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Power management optimization by fuzzy logic controller for hybrid energy storage system supported EV

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ABSTRACT: Due to the complementary characteristics of lithium-ion batteries and ultracapacitors, the hybrid energy storage system (HESS) has gained significant attention as an efficient approach to address the drawbacks of standalone battery-based energy systems in electric vehicles (EVs), especially under urban driving conditions. However, the efficient functioning of the HESS strongly depends on the implementation of a suitable energy management strategy (EMS). This research proposes a fuzzy logic control (FLC)-based EMS that is further enhanced using particle swarm optimisation (PSO) and ant colony optimisation (ACO) algorithms to improve overall system performance. However, the deployment of an appropriate energy management strategy (EMS) is a significant factor that plays a significant role in determining how efficiently the HESS operates. The purpose of this study is to establish a fuzzy logic control (FLC)-based environmental management system (EMS) that is further improved by employing particle swarm optimisation (PSO) and ant colony optimisation (ACO) algorithms in order to boost the overall performance of the system. The suggested method has as its primary objective the reduction of battery current stress and power peak variations. This will be accomplished by optimising 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.

Battery temperature is chosen as the cost function in the proposed optimisation framework. This is due to the fact that lithium-ion batteries (LIBs) are extremely sensitive to changes in temperature, in contrast to ultracapacitors (UCs), which are highly resistant to temperature changes. Using the developed electric vehicle (EV) model and the Urban Driving Schedule (UDDS), the optimised FLC integrated with the PSO algorithm is evaluated, and its performance is compared with that of the standard FLC strategy that is not optimised. The results of the simulation show that the suggested energy management system (EMS) is able to preserve around 5.4% of the battery capacity, while at the same time maintaining the maximum working temperature of the battery at 25.5 degrees Celsius. This indicates that thermal management has been improved, and energy storage performance has been enhanced.

KEYWORDS: Electric vehicle, Hybrid energy storage, energy management system, ultacapacitor, Li-Ion Battery

1. INTRODUCTION

There has been a strong push toward the development of electric vehicles (EVs) as an alternative to conventional automobiles powered by internal combustion engines [1,2]. This is due to the fact that there is a rising demand for environmentally friendly transportation systems all over the world, as well as the ongoing depletion of fossil fuel supplies. EVs are generally recognized for their exceptional energy efficiency, reduced emissions of greenhouse gases, low running costs, and environmentally benign performance. Over the course of the past several years, governments, researchers, and automotive manufacturers have all concentrated a substantial amount of emphasis on the deployment of EV technologies in order to reduce the amount of pollution that is released into the environment and the dependency on fuels that are produced from petroleum. Despite the fact that electric vehicles provide a multitude of advantages, the widespread adoption of these vehicles is constantly being hampered by a variety of technological difficulties. These limitations include a limited driving distance, a longer charging time, costly battery systems, the ageing of the battery, problems with thermal management, and an insufficient power response under transient operating circumstances [3].

The motivation behind this research originates from the increasing demand for efficient and sustainable electric transportation systems [2]. Although electric vehicles provide significant environmental and economic advantages, the limitations of conventional battery-based energy storage systems continue to restrict their performance and reliability. Urban driving conditions involve frequent acceleration, deceleration, and regenerative braking events that impose severe current fluctuations on lithium-ion batteries [22]. These operating conditions increase battery temperature, accelerate electrochemical degradation, and reduce battery lifespan. Replacing degraded batteries significantly increases the overall operational cost of electric vehicles [3-8]. The integration of ultracapacitors with lithium-ion batteries provides an effective solution for handling transient power demand and regenerative braking energy [7-10]. However, efficient coordination between the two energy sources is essential for maximizing system performance. Traditional rule-based EMS techniques are unable to provide optimal performance under all operating conditions [11]. Artificial intelligence and swarm optimization algorithms offer promising solutions for intelligent energy management in electric vehicles [12-16]. The capability of PSO and ACO algorithms to optimize fuzzy logic controllers motivates the development of advanced EMS frameworks capable of reducing battery stress and improving overall vehicle efficiency [17-20].

In the context of electric vehicle applications, the primary objective of this research effort is to design an intelligent energy management approach for a hybrid energy storage system that is built of ultracapacitors and lithium-ion batteries. The following is a presentation of the specific objectives that are linked with an investigation. The primary goal is to design and build a hybrid energy storage system that will be used in electric cars. This system will include ultracapacitors with lithium-ion batteries. The second aim is to design a fuzzy logic controller (FLC)-based energy management method for the purpose of establishing efficient and optimal power sharing between the ultracapacitor and the battery. To optimize the parameters and rule weights of the fuzzy logic controller using particle swarm optimization and ant colony optimization algorithms. To minimize battery current fluctuations, thermal stress, and degradation using optimized EMS techniques. To evaluate the performance of the optimized EMS under urban driving conditions using the Urban Dynamometer Driving Schedule. To compare the performance of optimized and unoptimized fuzzy logic controllers in terms of battery temperature, energy efficiency, and capacity retention. To improve battery lifespan and overall energy utilization efficiency of the electric vehicle.

2. METHODOLOGY

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. Specifically, the mathematical equations that correlate to these forces are supplied in Equations (1)–(4), whereas Equation (5) represents the overall tractive force that is required by the powertrain [21-28].

$$F_r = C_{rr}\ Mg\ \cos\alpha \qquad (1)$$

where F_r represents the rolling resistance force (N), C_{rr} the rolling coefficient, M the gross vehicle weight, g the gravitational acceleration (m/s^2), and α the inclination angle (degrees).

$$F_a = A C_d \rho v^2 \qquad (2)$$

where F_a represents the aerodynamic force (N), A the frontal area, C_d the coefficient of drag, ρ the air density (kg/m^3), and v the velocity of the vehicle (m/s).

$$F_g = Mg\ sin\alpha \quad (3)$$

where F_g represents the gradient force (N).

$$F_{acc} = Ma \qquad (4)$$

where F_{acc} represents the acceleration force (N) and a the acceleration (m/s^2).

$$F_t = F_a + F_g + F_r + F_{acc} \qquad (5)$$

In this equation, the symbol Ft represents the total tractive force that is exerted on the vehicle, and it is given in Newtons (N).

Table 1. Vehicle and motor specifications.

Vehicle Parameter	Value	Motor Parameters	Value
Frontal area, A	2.0380	Efficiency	0.909
Air density, ρ	1.20	Mass of motor (kg)	90
Drag coefficient,	0.190	Max. current (A)	485
Gravitational	9.8	Max. voltage (V)	120
Total mass (kg)	1490	Rated power (kW)	80
Vehicle wheelbase	2.5120		
Gear ratio	10		
Number of gears	1		
Rolling resistance	0.00680		

Equation (6) can be used to obtain the battery terminal voltage (U_t), which is also known as the DC bus voltage. Equation (7) is used to evaluate the associated battery power. When the battery current (I_{BAT}) is known, the battery terminal voltage (U_t) can be determined.

$$U_t = U_{OC,Bat} - R_0 . I_{Bat} \qquad (6)$$

$$P_{Bat} = I_{Bat} . U_t \qquad (7)$$

$$I_{Bat} = (U_{OC,Bat} - (U^2_{OC,Bat} - 4.R_0 .P_{Bat})^{1/2})/(2. R_o) \qquad (8)$$

$$SoC_{Bat} = SoC_{Bat,0} - (1/3600). \int(1/Ah_{Bat})\ dt \qquad (9)$$

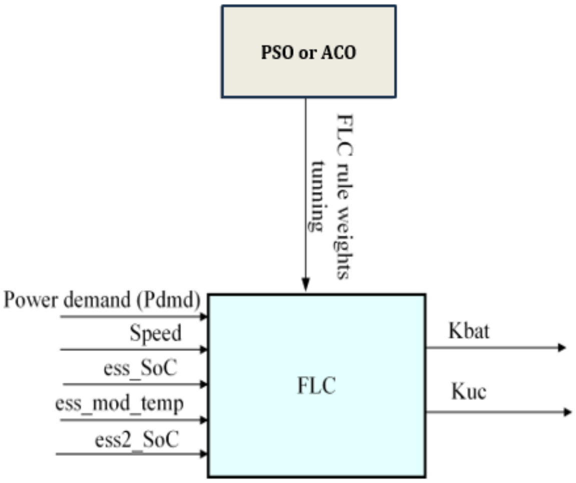

Figure 1: Block diagram representation

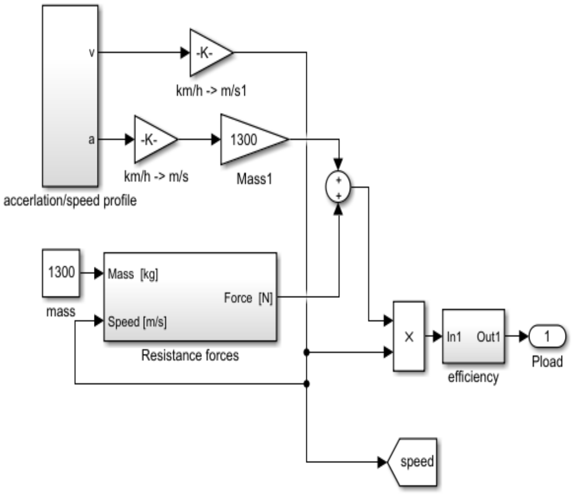

Figure 2: Internal detailed Simulink EV model.

The quadratic expression in shown in equation (8) is the current of battery, represented with variable name I_{BAT}; the battery SoC is represented as (SoC_{BAT}) is shown in Eq. (9), here ($SoC_{BAT,0}$) is represented by initial SoC, I_{BAT} is expressed as the current unit expressed as ampere-hour integration (Ah_{BAT}), the η_{BAT} is the battery efficiency.

Table 2 Battery–UC design parameters.

Parameters/Values	Battery	Ultracapaci
Min. cell voltage (V)	2	0
Max. cell voltage (V)	3.90	2.50
Normal voltage of pack (V)	195.0	175.0
Cell test temperature (°C)	0 to 42	0 to 42
Normal capacity	6 Ah	2500 F
No. of modules in series	18	140
No. of modules in parallel	2	4

An energy management system (EMS) is necessary for ensuring efficient energy sharing in the two storage devices 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 FLC is proposed for effective regulation of power flow within the 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.

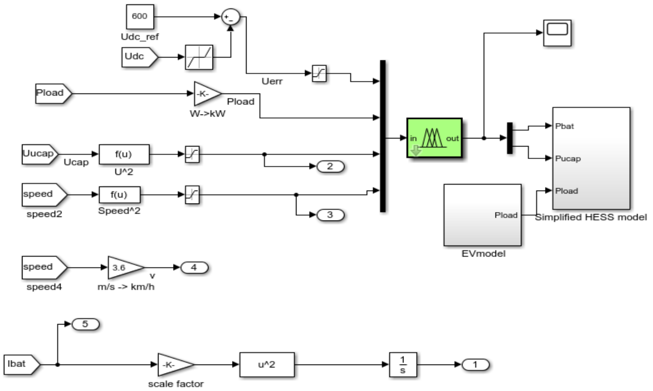

Figure 3: Complete Simulink Block Model for showing FUZZY controller, EV model and HESS model interconnection.

3. RESULTS

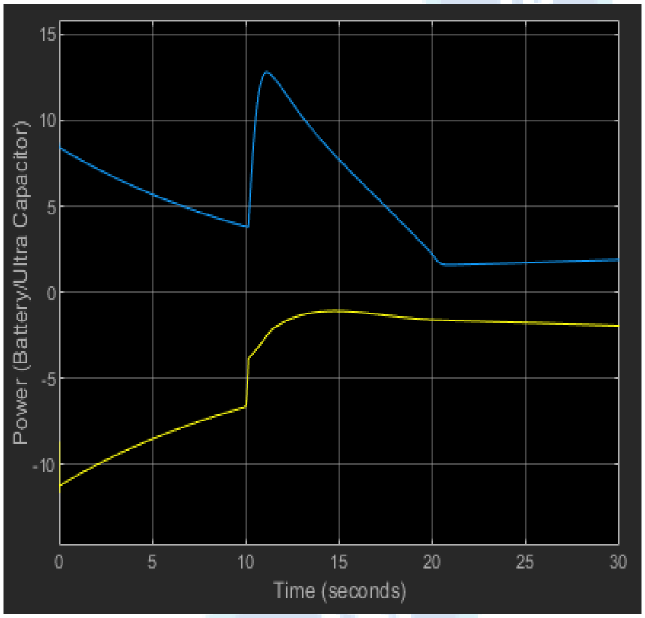

Figure 4: Battery (Yellow)/Ultracapacitor(blue) power variation with respect to time while running of EV model.

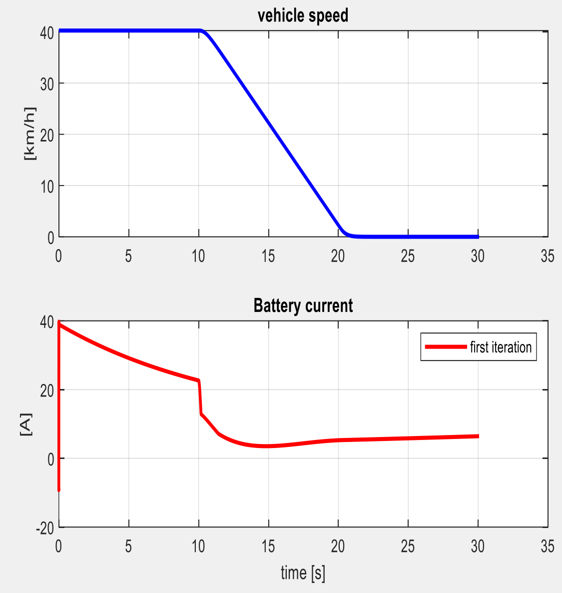

Figure 5: Vehicle speed (Top) and Battery current (bottom) with respect to time while running the optimization process.

Table 4.1 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 fuzzy logic-based energy management strategy was investigated for a battery–ultracapacitor hybrid energy storage system in an electric car. This approach was optimised through the use of particle swarm optimisation (PSO). The power requirement of an electric vehicle that corresponded to the driving cycle was initially determined by employing a battery energy source that was independent of any other generator. Following that, fuzzy logic rules were developed in order to distribute power between the ultracapacitor (UC) and the battery. These rules were formed depending on the operational parameters of the vehicle as well as the load demand. Ant colony optimisation (ACO) and particle swarm optimisation (PSO) were utilised to optimise the fuzzy logic weights in order to reduce the amount of battery deterioration that was brought on by considerable current changes. The cost function comprised of battery temperature was also introduced into the optimisation process.

The effectiveness of the energy management strategy (EMS) that was presented was tested by contrasting it with a typical fuzzy logic controller (FLC) that was not optimised. The optimisation method led to a significant decrease of 51% in peak current and an increase of 5.4% in battery capacity fade/degradation. Both of these improvements were positive outcomes. These findings demonstrate that the suggested energy management system (EMS) is capable of properly distributing drivetrain power demand while simultaneously controlling deterioration, assuring safe battery operation, reducing the danger of thermal runaway, minimising current stress, and increasing the lifespan of the battery.

All things considered, the ACO-optimized fuzzy logic control strategy for the hybrid battery–ultracapacitor system has a number of benefits, including efficient energy management, adaptive behaviour, and temperature-aware optimisation. However, it also has a number of drawbacks, such as the possibility of oversizing storage components and a limited adaptability to real-time driving conditions. better study will be done in the future to examine these constraints in order to better improve the energy management technique that has been presented for applications using electric vehicles.

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