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Optimised Power Management Fuzzy Control for EV Hybrid Energy Storage System

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ABSTRACT

As a result of the complementary qualities that batteries and ultra capacitors possess, a hybrid energy storage system (HESS) that consists of a lithium-ion battery and an ultracapacitor has emerged as an effective solution for overcoming the limitations that are associated with single battery energy sources in electric vehicles (EVs), particularly when driving in urban environments. On the other hand, in order to ensure that the HESS operates effectively, an appropriate energy management strategy (EMS) is required. The purpose of this study is to offer an EMS that is based on fuzzy logic control (FLC) and is optimized through the utilization of particle swarm optimization (PSO) and ant colony optimization (ACO) techniques. The suggested method has as its primary objective the reduction of battery current stress and power peak variations. This will be accomplished by optimizing the tuning of the weighting coefficients of the defined FLC rules through the use of ACO/PSO algorithms. As a result, the capacity retention of the battery will be improved, and the lifespan of the battery will be extended.

Key words: EMS, ACO, PSO, FLC, HESS, ultra-capacitor

1. INTRODUCTION

The increasing global demand for sustainable transportation and the rapid depletion of fossil fuel resources have accelerated the development of electric vehicles (EVs) as an alternative to conventional internal combustion engine vehicles [2]. Electric vehicles are recognized for their high energy efficiency, reduced greenhouse gas emissions, lower operating costs, and environmentally friendly operation. In recent years, governments, researchers, and automotive industries have focused extensively on the adoption of EV technology to reduce air pollution and dependence on petroleum-based fuels. However, despite the numerous advantages offered by EVs, several technical challenges still limit their widespread implementation. These challenges include limited driving range, long charging duration, high battery cost, battery degradation, thermal instability, and poor power response during transient operating conditions [3].

Lithium-ion batteries (LIBs) are widely utilized as the primary energy storage source in electric vehicles because of their high energy density, low self-discharge rate, and relatively long operational lifespan. Nevertheless, LIBs exhibit limitations when subjected to rapid charging and discharging cycles, especially during sudden acceleration, regenerative braking, and fluctuating urban driving conditions [7]. Frequent exposure to high current stress and peak power demands can increase battery temperature, accelerate aging mechanisms, reduce battery efficiency, and shorten battery life. Consequently, relying solely on a single battery system may not satisfy the dynamic power requirements of modern electric vehicles [8].

2. METHODOLOGY

The following is an outline of the structure that this chapter is organised into. In the beginning, the dynamics of the vehicle, the architecture of the drivetrain, and the hybrid energy storage system (HESS) model that is based on the battery and the ultracapacitor (UC) are described. Following that, a full development of the energy management system (EMS) for efficient power distribution is provided. This development includes the implementation and optimisation of the fuzzy logic controller (FLC). A comparison and analysis of the optimised EMS and the conventional EMS for HESS power management is presented in the concluding section of this article.

2.1 SYSTEM MODELING

There are two primary subsystems that make up the electric vehicle (EV) model. These subsystems are the drivetrain subsystem and the powertrain subsystem. The drivetrain portion includes the driving cycle, the dynamic properties of the vehicle, the arrangement of the wheels and axles, the driveline converter, the final drive unit, and the gearbox system. The powertrain subsystem, on the other hand, is made up of the battery pack, the ultracapacitor module, the DC/DC converter, the electric motor together with its controller, and the energy management system. Within this section, the primary focus of the discussion is on the modelling of the various components of the powertrain.

2.2 BATTERY MODEL

In the present study, a Saft lithium-ion battery (LIB) is utilised. This type of battery is characterised by the fact that its individual cells are connected to one another in both series and parallel configurations in order to build the battery pack modules. The primary characteristics of the battery pack that was chosen are outlined in Table 3, which can be seen here. When modelling the dynamic properties of the battery, the internal resistance (R_{int}) technique is utilised. In this approach, the battery pack is modelled as an equivalent electrical circuit that is composed of an open-circuit voltage source ($Uoc,_{BAT}$) that is coupled in series with an internal resistance (R_o) [16]. Equations (6)–(9) reflect the mathematical expression of the suggested battery model [25]. These equations define the battery model.

2.3 ULTRACAPACITOR MODEL

The Maxwell PC2500 ultracapacitor (UC) is chosen to serve as the auxiliary energy storage device in this chapter. The Resistance–Capacitance (RC) equivalent circuit model is utilised in order to simulate the operating properties of the UC. Equations (10)– (13) include the mathematical equations that regulate the RC model. These equations are discussed below. The equation (10) demonstrates that there is a direct connection between the voltage of the ultracapacitor and its state of charge (SOC). Within the context of these formulations, the term "remaining" refers to the storage capacity of the UC that is still available, while "Q_{total}" reflects the total storage capacity of the UC. The open-circuit voltage of the ultracapacitor is represented by the value V_{OCUC}, while the minimum and maximum operating voltages are denoted by the parameters V_{min} and V_{max}, respectively. Furthermore, C represents the UC capacitance, which is given in ampere-hours at the same time.

2.4 DC/DC CONVERTER MODEL

The DC/DC converter model is relatively complicated, and including the whole converter dynamics into the energy management system can result in a significant increase in the amount of computational work that needs to be done when it is implemented. As an alternative to the detailed converter model, an effective interpolation technique is utilised in order to diminish the level of complexity involved. The efficiency characteristics of the converter are kept in a lookup table that makes use of the voltage ratio between the energy storage devices and the UC power demand as input variables. This is due to the fact that the converter is directly associated with the ultracapacitor unit.

The efficiency behaviour of the DC/DC converter is depicted in Figure 18 of [26] as a piecewise linear relationship with regard to the converter power and voltage ratio. This is the case when the converter is operating under regular operating conditions.

2.5 HYBRID ENERGY STORAGE SYSTEM FORMATION

The configuration of the semi-active hybrid energy storage system (HESS) is utilised in the electric vehicle, as seen in Figure 3.1. This is due to the fact that it offers a suitable compromise between the economic feasibility and the performance of the system, as was discussed in Section 1 earlier. The battery pack, ultracapacitor pack, DC/DC converter, and energy management system are the components of the powertrain that are contained within the region that is outlined in dark blue. These components, when combined, constitute the entire HESS structure.

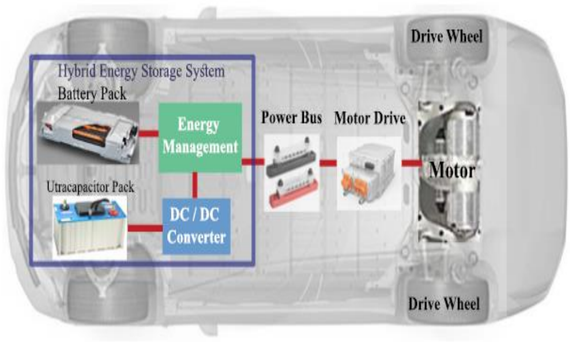

Figure 2.1.HESS architecture in the EV.

The energy management system that is depicted in the block that is shaded green is directly connected to the battery pack. On the other hand, the connection between the battery pack and the ultracapacitor must be made through the DC/DC converter that is situated in the part that is shaded blue. The hybrid energy storage system is characterised by a semi-active architecture, which is represented by this arrangement. The DC/DC converter contributes significantly to the management of voltage variations within this architecture, particularly during times of peak power consumption and when regenerative braking activities are being carried out. As a consequence of this, the converter contributes to the reduction of the current stress that is placed on the battery within the course of repeated cycles of charging and discharging, provides a summary of the specific parameter values that should be considered for the battery and ultracapacitor that are utilised in the HESS.

2.6 ENERGY MANAGEMENT STRATEGY

An energy management system (EMS) is necessary to ensure efficient power sharing between the two energy storage units while maximising the utilisation of available energy resources. In the present work, a hybrid EMS integrating particle swarm optimisation (PSO) or ant colony optimization (ACO) with fuzzy logic control (FLC) is proposed for effective regulation of power flow within the hybrid energy storage system (HESS). The developed control strategy is designed to reduce battery ageing effects, improve battery service life, and satisfy the varying dynamic operating conditions of the electric vehicle. This section primarily concentrates on the description and implementation of the EMS for the hybrid lithium-ion battery–ultracapacitor (LIB–UC) system. As part of the current research, a hybrid energy management system (EMS) that incorporates fuzzy logic control (FLC) and **ACO OR** PSO is presented for the purpose of efficiently regulating the flow of power within the hybrid energy storage system (HESS). The control approach that was created is intended to accomplish the following goals: limit the impacts of battery ageing; enhance the service life of the battery; and fulfil the variable dynamic operating circumstances of the electric vehicle. This section focuses mostly on the description and implementation of the energy management system (EMS) for the hybrid lithium-ion battery–ultracapacitor (LIB–UC) system.

2.7 FUZZY LOGIC CONTROL

Due to the fact that it is able to function without the need for an exact mathematical model or any prior system information, fuzzy logic control, also known as FLC, is widely utilised in systems that are both complicated and unpredictable. Managing the distribution of power between the ultracapacitor units and the battery units is accomplished through the utilisation of the FLC approach in the hybrid energy storage system (HESS) that has been presented. Fuzzification, fuzzy inference system (FIS), and defuzzification are the three primary stages that make up the controller, which functions in accordance with the laws of IF–THEN logic.

During the fuzzification stage, crisp numerical inputs are converted into linguistic fuzzy variables by utilising membership functions. These functions assign membership grades that correspond to the input data by application of membership functions. Following this, the fuzzy inference system uses a predetermined set of IF–THEN rules to determine the relationship that exists between the variables that are input and those that are output. In conclusion, the defuzzification process involves the transformation of the fuzzy output variables into precise numerical values by the utilisation of various approaches such as weighted sum, weighted average, or centroid algorithms.

The power demand (P$_{dmd}$), the normalised vehicle speed, the battery state of charge (ess_$_{SOC}$), the temperature of the battery module (ess_$_{mod\_temp}$), and the ultracapacitor state of charge (ess2$_{SOC}$) are the five input variables that are utilised in this work. A Sugeno-type FIS is utilised. Figure 2 depicts the membership functions that correspond to the variables that are input, whereas the membership functions that are output are linear in form and represent the power distribution coefficients (K). More precisely, the K$_{bat}$ membership function is specific to the battery, and the Kuc membership function is specific to the ultracapacitor.

3. RESULTS AND DISCUSSIONS

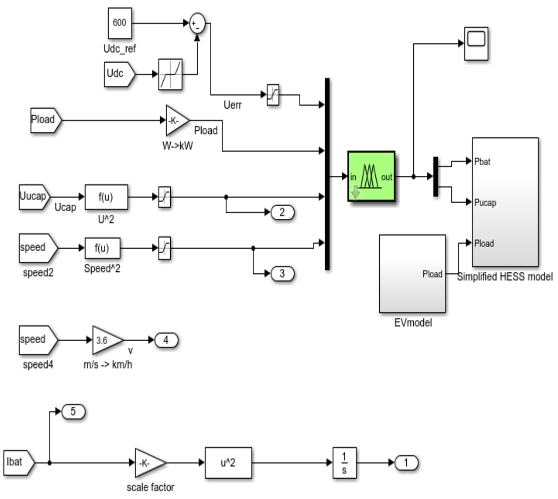

Figure 3.1 Complete Simulink Block Model for showing FUZZY controller, EV model and HESS model interconnection.

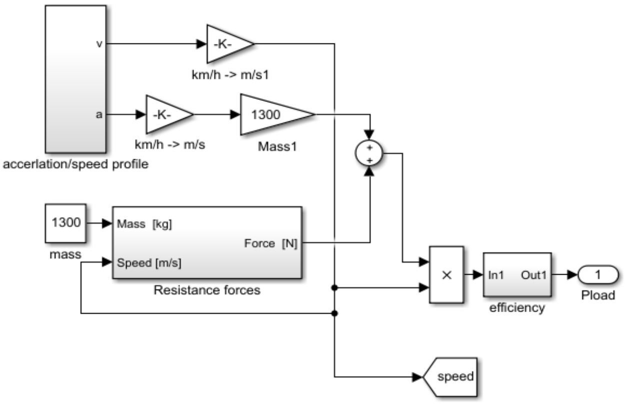

Figure 3.2 Internal detailed Simulink block diagram of EV model.

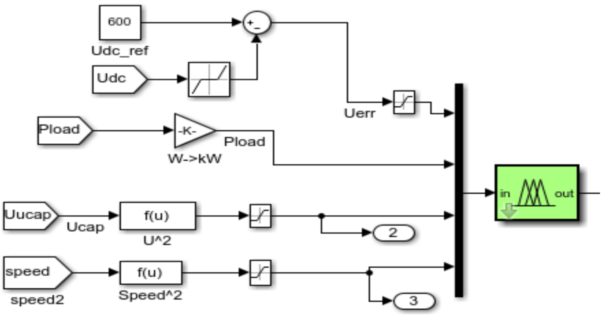

Figure 3.3 Fuzzy logic controller I/O conection

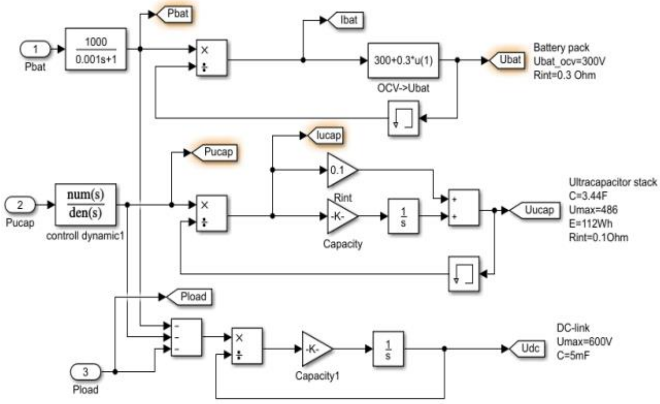

Figure 3.4 Simulink block model for HESS system description

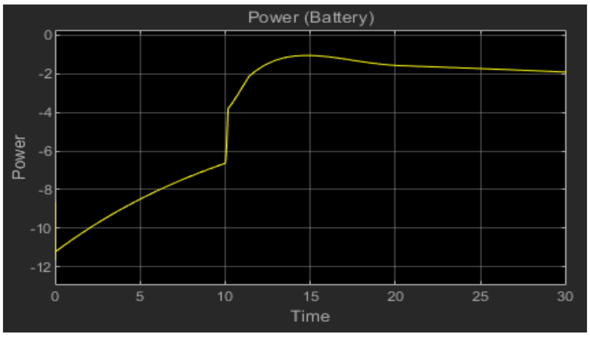

Figure 3.5 Battery power variation with respect to time while running of EV model

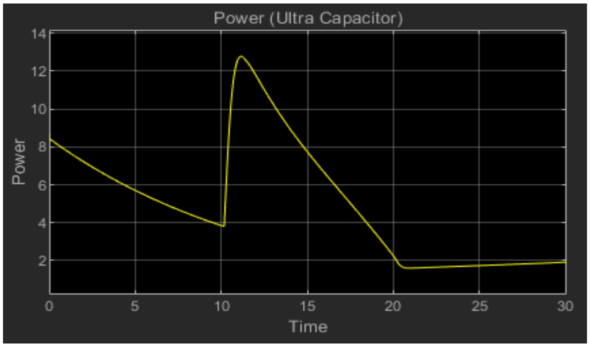

Figure 3.6 Ultracapacitor power variation with respect to time while running of EV model.

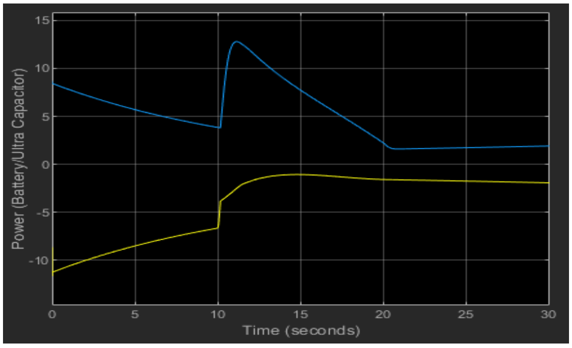

Figure 3.7 Battery (Yellow)/Ultracapacitor(blue) power variation with respect to time while running of EV model.

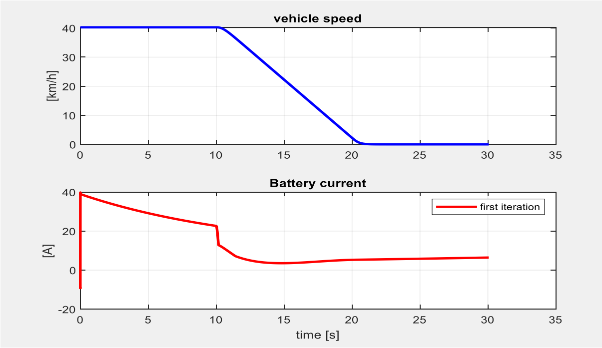

Figure 3.8 Vehicle speed (Top) and Battery current (bottom) with respect to time while running the optimization process.

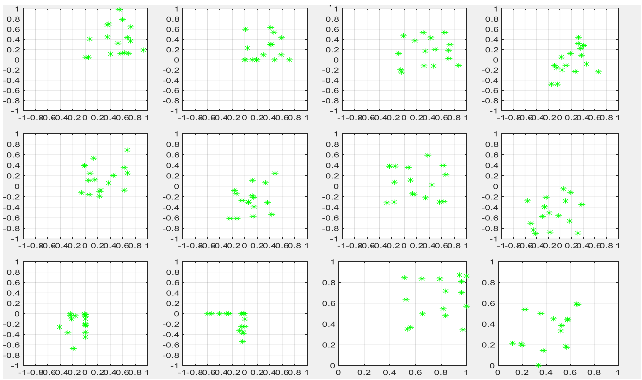

Figure 3.9 Initial position of solution (Fuzzy controller parameters) on running optimization

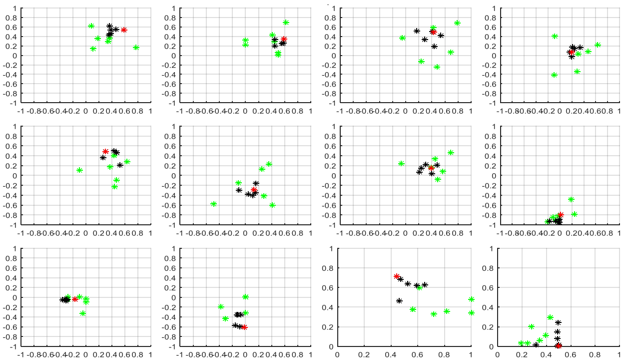

Figure 3.10 Final position of solution (Fuzzy controller parameters) on running optimization.

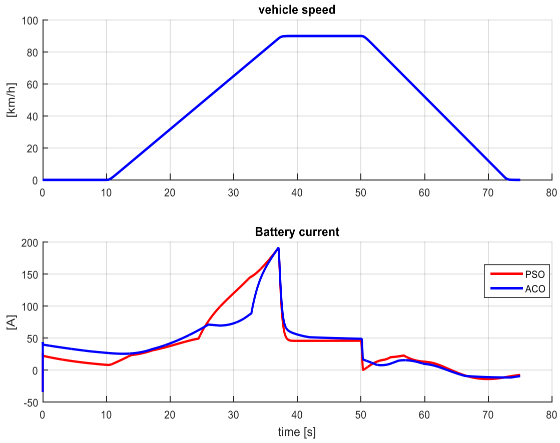

Figure 3.11 Dynamics of controlled output current by using PSO and ACO.

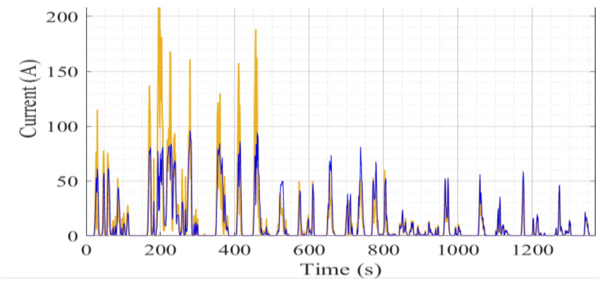

Figure 3.12. Comparing current fluctuation of PSO optimized (green) and ACO optimized (blue) EMSs.

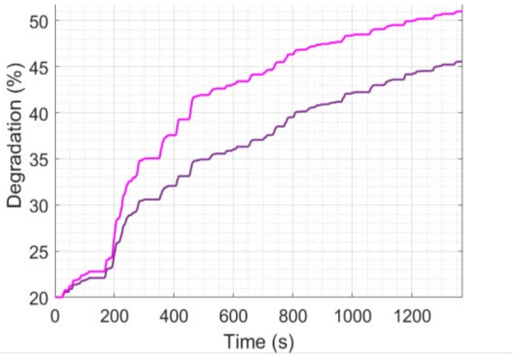

Figure 3.13. Contrasting degradation of the battery in ACO (dark blue)/PSO(light blue) optimized scenarios.

Table 1 Summary of results for the battery

Battery Variable	PSO optimized EMS	ACO optimized EMS
Peak current	240 A	116.3 A
Maximum power delivered	38.3 kW	21.1 kW
Capacity fade	50.9%	45.5%

4. CONCLUSIONS

In conclusion, a particle swarm-optimized fuzzy logic energy management of a Battery-UC hybrid storage system for an EV was investigated. First, the EV power demand based on the driving cycle was extracted from the single battery energy source. Subsequently, considering the EV's operational characteristics and power demand, fuzzy logic rules were developed to distribute the required power between the battery and UC simultaneously. Then, to address the problem of battery degradation due to large current fluctuation, the ACO/PSO was used to optimize the fuzzy logic weights, taking into consideration the battery's operating temperature as a cost function. The performance of the proposed EMS was assessed by comparing it with an unoptimized FLC. Optimization led to a significant 51% reduction in peak current and a 5.4% improvement incapacity fade/degradation. These findings demonstrate that the proposed EMS is efficient in splitting the power request from the drivetrain and minimizing degradation, thereby ensuring safe battery pack operation, reducing the risk of thermal runaway, minimizing battery current stress, and increasing the battery's lifespan. Overall, while the proposed ACO optimized fuzzy logic control of the hybrid battery-UC energy storage system offers numerous advantages in terms of efficient energy management, dynamic adaptation, and temperature-aware optimization, it also presents challenges such as oversizing each energy storage device and lack of adaptability to real-time driving data. These challenges will be addressed in future studies to further improve the proposed energy management strategy for electric vehicles.

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