Journal of Energy Systems

2023, 7(1)

2602-2052 DOI: 10.30521/jes.1107190 Research Article

# Modelling and fuzzy logic based control scheme for a series hybrid electric vehicle

Latif Kasım Uysal
Gazi University, Faculty of Technology, Automotive Engineering Department, Ankara, Türkiye, latifuysal@gazi.edu.tr
Necmi Altın*
Gazi University, Faculty of Technology, Electrical - Electronic Engineering Department, Ankara, Türkiye, naltin@gazi.edu.tr

Submitted: 21.04.2022
Accepted: 20.02.2023
Published: 31.03.2023

* Corresponding Author

**Abstract:** Ever stricter emission regulations, declining petroleum resources, increasing pollution, and global warming triggered an interest in e-mobility. Although fully electrified transportation is targeted, hybrid electric vehicles have become attractive during this transition period due to reasons such as battery challenges, range anxiety, grid capacity, and charging infrastructure. Hybrid electrical vehicles require challenging energy management systems due to the increasing number of components and energy conversions. This paper aims to introduce a simple yet effective control scheme to control the battery state-of-charge (SOC) and regenerative braking of a hybrid electric vehicle. For this purpose, a fuzzy logic controller is developed, three inputs as the SOC, driver demand, and vehicle velocity are defined. Instead of torque or power requirement, which are commonly used as controller inputs in the literature, a more straightforward method is adopted by using the accelerator and brake pedal positions. The controller manages the engine power and regenerative braking intensity. A series hybrid electric vehicle model is created in the MATLAB/Simulink environment to validate the performance of the proposed controller. The proposed controller aims to keep the SOC between 30-40% after charge depleting mode, and ensures prevention of regenerative braking at high SOC values to prevent overcharging. Simulations have been performed according to NEDC and WLTC, show that the proposed controller is able to realize design objectives.

***Keywords:*** *Energy management, Fuzzy logic control, Modeling, Series hybrid electric vehicle*

Cite this paper as: Uysal, L.K., & Altın, N., Modelling and fuzzy logic based control scheme for a series hybrid electric vehicle. *Journal of Energy Systems 2023; 7*(1): 106-120, DOI: 10.30521/jes.1107190



**Nomenclature**

| | | | |
|---|---|---|---|
| **Abbreviations** | | $\theta$ | climbing angle |
| BWS | Battery Working State | $\rho$ | density |
| DP | Dynamic Programming | $Q_n$ | nominal charge |
| ECMS | Equivalent Consumption Minimization Strategy | $s$ | equivalence factor |
| EM | Electric Motor | $t$ | time |
| HEV | Hybrid Electric Vehicle | $V$ | velocity |
| ICE | Internal Combustion Engine | $\theta$ | climbing angle |
| LHV | Lower Heating Value | $\rho$ | density |
| NEDC | New European Driving Cycle | **Subscripts** | |
| SHEV | Series Hybrid Electric Vehicle | $U$ | upper limit |
| SOC | State of Charge | $a$ | air |
| SOH | State of Health | $acc$ | acceleration |
| WLTC | Worldwide harmonized Light-duty Test Cycle | $aero$ | aerodynamic |
| WLTP | Worldwide harmonized Light-duty vehicles Test Procedure | $bat$ | battery |
| **Symbols** | | $cha$ | charge |
| $A$ | cross-sectional area of the vehicle | $cl$ | climbing |
| $C_d$ | aerodynamic drag coefficient | $dem$ | demand |
| $F$ | force | $dis$ | discharge |
| $f_r$ | rolling resistance coefficient | $e/g$ | engine/generator |
| $g$ | the acceleration of gravity | $eq$ | equivalent |
| $m$ | mass | $f$ | fuel |
| $\dot{m}$ | fuel consumption rate | $L$ | lower limit |
| $P$ | power | $regen$ | regenerative braking |
| $Q_n$ | nominal charge | $roll$ | rolling |
| $s$ | equivalence factor | $trac$ | traction |
| $t$ | time | $v$ | vehicle |
| $V$ | velocity | | |

## 1. INTRODUCTION

Road transportation is an essential part of our lives. Since the invention of the starter motor and the first mass-produced vehicle, the number of vehicles with internal combustion engines have steadily increased. As a result, traffic-related problems also become a part of our lives. In addition, with the increasing number of vehicles and driving distances, another effect of vehicles has risen up. Today, road transportation is considered as an important factor in air pollution. To decrease this effect and some other concerns related to the energy security, people have started to focus on e-mobility solutions. Due to the policies of governments and manufacturers, the vehicle propulsion systems are being electrified. It is aimed that fully electric vehicles will dominate the market in next 20-30 years. It is observed that automotive manufacturers are abandoning developing or producing diesel engines and trying to increase their market share of electric vehicles. However, high prices, volumes and sizes, and limited range capacity of batteries used in the full electrical vehicles make the hybrid electrical vehicles (HEVs) attractive solution in this transition period. Many researchers have focused on different topologies, control schemes and other topic of HEVs.

Fully electric vehicles have higher operating efficiencies than the vehicles with the internal combustion engines due to the higher efficiency characteristics of the electrical components. In addition, they have simpler architectures with fewer components and are considered to be zero-emission vehicles, latter meaning they do not require emission management. The hybrid vehicles, on the other hand, have systems such as electrical machines such as generator and drive motor, battery, and power electronic converters in addition to the systems in conventional vehicles. The increasing number of components and efficiency characteristics of the components, which may conflict, necessitate energy management strategies. Energy management systems primarily aim to minimize fuel consumption while satisfying the driver's power demand. Some studies (i.e. Refs. [1,2]) also consider the battery aging in energy management systems.

There are various studies on energy management of series hybrid electric vehicles with a fuzzy logic controller. Johanyák and Ailer [3] developed a fuzzy logic controller for a series hybrid electric vehicle. A cost function was used to optimize the fuzzy rules. Liu et al., [4] developed a controller that consisting of two parts, namely fixed SOC control and range optimization for a series hybrid electric vehicle. The fuzzy logic controller was used for constant SOC control, and the ant colony algorithm was used for power flow control. Mahyiddin et al., developed a fuzzy logic controller for a series hybrid electric vehicle, and examined the effect of membership functions of different shapes and sizes on battery charge-discharge, concluding the trapezoidal and triangular membership functions were more effective in terms of fuel consumption [5]. Li and Sharkh in Ref. [6] implemented a fuzzy logic controller method to control the energy flow in the plug-in HEV. The fuzzy logic controller was used to decide the power distribution between the battery and the ICE based on a new variable they defined as the battery working state (BWS), considering both the SOC and the battery terminal voltage. With this new variable, it was aimed to prevent excessive charge or discharge of the battery when the SOC estimation was incorrect. Fuzzy logic was also used in the control schemes of parallel, series-parallel, and autonomous vehicles. Sher and Chen [7] applied fuzzy logic control for a parallel hybrid architecture and investigated the effect of the controller on engine efficiency and emissions as well as characteristics such as climbing and acceleration performance, which were not generally studied in the literature. Phan and Bab-Hadiashar [8] compared the performances of Type-1 fuzzy logic controller and an Interval Type-2 fuzzy logic controller for an autonomous parallel hybrid electric vehicle. They concluded that the Interval Type-2 controller outperformed the Type-1 controller but brought an implementation complexity. Singh and Bansal [9] used fuzzy logic to develop a controller based on torque demand, battery state-of-charge and regenerative braking for a series/parallel vehicle. They also ran the hardware-in-loop simulations.

The above mentioned studies prove that the fuzzy logic can successfully be applied to energy management systems of hybrid vehicles. In this study, a vehicle with series hybrid architecture is modelled and an energy management algorithm based on fuzzy logic controller is designed in order to keep the battery charge state constant at a certain level. A three-input two-output fuzzy logic controller is designed to reach design objectives. The SOC level, the output of the PI controller describing the driver commands, and the vehicle speed are determined as the inputs of the controller and explained with 7 and 4 membership functions, respectively. The change in ICE power and the regenerative braking state are determined as two output signals and given with 7 and 4 membership functions, respectively. Since the modeled vehicle is a plug-in HEV, the charge depleting mode is active until the SOC decreases to 35%. Then, the controller is enabled and kept the SOC in predefined range (30-40%). The proposed system is modelled in MATLAB/Simulink and the simulation studies are performed to verify the performance of the proposed controller according to NEDC and WLTP cycles.

## 2. CONTROL STRATEGIES FOR SERIES HYBRID ELECTRIC VEHICLES

Hybrid electric vehicles are basically classified as series, parallel, and series/parallel hybrid electric vehicles. Series hybrids are the simplest vehicles in these classes in terms of both configuration and energy management. In series hybrids, the internal combustion engine provides mechanical power to the generator and generates electricity. The generated electricity is used to charge the batteries or directly drive the electric motor depending on the vehicle's operating mode. As shown in Fig. 1, the ICE has no mechanical connection with the wheels, only the electric motor is used to drive the vehicle [10]. Various series hybrid architectures are possible, which including a single electric motor, two electric motors, and separate electric motor for each wheel, with or without gearboxes.

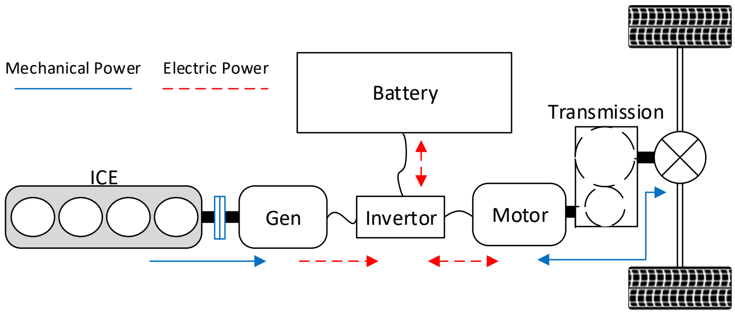



*Figure 1. The structure of the series hybrid electric vehicle.*

The fact that the ICE is not mechanically connected to the drive system provides flexibility to SHEVs, and the ICE/generator can be freely positioned in the vehicle. The need for transmission elements such as gearboxes can be eliminated. Thanks to the lack of mechanical connection, the ICE can be operated at the desired speed. Thus, the fuel consumption and emissions of the ICE can be reduced by operating it in a high efficiency zone, and engine downsizing becomes possible. Series hybrids are most efficient in urban traffic with a lot of stop-and-go [10].

The ICE, generator, and EM are designed to meet all the power requirement of the vehicle in series hybrid applications. As a result, weights, dimensions and costs increase. Another disadvantage of these vehicles is the number of energy conversions. The kinetic energy produced by the engine is converted to electricity by the generator, and converted back to kinetic energy by the traction motor [10]. A good energy management strategy enabling the decrease in ICE/generator losses and increase in efficiency in power electronics and electric motors would effectively overcome this drawback. A series hybrid drive system can operate in different modes depending on the driver's desire and driving conditions. These operating modes can be listed as follows [11]:

1) *Hybrid traction mode*: When there is a high power demand, both the ICE/generator set and the batteries provide energy to the drive motor.
2) *Battery only mode*: The energy needed by the electric motor is supplied only by the battery.
3) *ICE/generator mode only:* The power requirement is provided by the internal combustion engine/generator.
4) *Charging mode of the battery from the ICE/generator*: The battery must be charged when its energy drops to a certain minimum level. This can be provided by regenerative braking and the ICE/generator. However, generally the energy obtained from regenerative braking is not sufficient. The ICE/generator's surplus of power after EM's power demand is satisfied is used to charge the battery.
5) *Regenerative braking mode*: While the vehicle is braking, some of its kinetic energy is converted into electrical energy by the drive motor and the battery is charged.

The energy consumption of HEVs is largely dependent on energy management strategies. Energy management systems respond to instantaneous power demand from different energy sources while complying with various constraints. Although the energy management strategies applied in HEVs are diverse, they are generally considered in two groups as rule-based and optimization-based strategies [12,13]. In rule-based controllers, rules are created based on heuristics, engineering knowledge, and mathematical models. Optimization-based controllers work to minimize a cost function in a predefined trip. The cost function is a function generally defined as vehicle energy consumption or emissions [14]. Optimization strategies can be classified as global optimization and real-time methods. Global optimization methods, such as dynamic programming (DP), provide the optimum solution. These methods require complete knowledge of the road conditions and vehicle speed for a specific trip. Therefore, they are non-causal and are not applicable in real-time systems. Global optimization methods are generally used to evaluate other methods. Real-time optimization methods are causal methods. They either make short-term predictions of future conditions or work with the instantaneous data but are sub-optimal [15].

The rule-based methods are generally divided into two groups as deterministic and fuzzy logic methods. Fuzzy logic control systems have the advantages of robustness and adaptability. They are accepted to be suitable for the control of HEVs as they are suitable for multi-domain, nonlinear and time-varying systems [4,12,16]. The use of fuzzy logic controller can help circumvent the need for rigorous mathematical modeling [17].

The thermostat control strategy is the most basic series HEV control strategy with its simplicity, robustness and good fuel economy. [18]. In this strategy, the ICE/generator is operated entirely according to the battery SOC. When the battery charge reaches its maximum level, the ICE stops, the vehicle is driven by the battery energy. When the SOC drops to a lower level, the ICE is started and the battery is charged. The ICE can be operated continuously in the optimum efficiency zone [11]. A demonstration is given in Fig. 2. The method can be expressed as seen in Eq. 1:

$$S(t) = \begin{cases} 0 & SOC(t) \geq SOC_U \\ 1 & SOC(t) \leq SOC_L \\ S(t^-) & SOC_L < SOC(t) < SOC_U \end{cases} \tag{1}$$

Here $SOC_U$ and $SOC_L$ show the upper and lower limit of the SOC, $S$ is the state of the ICE/generator and $S(t^-)$ is the state in the previous time step.

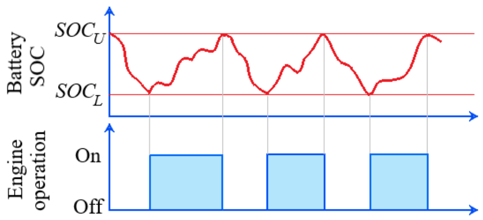


*Figure 2. Demonstration of thermostat control method.*

The power follower control system generally allows the primary source (ICE/generator) to track the engine load by considering the change in SOC. For low motor load and high SOC, the secondary source (battery) powers the vehicle. On the contrary, for high driving power or low SOC, the ICE/generator is operated to meet the load demand. These situations are given in Eq. 2 after Ref. [18]:

$$S(t) = \begin{cases} 0 & SOC(t) \geq SOC_U \text{ and } P_{dem} < P_{\min} \\ 1 & SOC(t) \leq SOC_L \text{ and } P_{dem} > P_{bat,max} \\ S(t^-) & SOC(t) \geq SOC_L \text{ and } P_{dem} < P_{bat,max} \end{cases} \quad (2)$$

Here $P_{min}$ is the minimum power of the ICE/generator, and $P_{dem}$ is power demand, and $P_{bat,max}$ is the maximum power the battery can provide.

The idea in Equivalent Consumption Minimization Strategy (ECMS) is to calculate the total fuel consumption as the sum of the actual fuel burned by ICE and the equivalent fuel consumption of the electric motor. Thus, the energy used in the battery and the ICE fuel consumption are represented jointly. The equivalent fuel consumption is calculated in real time as a function of current parameters measured by the system. A future prediction is not required and the control can be realized with a few control parameters. The only downside of this strategy is that the vehicle does not guarantee charging sustainability [10]. The ECMS strategy has received significant attention in the literature both as a management strategy and benchmark. The aim of this strategy is to minimize a fuel consumption function which is defined as follows [18]:

$$m_{eq} = \int_0^{t_f} \dot{m}_{eq}\, dt \quad (3)$$

$$\dot{m}_{eq} = \begin{cases} \dot{m}_f(P_{e/g}) - s_{dis}\dfrac{P_{bat}}{LHV}, & P_{bat} \geq 0 \\ \dot{m}_f(P_{e/g}) - s_{cha}\dfrac{P_{bat}}{LHV}, & P_{bat} < 0 \end{cases} \quad (4)$$

where $m_{eq}$ and $\dot{m}_{eq}$ are the equivalent consumption and equivalent consumption rate, $\dot{m}_f$ is the fuel consumption rate of the ICE/generator, $P_{e/g}$ is the power of the ICE/generator, LHV is the lower heating value of the fuel, $s_{dis}$ and $s_{cha}$ are equivalence factors to convert battery energy to fuel consumption during charging and discharging states.

In the maximum battery SOC control strategy, the demanded power requirement is met while keeping the battery charge level at a high value. The ICE/generator operates as a primary energy source and the battery as a secondary energy source. The constant high battery SOC allows continuous high performance operation. This strategy targets applications where performance is important [11]. Fig. 3 shows the operating modes according to the maximum SOC strategy.

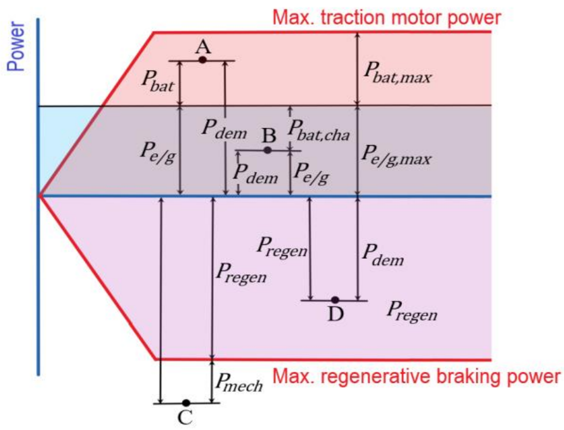



*Figure 3. Representation of maximum SOC strategy [11].*

In the figure, while point A represents the hybrid traction mode in which the ICE/generator and the battery operate together, point B shows the ICE/generator only mode. In this mode, excess power of the ICE/generator can be used to charge the battery. Point C represents the hybrid braking mode, both mechanical braking and regenerative braking take place. Point D shows regenerative braking only mode.

## 3. MATERIAL AND METHOD

In order to test the proposed controller, a series hybrid vehicle model is developed. For the model, the first generation Chevrolet Volt is taken as a base. Normally, the vehicle has different working modes than a standard series HEV. For instance, in high speed cruising mode, the generator is used as a traction motor, or in high power situations both the generator and traction motor are coupled to drive the vehicle. The vehicle is modeled as a series hybrid in the study, where the generator is only coupled to the engine and generates electricity. Details of the models and simulation data are given in this section. The information about the modeled vehicle and the values used in the simulation are listed in Table 1.

*Table 1. The vehicle and simulation data.*

| Parameter | Value |
|---|---|
| Curb weight | 1715 kg |
| Width | 1798 mm |
| Height | 1430 mm |
| Clearance from ground | 119 mm |
| Aerodynamic drag coefficient | 0.287 |
| ICE power | 63 kW@4800 rpm |
| Generator power | 55 kW |
| EM power | 111 kW |
| EM torque | 370 Nm |
| Battery | 16 kWh |
| Air density,$\rho$ | 1.225 kg/m3 |
| Rolling resistance coefficient, $f_r$ | 0.015 |

### 3.1. Models Used in the Simulations

The model shown in Fig. 4 is designed for simulation. According to the model, the driver uses the accelerator and brake pedals to reach a reference speed. The controller interprets the signal from the driver as drive and brake torques, and gives commands to increase the power of the ICE/generator or to perform regenerative braking by considering the speed and state of charge. PI signals greater than zero are interpreted as acceleration commands and electric motor is driven accordingly. Both the drive torque and the road resistances have effects on the vehicle. They are compared and new acceleration and velocity values are calculated. The actual speed is fed back to the PI controller. New speed and acceleration values are also sent to the resistance model to calculate new resistance values.

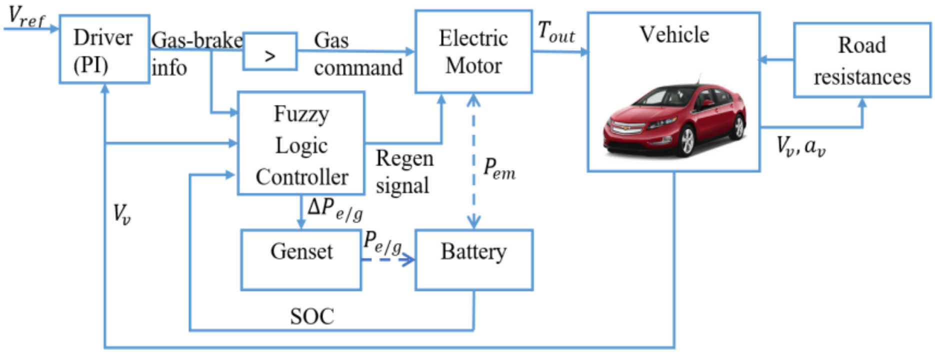


*Figure 4. Schematic of the model used in the simulation.*

### 3.1.1. Driver model

In order to simulate driver behavior, a model consisting of a PI controller which is so-called automatic driver is used. The reference speed (driving cycle) and the actual speed of the vehicle are inputs of this model. The driver model tries to follow the reference speed. When the reference speed is higher than the actual speed, PI output increases, and when the actual speed is higher, then PI output decreases. The output signal is saturated in the range of [-1, 1]; negative values are interpreted as brake and positive values are as gas commands.

### 3.1.2. Electric motor

Different methods can be used in electric motor modeling. One method is to use lookup tables based on the experimental data. Another method is to use the dynamic equations of the motor. These models are modeled with state-space equations. If the dynamics of each component are essential in a drive system, dynamic models are preferred as in Ref. [19].

In the study, the traction motor of the vehicle is a permanent magnet synchronous machine. The EM model is created by using the characteristic curves given in Fig. 5 with lookup tables. The signal from the PI controller is used in the electric motor model, and a linear relationship is established with the maximum torque value of the motor at that speed, and the torque value provided by the motor is calculated. Instantaneous efficiency value is obtained by using torque and motor speed.

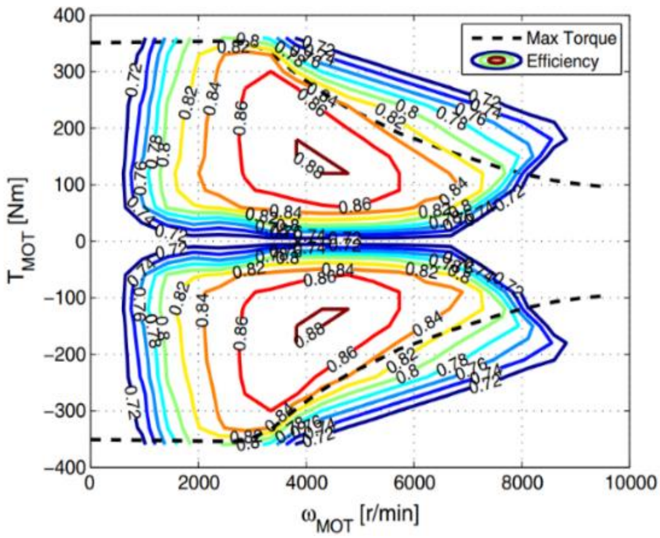


*Figure 5. EM torque and efficiency curves [20].*

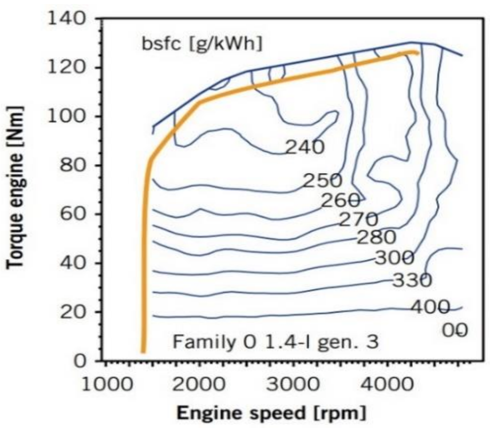
### 3.1.3. Regenerative braking

Regenerative braking is one of the most important advantages of hybrid electric vehicles over conventional vehicles. In city driving, about one-third to one-half of the driving energy is lost due to braking. Thanks to regenerative braking, some of this energy can be recovered and the driving range is prolonged [21]. In the model, the amount of the requested braking torque that the drive motor can supply is converted into electrical energy during braking. For the torque and conversion efficiency that the motor can provide, again the curves given in Fig. 5 are used. The portion of the graph with negative torque values represents regenerative braking. In the study regenerative braking is prevented at low speeds (<15 km/h) or high SOC (>98%) situations.

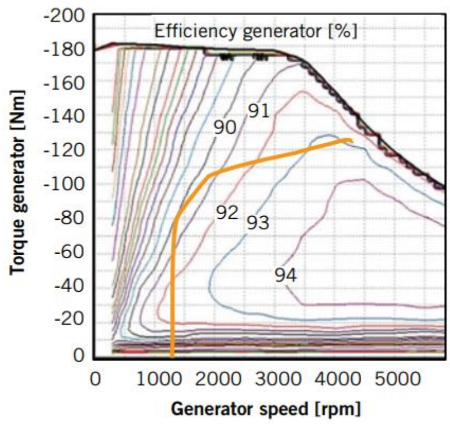
### 3.1.4. Internal combustion engine and generator

In the modeling of ICEs, dynamic equations can be used as well as characteristic curves obtained from test data. The ICE used in the simulations is 1.4 liter 3$^{rd}$ generation Family 0 engine. In the study, the ICE information given in Fig. 6 is used with the help of a lookup table, and it is assumed that the engine runs on the marked line following Ref. [22]. The generator should be appropriately selected to ensure that it is compatible with the power of the ICE. Besides, the ICE's high efficiency operating area and the efficiency region of generator should be compatible. If necessary, a reduction can be applied.

The ICE and the generator are connected via a coupling and operate at the same speed in the modeled system. The characteristic curves of the permanent magnet synchronous motor with a power of 55 kW are also given in Fig. 6.




*(a)*




*(b)*

*Figure 6. The specific fuel consumption map of the (a) ICE and (b) generator characteristics [22].*

### 3.1.5. Battery model

The variables such as battery SOC and state of health (SOH) cannot be directly measured on the battery. For this reason, battery models that can draw accurate results from measurable values are needed. [23,24]. Various methods have been developed for modeling batteries. These methods are generally grouped as electrochemical, statistical and equivalent circuit models.

In the electrochemical modeling approach, the battery internal structure is modeled, and its behavior is tried to be examined. It requires aware of many variables regarding the battery structure and the model created includes complex differential equations. In addition, many parameters such as the battery electrode thickness, the electrolyte current salt density, and the temperature capacity should be determined. The models describe the chemical processes taking place in the battery in detail. They are the most accurate models. However, they are complex, difficult to configure, and require high processing power [23,25,26,27].

In the statistical models, battery parameters are obtained by using the sample data sets. Tables or graphs giving the characteristics of the battery from the measurement results obtained for different operating conditions can be prepared and used in the simulations. Although they are not as accurate as physical models, they are simpler and faster methods. In the equivalent circuit models, the battery characteristics are tried to be expressed with basic electrical elements. They are simpler and faster than electrochemical models. Nevertheless, many experiments are required to create the required tables as in Ref. [25,28].

The Coulomb count method is used as a battery model in the study. This method measures the discharge current of a battery and integrates the discharge current over time to estimate the SOC. It can be modeled with a simple expression as follows:

$$SOC(t) = SOC(t-1) + (I(t)/Q_n)\,\Delta t, \tag{5}$$

where $Q_n$ is the nominal capacity and $I(t)$ is the discharge current [27].

### 3.2. Longitudinal Vehicle Dynamics

The vehicle dynamic model is defined by the force balance equation, where the total driving force is calculated as given in Eq. 6 including the sum of rolling resistance, aerodynamic drag, acceleration resistance and climbing resistance after Refs. [29,30]:

$$F_{trac} = F_{aero} + F_{acc} + F_{roll} + F_{cl} \tag{6}$$

where, $F_{aero}$ represents the aerodynamic drag force, $F_{acc}$ is the acceleration or inertial resistance, $F_{roll}$ is the rolling resistance, $F_{cl}$ represents the climbing resistance. $F_{trac}$ is the driving force that must be applied to the wheel to meet these resistance forces. Among them, the aerodynamic resistance is the resistance force created by the air on the vehicle. The turbulence region formed behind the vehicle is most effective in the formation of this resistance force. In contrast to the low pressure in this area, high pressure occurs in front of the vehicle, and the pressure difference causes resistance. The other factor is the friction force that occurs as the air passes through and across the vehicle. Due to the general structure of automobiles, the force caused by turbulence is much greater than the force caused by friction as in Ref. [24]. Eq. 7 may be used to calculate aerodynamic resistance force:

$$F_{aero} = 0.5 C_d \rho_a A (V_v - V_a)^2, \tag{7}$$

where, $C_d$ shows the aerodynamic drag coefficient of the vehicle, $\rho$ is the density of the air, $A$ is the cross-sectional area in the direction of travel, $V_v$ is the vehicle's speed, $V_a$ is the velocity component of the wind in the direction of the wind. $V_a$ can take negative values, meaning that the wind may be blowing in the vehicle's direction of travel. In this study, it is assumed that the air was still. In this case expression in Eq. 8 can be used for aerodynamic resistance:

$$F_{aero} = 0.5 C_d \rho_a A {V_v}^2 \tag{8}$$

The acceleration resistance is the force that must be applied to the vehicle to accelerate according to Newton's second law of motion. It can be represented by Eq. 9, where $m_v$ is the mass of the vehicle.

$$F_{acc} = m_v dV_v/dt \tag{9}$$

The rolling resistance is a resistance that occurs depending on the vehicle's weight and the tire's rotation. As the tire rotates on the road, the tire is constantly deformed with the vehicle's weight and this deformation creates a force contrary to the motion of the vehicle. Assuming that the tire pressure is constant, the rolling resistance is expressed by Eq. 10 [24].

$$F_{roll} = m_v g \cos\theta \, f_r \tag{10}$$

where $g$ is the acceleration of gravity, $f_r$ the rolling resistance coefficient, $\theta$ is the climbing angle. It should be noted that $f_r$ is heavily dependent on tire build and pressure. The hill resistance is the force caused by the component of vehicle weight parallel to the road. It does not always try to slow the vehicle down, but will try to accelerate it in case of downhill travel. The hill resistance can be expressed as follows:

$$F_{cl} = m_v \, g \sin\theta. \tag{11}$$

When each force expression is written into the relevant place in Eq. 12, Eq. 6 can be rewritten as,

$$F_{trac} = 0.5 C_d \rho_a A V_v^{\,2} + m_v dV_v/dt + m_v g \cos\theta \, f_r + m_v g \sin\theta. \tag{12}$$

This is the force balance on traction wheels. During the trip, the driver model demands torque from EM to satisfy this condition. In the simulations, the road gradient is not considered. Therefore, the climbing resistance is eliminated, and Eq. 12 is further simplified to Eq. 13:

$$F_{trac} = 0.5 C_d \rho_a A V_v^{\,2} + m_v dV_v/dt + m_v g f_r. \tag{13}$$

### 3.3. Fuzzy Logic Controller

The functions of the controller can be defined as keeping the battery SOC at specific values and managing regenerative braking. For these purposes, a fuzzy logic controller with three inputs and two outputs is designed. The SOC, output of the PI controller and the vehicle speed are determined as the inputs of the controller as seen in Fig. 7. While seven memberships are used to map the SOC and the output of the PI controller inputs, the velocity input is explained with two membership functions. Two controller outputs are the ICE power change and a coefficient determining the state of regenerative braking. The ICE power change is explained with 7 membership functions and 4 membership functions are described to generate the state of regenerative braking output. The controller lets the charge-depleting mode continue until SOC falls to a value of 35%, and then tries to keep the SOC between 30-40%.

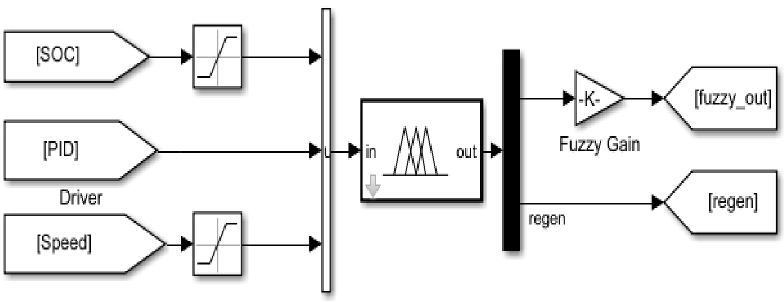
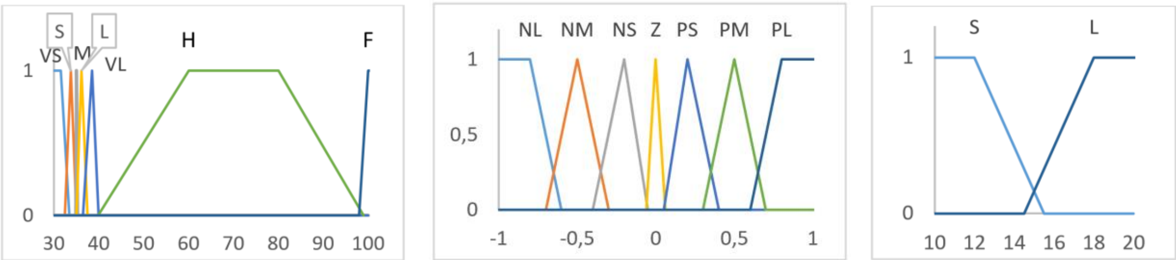



*Figure 7. The fuzzy controller model.*

Membership functions of three inputs are given in Fig. 8(a-c). The notation used here can be summarized as follows: "*Z*", "*S*", "*M*", and "*L*" are "*zero*", "*small*", "*medium*", and "*large*" respectively. "*P*" and "*N*" stand for "*positive*" and "*negative*", respectively. "*H*" is "*high*", "*F*" is "*full*", and "*V*" is "*very*". The SOC is intended to be kept between 30-40%, therefore several functions are placed in this interval. Function "*F*" is defined to prevent overcharging.

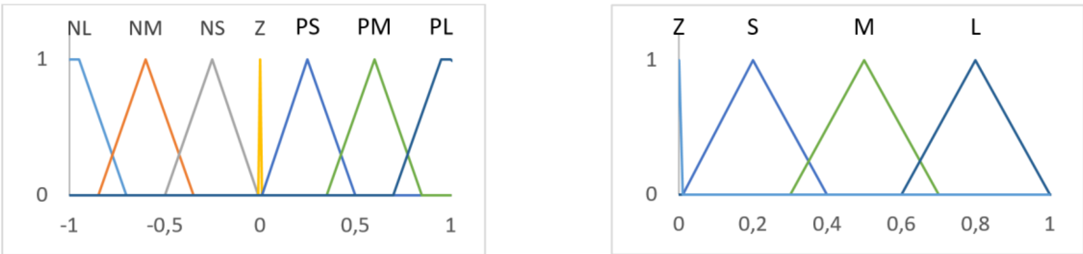



*(a)* *(b)* *(c)*

*Figure 8. Membership functions of (a) SOC, (b) driver, and (c) velocity inputs, respectively.*

For the driver input, seven partitions are created to ensure a proper distinction between the braking and acceleration. Membership functions for the speed input set the limit for regenerative braking.

Fig. 9(a,b) shows the controller's output membership functions. First output controls the ICE/generator power change. A value between [-1,1] is obtained depending on the driver's demand and the state of charge. A gain block is used afterward to calculate the actual change. Functions of regenerative braking output are triggered depending on the brake command of the driver.




*(a)* *(b)*

*Figure 9. Membership functions of (a) ICE/generator power change output and (b) regenerative braking output, respectively.*

Figs. 10(a,b) show the rules for regenerative braking and the ICE power change. Since there are three inputs, the input-output relationship of regenerative braking is represented with two three-dimensional surface maps.

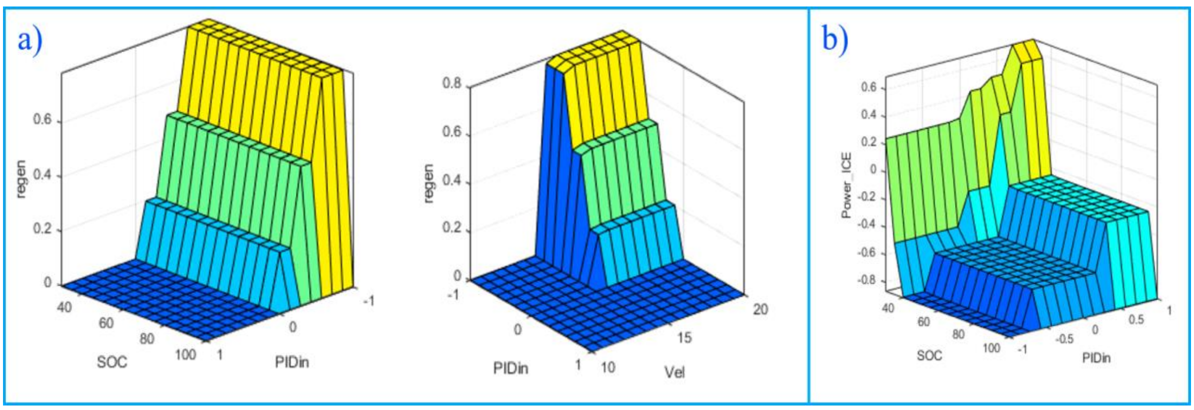
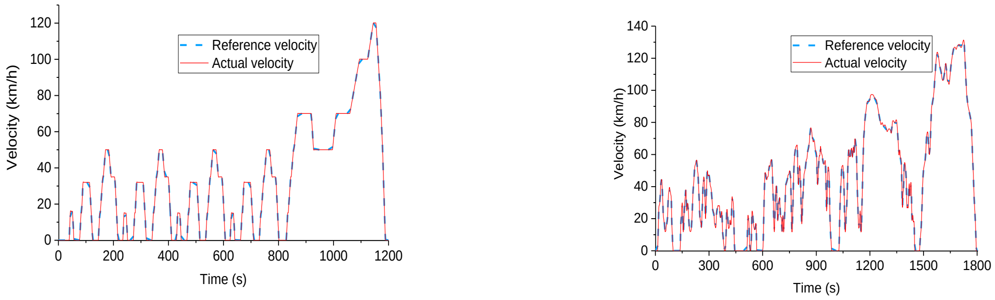



*Figure 10. Surface view of the rules for a) regenerative braking, b) the ICE power change.*

It can be noted that the SOC - velocity plane does not affect the rules. Rules are heavily dependent on driver demand. The velocity and SOC inputs are mostly there to set the limits for regenerative braking. ICE power change rules yield negative values above 40% SOC to stop the engine from charging the battery beyond this limit. The power of the ICE is only increased if the SOC is below 35%, or around 35% and the driver demand is high. This output yields the highest values when the SOC is very low and the demand is very high.

## 4. RESULTS AND DISCUSSION

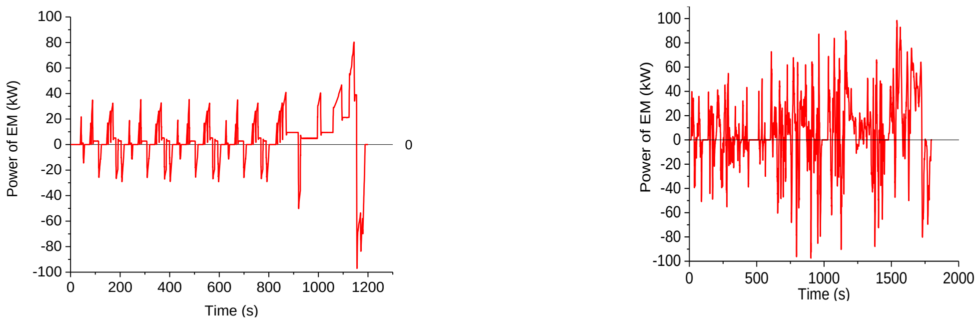
The reference velocity and the resulting velocity profiles for WLTC and NEDC simulations are shown in Figs. 11(a,b). The compatibility of the two curves in each graph shows that the driver model is working correctly and the vehicle can follow the driving cycle with great tracking accuracy.




*(a)* *(b)*

*Figure 11. Reference and actual velocities of (a) NEDC simulation, and (b) WLTC simulation.*

The EM power change during a single NEDC and a single WLTC are given in Fig. 12(a,b). Since NEDC is more monotonous than WLTC, the motor power curve also has a more monotonous appearance. In the WLTC simulation, EM has a more dynamic graph due to higher accelerations.




*(a)* *(b)*

*Figure 12. Electric motor power change in (a) NEDC simulation, and (b) WLTC simulation.*

Longer test cycles are better for analyzing the battery SOC change and fuel consumption. Therefore, NEDC is repeated ten times (110.2 km), and WLTC is repeated five times (116.3 km). The fuel consumption and SOC variation graphs obtained in the simulations are shown in Fig. 13(a,b). The NEDC consumption average is 3832 g/100 km, and the WLTC average is 5253 g/100 km. If the gasoline density is taken as 740 kg/m$^3$, values of 5.2 lt/100 km for NEDC and 7.1 lt/100 km for WLTC are obtained. Fuel consumption increases due to the more dynamic nature of WLTC. The SOC control was one of the targets of the controller. Since the simulated vehicle is a plug-in hybrid, the charge is allowed to drop to 35%. After that, the SOC is kept between 30-40% in both cycle simulations.

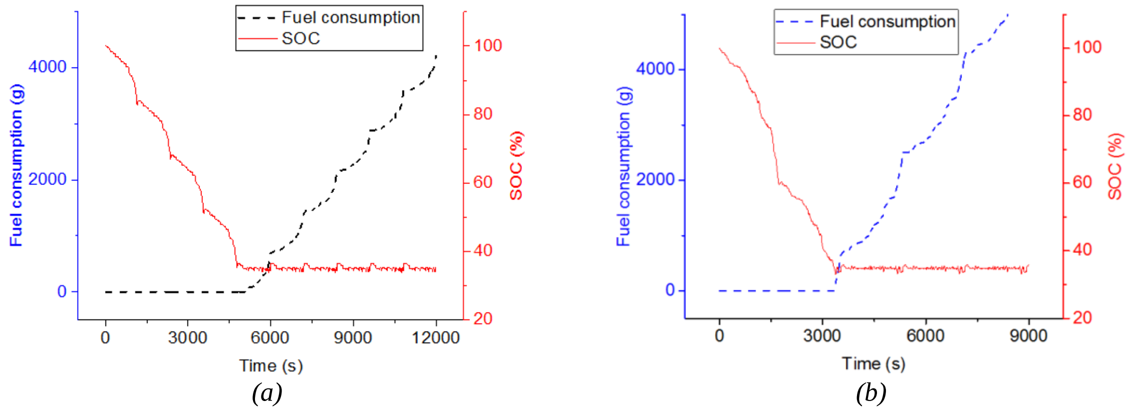



*Figure 13. Fuel consumptions and SOCs of (a) NEDC simulation, and (b) WLTC simulation, respectively.*

Fig. 14(a,b) show regenerative braking in different scenarios. In the first case, the SOC is above the upper level where charging is not allowed. The figure shows that the regenerative braking signal is "0" despite braking, and the regenerative braking does not occur in this situation. In the second case, the SOC is lower, so regenerative braking is allowed. The proposed controller allows the regenerative breaking and charging of the battery when the SOC is lower than the determined upper limit. At lower speeds, regenerative braking is disabled due to the physical limitations of the electric motor. This limit is accepted to be 15 km/h and defined by the velocity input of the controller.

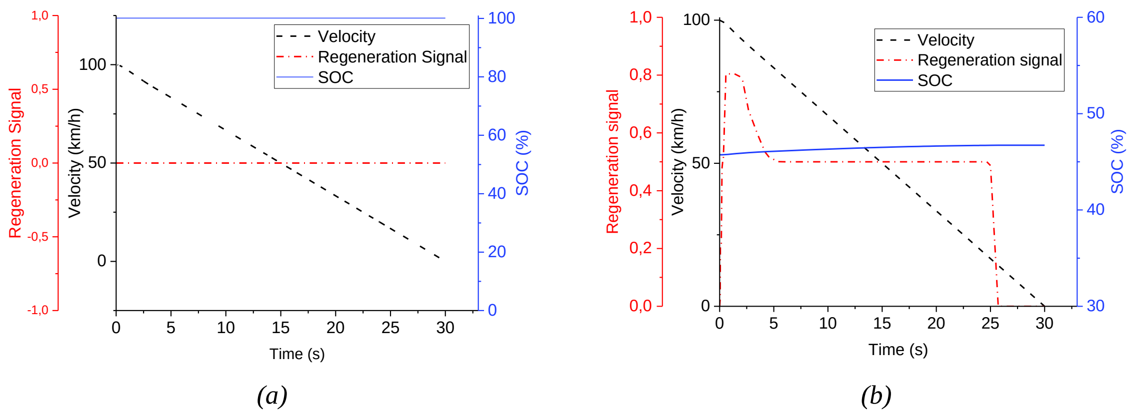



*Figure 14. Regenerative braking, when the SOC is (a) very high, and at (b) lower SOC levels.*

## 5. CONCLUSION

In this study, a fuzzy logic based controller for the energy management of a series HEV is proposed. The aim of the controller is to keep the state of charge between 30-40% after charge depleting mode and ensure that regenerative braking does not occur at high battery SOC to prevent overcharging. Therefore, a three-input two-output fuzzy logic controller is designed. In order to test the controller, a series hybrid model is created based on the first-generation Chevrolet Volt, and simulations are performed in the MATLAB/Simulink environment. The proposed controller is tested with NEDC and WLTC test cycles. Its performance on keeping the SOC level at desired region, decreasing fuel consumption and controlling the regenerative braking are explored. The results prove that despite the proposed controller is simple, it can keep the SOC between predetermined values, decrease the fuel consumption, and manage the regenerative braking.

The fuzzy control requires tuning of rules, which can be tedious with the increasing number of inputs and membership functions. Regardless the rules are dependent on human intuition; it can be set without the certainty of a mathematical model. This makes implementing rules easier, if not optimal. For optimal solutions, an optimization strategy such as DP can be considered, which is not in the scope of this study. Still, it may be possible to obtain better results by increasing membership functions or finding better membership functions than the existing ones.

**REFERENCES**


[1] Shafikhani, I, Sundström, C, Åslund, J, Frisk, E. MPC-based energy management system design for a series HEV with battery life optimization. In: 2021 European Control Conference (ECC). 29 June-2 July 2021.IEEE, Delft, Netherlands: pp. 2591-2596. DOI: 10.23919/ECC54610.2021.9655224

[2] Cheng, M, B. Chen, Nonlinear Model Predictive Control of a Power-Split Hybrid Electric Vehicle with Consideration of Battery Aging. *Journal of Dynamic Systems, Measurement, and Control* 2019;*141*(8): 081008.DOI: 10.1115/1.4042954

[3] Johanyák, Z, Ailer, PG, Göcs, L. A Simple Fuzzy Logic Based Power Control for a Series Hybrid Electric Vehicle.In: 6th International Scientific and Expert Conference of the International TEAM Society;6-8 Oct. 2015: Kecskemet, Hungary: pp. 207-212

[4] Liu, X, Fan, Q, Zheng, K, Duan, J, Wang, Y. Constant SOC control of a series Hybrid Electric Vehicle with long driving range. In: 2010 IEEE International Conference on Information and Automation; 20-23 June 2010: IEEE, Harbin, China:pp. 1603-1608. DOI: 10.1109/ICINFA.2010.5512260.

[5] Mahyiddin, S.H., Mohamed, M. R., Mustaffa, Z.,Khor, A. C., Sulaiman, M. H., Ahmad, H., Rahman, S. A.Fuzzy logic energy management system of series hybrid electric vehicle. In: 4th IET Clean Energy and Technology Conference (CEAT 2016); 14-15 Nov. 2016:Kuala Lumpur, Malaysia: Institution of Engineering and Technology, pp. 1-6.DOI: 10.1049/cp.2016.1267.

[6] Li, S.G., Sharkh, S. M., Walsh, F.C., Zhang, C.N. Energy and Battery Management of a Plug-In Series Hybrid Electric Vehicle Using Fuzzy Logic. *IEEE Transactions on Vehicular Technology* 2011; *60*(8):3571-3585.DOI: 10.1109/TVT.2011.2165571.

[7] Sher, F., Chen, S., Raza, A., Rasheed, T., Razmkhah, O., Rashid, T., Rafi-ul-Shan, P.M., Erten, B. Novel strategies to reduce engine emissions and improve energy efficiency in hybrid vehicles. *Cleaner Engineering and Technology* 2021; *2*: 100074. DOI: 10.1016/j.clet.2021.100074.

[8] Phan, D., Bab-Hadiashar, A., Fayyazi, M., Hoseinnezhad, R., Jazar, R.N., Khayyam, H. Interval Type 2 Fuzzy Logic Control for Energy Management of Hybrid Electric Autonomous Vehicles. *IEEE Transactions on Intelligent Vehicles* 2021; *6*(2): 210-220. DOI: 10.1109/TIV.2020.3011954.

[9] Singh, K, Bansal, H, Singh, D. Feed-forward modeling and real-time implementation of an intelligent fuzzy logic-based energy management strategy in a series–parallel hybrid electric vehicle to improve fuel economy. *Electrical Engineering* 2020; *102*: 967–987. DOI: 10.1007/s00202-019-00914-6

[10] Zhang, H, Cao, D, Du, H. Modeling, Dynamics and Control of Electrified Vehicles.NSW, Australia; Woodhead Publishing, 2017, pp. 123,168.

[11]Ehsani, M, Gao, Y, Emadi, A. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design. Boca Raton: CRC Press, 2010. pp. 254-258.

[12]Zhang, P, Yan, F, Du, C. A comprehensive analysis of energy management strategies for hybrid electric vehicles based on bibliometrics. *Renewable and Sustainable Energy Reviews* 2015;*48*: 88-104. DOI: 10.1016/j.rser.2015.03.093

[13]Bhaskar, P.B., Deshmukh, S., Khannan, P., Shaik, A.Recent Trends on Drivetrain Control Strategies and Battery Parameters of a Hybrid Electric Vehicle.*SAE International*2019; 1-12. DOI: 10.4271/2019-28-0155

[14]Basma, H., Mansour, C., Halaby, H., Baz Radwan, A.Methodology to Design an Optimal Rule-Based Energy Management Strategy Using Energetic Macroscopic Representation: Case of Plug-In Series Hybrid Electric Vehicle.*Advances in Automobile Engineering* 2018; *7*(3): pp. 1000188-1000188.DOI: 10.4172/2167-7670.1000188.

[15]Zhang, B., Zhang, J., Xu, F., Shen, T. Optimal control of power-split hybrid electric powertrains with minimization of energy consumption. *Applied Energy* 2020; *266*: 114873. DOI: 10.1016/j.apenergy.2020.114873.

[16]Bayındır, K, Gözüküçük, M, Teke, A. A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. *Energy Conversion and Management* 2011; *52*: 1305-1313.DOI: 10.1016/j.enconman.2010.09.028.

[17]Chen, Z, Zhang, X, Mi, CC. Slide Mode and Fuzzy Logic Based Powertrain Controller for the Energy Management and Battery Lifetime Extension of Series Hybrid Electric Vehicles. *Journal of Asian Electric Vehicles* 2010;*8*(2): 1425-1432.DOI: 10.4130/jaev.8.1425.

[18]Shabbir, W, Evangelou, SA. Threshold-changing control strategy for series hybrid electric vehicles. *Applied Energy* 2019; *235*: 761-775. DOI: 10.1016/j.apenergy.2018.11.003.
[19]Zoroofi, S. Modeling and Simulation of Vehicular Power Systems.MSc, Chalmers University of Technology, Göteborg, Sweden, 2008.
[20]Onori, S, Tribioli, L. Adaptive Pontryagin's Minimum Principle supervisory controller design for the plug-in hybrid GM Chevrolet Volt. *Applied Energy* 2015; *147*: 224-234. DOI: 10.1016/j.apenergy.2015.01.021.
[21]Pan, C, Wang, J., Dai, W., Chen, L., Chen, L. Constant current control for regenerative braking of passive series hybrid power system. *International Transactions on Electrical Energy Systems* 2020; *30(11)*: e12577. DOI: 10.1002/2050-7038.12577.
[22]Grebe, UD, Nitz, LT. Voltec – The Propulsion System for Chevrolet Volt and Opel Ampera. *ATZ Auto Technology* 2011; *11*(2): 28-35.
[23]Muratoğlu, Y, Alkaya, A. Elektrikli Araç Teknolojisi ve Pil Yönetim Sistemi – İnceleme [Electric Vehicle Technology and Battery Management System – Review]. *Elektrik Mühendisliği* 2016; *458*: 10-14.
[24]Lim, D.Y., Im, J.K., Choi, J.H., Chung, G.B.PSIM Simulator for Analysis of Series HEV Operation. *The Transactions of the Korean Institute of Power Electronics* 2010; *15*(6)*:*487-497. DOI: 10.6113/TKPE.2010.15.6.487.
[25]Omar, N., Widanage, D., Abdel Monem, M., Firouz, Y., Hegazy, O., Van den Bossche, P., Coosemans, T., Van Mierlo, J. Optimization of an advanced battery model parameter minimization tool and development of a novel electrical model for lithium-ion batteries. *International Transactions on Electrical Energy Systems* 2014; *24*(12): 1747-1767. DOI: 10.1002/etep.1815.
[26]Wang, Y., Tian, J., Sun, Z., Wang, L., Xu, R., Li, M., Chen, Z. A comprehensive review of battery modeling and state estimation approaches for advanced battery management systems. *Renewable and Sustainable Energy Reviews* 2020; *131*: 110015. DOI: 10.1016/j.rser.2020.110015.
[27]Manthopoulos, A, Wang, X. A Review and Comparison of Lithium-Ion Battery SOC Estimation Methods for Electric Vehicles. In: IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society,18-21 October 2020: IEEE, Singapore: pp. 2385-2392.
[28]Jongerden, M, Haverkort, BR. Battery Modeling. Enschede, Holland:Centre for Telematics and Information Technology, University of Twente, 2008.
[29] Williamson, S., Energy Management Strategies for Electric and Plug-in Hybrid Electric Vehicles. New York,USA: Springer,2013.
[30] Chen, B, Evangelou, SA, Lot, R. Series Hybrid Electric Vehicle Simultaneous Energy Management and Driving Speed Optimization. *IEEE/ASME Transactions on Mechatronics* 2019; *24*(6): 2756-2767. DOI: 10.1109/TMECH.2019.2943320.