on the battery only (I_{Bat_RMS}=60.79 A).

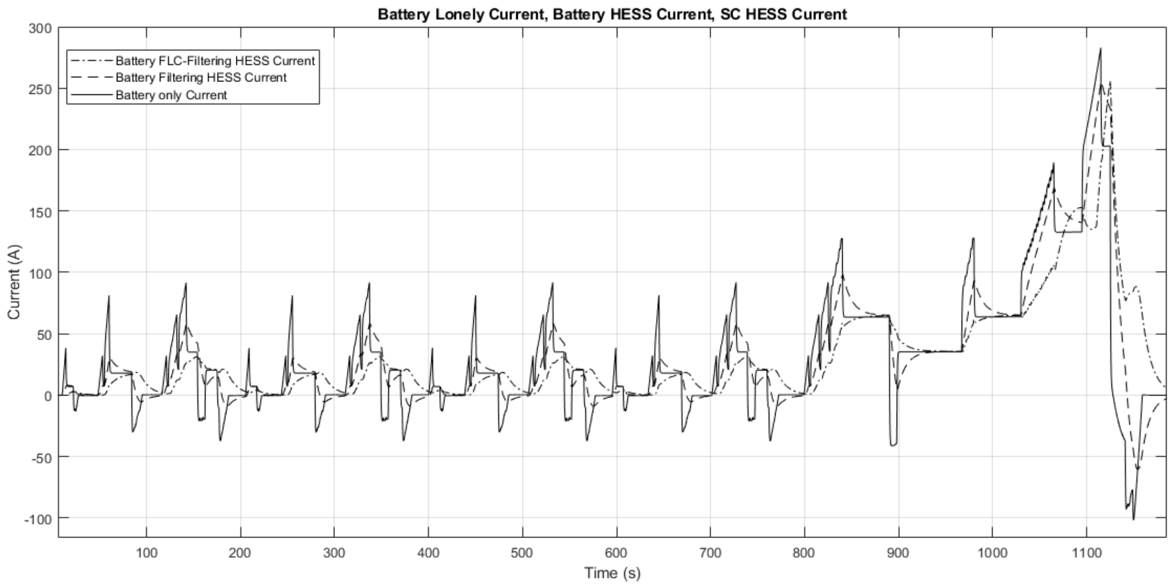

Figure 12. Battery EMSs and battery only architecture currents comparison

5. CONCLUSION

In summary, this paper presents an EMS for a battery/SC based HESS supplying a Pure EV. Active parallel topology has been adopted to control the dual sources separately, allowing a flexible power management. A power management system uses rule based FLC combined with power filtering to provide an efficient distribution of power requirements between battery and SCs. Several criteria were considered for an evaluation of the proposed fuzzy logic controller such as the robustness of the decisions made by the developed EMS, the minimization of the battery current variation and the SC's state of charge difference, the reduction of the battery current RMS and the stability of the DC BUS voltage.

The simulation model is organized using the EMR approach and created using MATLAB/Simulink. The simulation results show that the proposed EMS provides better performance of global control comparing with the classical EMS based on filtering and battery only ESS architecture, independently of the used driving cycle. The proposed solution satisfies the criteria defined previously and can effectively limit the battery degradation by reducing the RMS value of the battery current by 16.82%. Therefore, future research should be conducted for the same EMS using an experimental platform, to evaluate the performance of the developed power management strategy. The FLC-based EMS will be implemented on a field programmable gate array (FPGA) using the digital signal processor (DSP)-Builder platform and evaluated with a hardware-in-the-loop architecture with dSPACE interface.

REFERENCES

[1] IEA, "CO2 emissions from fuel combustion 2014," *OECD*, Annual report of International Energy Agency (IEA), Paris, Nov. 2014. doi: 10.1787/co2_fuel-2014-en.
[2] C. C. Chan, Y. S. Wong, A. Bouscayrol, and K. Chen, "Powering sustainable mobility: roadmaps of electric, hybrid, and fuel cell vehicles [point of view]," *Proceedings of the IEEE*, vol. 97, no. 4, pp. 603–607, Apr. 2009, doi: 10.1109/JPROC.2009.2012990.

[3] N. Omar *et al.*, "Lithium iron phosphate based battery–assessment of the aging parameters and development of cycle life model," *Applied Energy*, vol. 113, pp. 1575–1585, Jan. 2014, doi: 10.1016/j.apenergy.2013.09.003.

[4] S. Dusmez and A. Khaligh, "A supervisory power-splitting approach for a new ultracapacitor–battery vehicle deploying two propulsion machines," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 3, pp. 1960–1971, Aug. 2014, doi: 10.1109/TII.2014.2299237.

[5] J. M. Blanes, R. Gutierrez, A. Garrigos, J. L. Lizan, and J. M. Cuadrado, "Electric vehicle battery life extension using ultracapacitors and an FPGA controlled interleaved buck-boost converter," *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5940–5948, Dec. 2013, doi: 10.1109/TPEL.2013.2255316.

[6] R. Xiong, H. Chen, C. Wang, and F. Sun, "Towards a smarter hybrid energy storage system based on battery and ultracapacitor - a critical review on topology and energy management," *Journal of Cleaner Production*, vol. 202, pp. 1228–1240, Nov. 2018, doi: 10.1016/j.jclepro.2018.08.134.

[7] D.-D. Tran, M. Vafaeipour, M. El Baghdadi, R. Barrero, J. Van Mierlo, and O. Hegazy, "Thorough state-of-the-art analysis of electric and hybrid vehicle powertrains: Topologies and integrated energy management strategies," *Renewable and Sustainable Energy Reviews*, vol. 119, Mar. 2020, doi: 10.1016/j.rser.2019.109596.

[8] A. Santucci, A. Sorniotti, and C. Lekakou, "Power split strategies for hybrid energy storage systems for vehicular applications," *Journal of Power Sources*, vol. 258, pp. 395–407, Jul. 2014, doi: 10.1016/j.jpowsour.2014.01.118.

[9] M. A. Silva, H. N. de Melo, J. P. Trovao, P. G. Pereirinha, and H. M. Jorge, "An integrated fuzzy logic energy management for a dual-source electric vehicle," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2013, pp. 4564–4569, doi: 10.1109/IECON.2013.6699871.

[10] J. P. Trovao, M. R. Dubois, M.-A. Roux, E. Menard, and A. Desrochers, "Battery and supercapacitor hybridization for a pure electric three-wheel roadster," in *2015 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Oct. 2015, pp. 1–6, doi: 10.1109/VPPC.2015.7352904.

[11] H. Yin, W. Zhou, M. Li, C. Ma, and C. Zhao, "An adaptive fuzzy logic-based energy management strategy on battery/ultracapacitor hybrid electric vehicles," *IEEE Transactions on Transportation Electrification*, vol. 2, no. 3, pp. 300–311, Sep. 2016, doi: 10.1109/TTE.2016.2552721.

[12] Y. Wang, W. Wang, Y. Zhao, L. Yang, and W. Chen, "A fuzzy-logic power management strategy based on markov random prediction for hybrid energy storage systems," *Energies*, vol. 9, no. 1, Jan. 2016, doi: 10.3390/en9010025.

[13] J. J. Eckert, L. C. D. A. Silva, F. G. Dedini, and F. C. Correa, "Electric vehicle powertrain and fuzzy control multi-objective optimization, considering dual hybrid energy storage systems," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 4, pp. 3773–3782, Apr. 2020, doi: 10.1109/TVT.2020.2973601.

[14] "Fiche technique Kia Picanto III 1.0 T-GDi 100ch GT Line Premium," L'argus. https://www.largus.fr/fiche-technique/kia/picanto/iii/2020/berline+5+portes/10+t-gdi+100+gt+line+premium-2293919.html (accessed Apr. 26, 2021).

[15] S. M. Faresse, M. Assini, and A. Saad, "Hybrid energy storage system optimal sizing for urban electrical bus regarding battery thermal behavior," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, pp. 2894–2911, Jun. 2020, doi: 10.11591/ijece.v10i3.pp2894-2911.

[16] J. Cao and A. Emadi, "A new battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 122–132, Jan. 2012, doi: 10.1109/TPEL.2011.2151206.

[17] J. Li, Z. Fu, and X. Jin, "Rule based energy management strategy for a battery/ultra-capacitor hybrid energy storage system optimized by pseudospectral method," *Energy Procedia*, vol. 105, pp. 2705–2711, May 2017, doi: 10.1016/j.egypro.2017.03.920.

[18] A. Bouscayrol, W. Lhomme, P. Delarue, B. Lemaire-Semail, and S. Aksas, "Hardware-in-the-loop simulation of electric vehicle traction systems using energetic macroscopic representation," in *IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics*, Nov. 2006, pp. 5319–5324, doi: 10.1109/IECON.2006.347679.

[19] P. Delarue, A. Bouscayrol, and E. Semail, "Generic control method of multileg voltage-source-converters for fast practical implementation," *IEEE Transactions on Power Electronics*, vol. 18, no. 2, pp. 517–526, Mar. 2003, doi: 10.1109/TPEL.2003.809349.

[20] M. Wieczorek and M. Lewandowski, "A mathematical representation of an energy management strategy for hybrid energy storage system in electric vehicle and real time optimization using a genetic algorithm," *Applied Energy*, vol. 192, pp. 222–233, Apr. 2017, doi: 10.1016/j.apenergy.2017.02.022.

[21] V. Sandeep, S. Shastri, A. Sardar, and S. R. Salkuti, "Modeling of battery pack sizing for electric vehicles," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 11, no. 4, pp. 1987–1994, Dec. 2020, doi: 10.11591/ijpeds.v11.i4.pp1987-1994.

[22] J. Khalfi, N. Boumaaz, A. Soulmani, and E. M. Laadissi, "An electric circuit model for a lithium-ion battery cell based on automotive drive cycles measurements," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2798–2810, Aug. 2021, doi: 10.11591/ijece.v11i4.pp2798-2810.

[23] K. Agbli, D. Hissel, M.-C. Péra, and I. Doumbia, "Energetic macroscopic representation (EMR): New approach for multiphysics energetic flows modelling," *IFAC Proceedings Volumes*, vol. 45, no. 21, pp. 723–728, 2012, doi: 10.3182/20120902-4-FR-2032.00126.

[24] K. Chen, A. Bouscayrol, A. Berthon, P. Delarue, D. Hissel, and R. Trigui, "Global modeling of different vehicles using energetic macroscopic representation," in *2008 IEEE Vehicle Power and Propulsion Conference*, Sep. 2008, pp. 1–7, doi: 10.1109/VPPC.2008.4677728.

[25] J. P. Hautier and P. J. Barre, "The causal ordering graph - a tool for modelling and control law synthesis," *Studies in Informatics and Control Journal*, vol. 13, no. 4, pp. 265–283, 2004

[26] A. Bouscayrol, P. Delarue, W. Lhomme, and B. Lemaire-Semail, "Teaching drive control using energetic macroscopic representation — from maximal to practical control schemes," in *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, Sep. 2015, pp. 1–10, doi: 10.1109/EPE.2015.7311683.

[27] A. Castaings, W. Lhomme, R. Trigui, and A. Bouscayrol, "Energy management in EVs using battery and supercapacitors: Algebraic loop issue," in *2014 16th European Conference on Power Electronics and Applications*, Aug. 2014, pp. 1–9, doi: 10.1109/EPE.2014.6910948.

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