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Energy Management System in Battery Electric Vehicle Based on Fuzzy Logic Control to Optimize the Energy Consumption in HVAC System

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Abstract: This particular research has been conducted at University Putra Malaysia (UPM) to investigate the applicability of fuzzy logic technique in enhancing the energy management of battery-powered electric vehicle (BEV). Because of the increasing demand of BEVs, there is a need to increase the battery power while fulfilling the conflicting of battery power needs and power consuming needs for motor and auxiliaries (such as HVAC). The balance between keeping the comfort of HVAC use and increasing the battery range is complicated and the support of Artificial Intelligence can be useful. The study integrated an energy management system, which is using the designed Fuzzy Logic strategy, to enhance the drain of battery power capacity. The simple black box design of the EMS system has two inputs, State of Charge (SoC) and Speed, and three outputs, Heated Seats, Front HVAC, and Rear HVAC. The membership functions of output fuzzy of the Front HVAC, which shows that every output has three equal categories, 1/3, 2/3, 3/3, associated with low, mid, and high. The same approach of membership functions is applied for Rear HVAC, and Heated Seat. The three outputs of the HVAC system assumed to have a constant load of 1000 Watt each and have three equal categories, low, medium, and high. The fuzzy logic design uses a strategy of nine rules. The simulation is applied on MATLAB Simulink environment and the tests are using two driving cycles, the New European Driving Cycle (NEDC) and Japan 10-15. The results show that using the managed HVAC strategy can increase the battery driving range by 9.8-20.4% compared with the full-unmanaged HVAC strategy.

Keywords: Energy Management System; Battery Electric Vehicle; Fuzzy Logic Controller; HVAC System; Driving Cycles; State of Charge; Energy Consumption

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1. Introduction

Increasing damaging effects of climate change and exhausting of crude oil supplies have encouraged governments as well as vehicle industry to create alternate transport solutions to meet up with the needs of higher efficiency, low noise, and climate friendly emission. Battery Electric Vehicles (BEVs) are created as a zero emission design of transportation[1] [2]. Recently, the advancement of power storage technologies, electrical design, and manufacturing make the use of BEVs feasible. However, increasing the driving range of BEVs is one of the main challenges to spread worldwide. The driving range is restricted to the accessible battery power that is certainly restricted by the battery-pack design restrictions, e.g. size, price, and amount. The minimal driving range along with its incorrect estimation might make the owners cut their day trips smaller to be able to stay away from driving stranded (range anxiety) [3].

Huge production of fuel-based vehicles has increased worldwide worries on energy conservation as well as setting protection goals to environment. The historical worries are associated to the depletion dread of world top power dealer (fossil fuels) while the latter; worries are associated to the implications of pollution emissions produced by fuel consumption. These worries, make the production and development of battery electric vehicles (BEVs) in worldwide demand a feasible alternative solution [4].

Today many companies try to balance the battery usage for enhancing the accessible battery capacity, raising the driving range, and extending the battery lifetime. In the majority of the remedies to enhancing the driving range as well as battery lifetime, the quantity of the energy needed by HVAC system must be managed to reach the most efficient power control approach [1].

At present, the primary key challenge of BEV is the minimal driving range as BEV depends on battery as the one source of energy. The battery thus, should have adequate power to travel the planned range and provide all driving force as well as auxiliary loads. However, by raising the capacity of battery to boost the power capability is only going to imply a penalty on the vehicle weight and cost. An encouraging method to boost the power efficiency is by applying energy management system (EMS) to control the power by command and matching the electrical power flow inside HVAC system to obtain optimum method effectiveness [5].

This particular study is aiming to increase the battery range of BEV, since the primary key challenge of BEV is the limitation in driving range as BEV depends on battery as its lone source of energy. Additionally, this particular study has been testing the feasibility of Fuzzy Logic controller to enhance the efficiency of HVAC system and then increase the battery range of BEV.

In this particular research, Fuzzy Logic Controller is utilized in the Battery Electric Vehicle Model (BEV) to manage the energy consumption from HVAC System. Additionally, BEV design was simulated mathematically based on Backward-Facing approach technique at the MATLAB software package. Furthermore, the study is using the technical specifications of the LG-Proton IRIZ BEV. Additionally, for travel simulation two approaches have been used the New European Driving Cycle (NEDC) and Japan10-15. The results of the proposed EMS system implementation are revealed three empirical scenarios for validation, SoC without HVAC load, SoC with HVAC full-unmanaged load and SoC with HVAC controlled load by fuzzy-logic controller.

2. Battery Electric Vehicle Model

2.1 Simulink Modelling of Proposed BEV

The modelling of proposed BEV has been performed in the MATLAB-Simulink environment and ADVISOR [6], [7]. The vehicle is configured according to Backward Facing model and consists of; Transmission, Electric Motor, Battery Charge Controller, DC-DC Converter, Driving Cycle, and Longitudinal Vehicle Dynamic Model, Auxiliary Load Model. The mathematical equation for battery state of charge (SoC) is given as the following [8]:

$$SoC = (C_{max} - C_{used}) / C_{max} \qquad (1)$$

Where SoC is the state of charge, C_{max} is the maximum capacity of the energy storage system, and C_{used} is the used capacity of the energy storage.

The proposed BEV model is designed based on the technical specifications of the LG-Proton IRIZ BEV to be mapped with the Malaysian standards [2]. In this research, the vehicle simulation model was an improved model adopted from a previous design, which has been proposed by the authors in a previous academic paper. The New European driving cycle (NEDC) and Japan 10-15 driving cycle have been used. In addition, the proposed energy management system (EMS) is based on a Fuzzy Logic controller and is integrated into the BEV design to control the HVAC consumption.

2.2 Battery Electric Vehicle Technical Specification and Drive Cycle

In this Research, the technical specifications of the PROTON IRIZ (BEV) have been used [2]. Table 1 shows the desired specifications. Moreover, in this research has been used The New European driving cycle (NEDC) and Japan 10-

15 driving cycle as shown in Table 2 and Figures 1 and 2. In European driving cycle, urban limit is at 50 km/h and highway limit is at 120 km/h. In Japan 10-15 driving cycle, urban limit is at 40 km/h and highway limit is at 70 km/h.

Table 1 - LG-Proton IRIZ BEV technical specification [6]

Drivetrain Parameters	
Drive System	Front wheel drive
Curb Weight	918 Kg
Adds wright (Cargo)	56 Kg
Gross Weight	1516 kg
Wheel/Axe	Front Wheel Drive 195/55R15 (Standard)
Accessories	Variable ACC_Small_Car
Powertrain	EV – Manual – PTC_EV
Rated Voltage	330 V
Rated Capacity	39.6 Kwh, 120 Ah
Rated Lifetime	10 years \ 160,000 km
Motor Type	PMAC (YASA-400)
Max Output	116 Kw
Max Torque	360 Nm
Transmission	Single Speed 3.37:1
Normal Voltage	56V *6 Module=330V
Total Cells	60 6 * Module=360 Cells
Total Weight	360 1.5 * Kg=540 Kg

Table 2 - The New European driving cycle (NEDC) and Japan 10-15 driving cycle Information [9]

No	Cycle Name	Uses	Distance (M)	Duration (S)	Average Speed (Km/h)	Max Speed (Km/h)
1	NEDC Cycle	Inside City for Small Car	11017	33.6	1108	120.09
2	Japanese 10-15 Cycle	Inside City for Small Car	4165	22.7	660	70.09

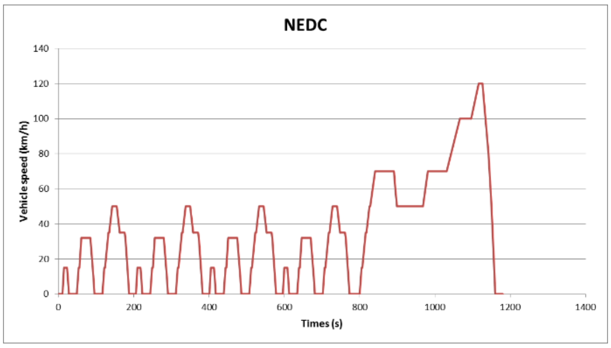

Fig. 1 - New European Driving Cycle (NEDC) [9]

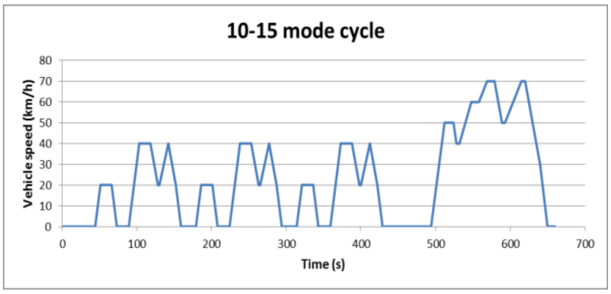

Fig. 2 - Japan 10-15 Driving Cycle [9]

3. Methodology

The proposed model is a refined model, which is designed based on the components of the MATLAB-Simulink and ADVISOR tool [7]. The vehicle is configured according to Backward Facing Model as in Figure 3 and consists of; Transmission, Electric Motor, Battery Charge Controller, DC-DC Converter, Driving Cycle, and Longitudinal Vehicle Dynamic Model, Auxiliary Load Model, and AI controller.

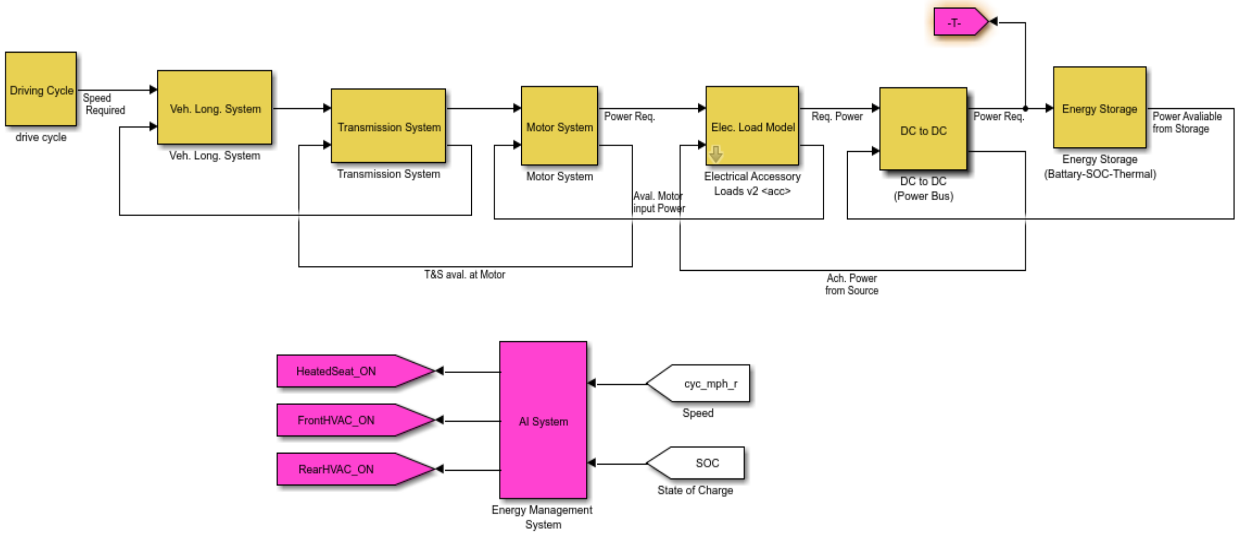

Fig. 3 - BEV Model Simulation with Fuzzy Logic Controller

3.1 Design of Energy Management System Strategy

The study integrated an energy management system, which is using the designed Fuzzy Logic strategy, to enhance the drain of battery power capacity. The simple black box design of the EMS system has two inputs, State of Charge (SoC) and Speed. Moreover, it has three outputs, Heated Seats, Front HVAC, and Rear HVAC.

3.2 Fuzzy Logic Controller

Fuzzy logic is one of the artificial intelligences (AI) techniques that employed in BEV-Fuzzy Logic integration to control the HVAC power consumption. As seen in Figure 4 the block design of the Fuzzy Logic controller (FLC) consists of two inputs State of Charge (SoC) and Speed, and three outputs, Heated Seats, Front HVAC, and Rear HVAC.

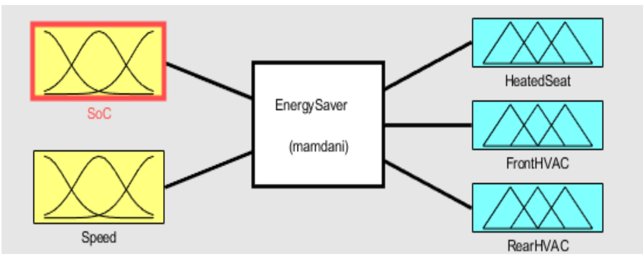

Fig. 4 - Fuzzy Logic Controller

To obtain the most efficient load consumption, of the three desired HVAC components, two inputs are used to drive the controller:

- SoC: represents the remaining capacity of the power storage system and scaled as a percentage fraction from 0 to 100.
- Speed: represents the active automobile speed, which is coming from the driving cycle simulation and measured in km/h

Figure 5 shows the membership functions of input fuzzy of the SoC input, which shows that every input has three equal categories, 1/3, 2/3, 3/3, associated with low, mid, and high. The same approach of membership functions is applied for speed input. The study used Centroid defuzzification method.

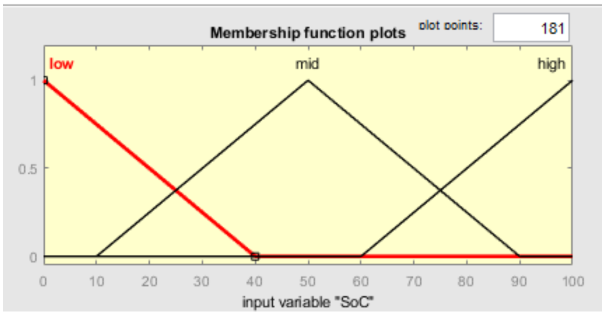

Fig. 5 - The membership functions of the input, SoC

The three desired HVAC components are:

- Front HVAC: represents the main HVAC, which facilitates the driver, and measured in watt with the assumption of fixed load off 1000 watt.
- Rear HVAC: represents the main HVAC, which facilitates the passengers, and measured in watt with the assumption of fixed load off 1000 watt.
- Heated Seat: represents the auxiliary seat heating in modern vehicles, which facilitates the driver, and measured in watt with the assumption of fixed load off 1000 watt.

Figure 6 shows the membership functions of output fuzzy of the Front HVAC, which shows that every output has three equal categories, 1/3, 2/3, 3/3, associated with low, mid, and high. The same approach of membership functions is applied for Rear HVAC, and Heated Seat. The study used Centroid defuzzification method.

The fuzzy logic strategy is depending upon the number of inputs and its categorical structure. The particular design of this study assumed that the two inputs have three equal categories, low, medium, and high. The three outputs of the HVAC system assumed to have a constant load of 1000 Watt each and have three equal categories, low, medium, and high. For simplification, the three outputs are controlled as one group. As seen in Table 3, the possible inputs and outputs are nine, which are the outcome of the nine rules that sets the fuzzy logic algorithm or strategy. The rules of the fuzzy logic strategy are as the following:

1. If {(SoC is high)} and (Speed is low)} then {(Heated Seat is high) and (Front HVAC is high) and (Rear HVAC is high)}
2. If {(SoC is high)} and (Speed is mid) then {(Heated Seat is high) and (Front HVAC is high) and (Rear HVAC is high)}
3. If {(SoC is high)} and (Speed is high) then {(Heated Seat is mid) and (Front HVAC is mid) and (Rear HVAC is mid)}
4. If {(SoC is mid)} and (Speed is low) then {(Heated Seat is mid) and (Front HVAC is mid) and (Rear HVAC is mid)}
5. If {(SoC is mid)} and (Speed is mid) then {(Heated Seat is mid) and (Fr0ntHVAC is mid) and (Rear HVAC is mid)}
6. If {(SoC is mid)} and (Speed is high) then {(Heated Seat is low) and (Front HVAC is low) and (Rear HVAC is low)
7. If {(SoC is low)} and (Speed is low) then {(Heated Seat is low) and (Front HVAC is low) and (Rear HVAC is low)}
8. If {(SoC is low)} and (Speed is mid) then {(Heated Seat is low) and (Front HVAC is low) and (Rear HVAC is low)}
9. If {(SoC is low)} and (Speed is high) then {(Heated Seat is low) and (Front HVAC is low) and (Rear HVAC is low)}

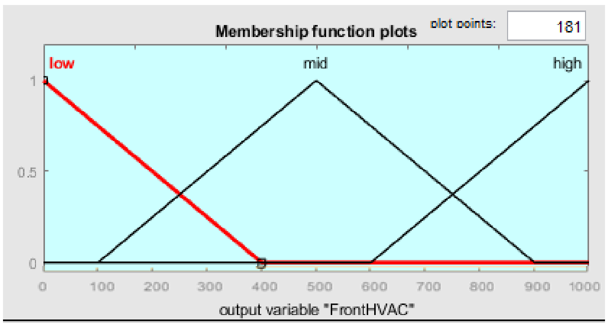

Fig. 6 - The membership functions of the output, Front HVAC

Table 3: Inputs and outputs for membership function

Input		**Output**		
SoC Status	**Speed Status**	**Heated Seats**	**Front HVAC**	**Rear HVAC**
High	Low	High	High	High
High	Medium	High	High	High
High	High	Medium	Medium	Medium
Medium	Low	Medium	Medium	Medium
Medium	Medium	Medium	Medium	Medium
Medium	High	Low	Low	Low
Low	Low	Low	Low	Low
Low	Medium	Low	Low	Low
Low	High	Low	Low	Low

4. Findings

In this particular research, three scenarios have been performed to examine the proposed BEV-Fuzzy design. The first scenario is the basic design with no HVAC load at all, the second scenario is the basic design with full-unmanaged HVAC load and the third scenario is the Fuzzy logic integrated design with controlled HVAC load. The three scenarios have been performed to measure the SoC-Time consumption score, which scaled in second how long it takes to drain the SoC from 100% to 0%. The three measures are applied two times for two different driving cycles, NEDC and Japan 10-15.

4.1 Simulation Results of Basic System Model with No HVAC Load

The basic model with no HVAC load could be a good reference score. In actual automobile specifications, manufacturers normally report a score for maximum range, which refers to the maximum travel time/distance for a full power tank of capacity. For this study, the maximum travel range is 31884 seconds (NEDC) and 46098 seconds (Japan 10-15). For the basic model with no HVAC load and based on the NEDC driving cycle, the automobile can travel for 297.6 km within 8.86 hours in an average speed of 33.6 km/h. For the basic model with no HVAC load and based on the Japan 10-15 driving cycle, the automobile can travel for 290.7 km within 12.8 hours in an average speed of 22.7 km/h. Figures 7 and 8 show the related SoC scores.

4.2 Simulation Results of Basic System Model with Full-Unmanaged HVAC Load

The basic model with full HVAC load is essential, as it is the control status when comparing success of the proposed integrated fuzzy design. With the assumption of a constant accumulative load of 3000 watt for HVAC system, the travel range will be reduced by a significant rate. For this study, the travel range is 20774 seconds (NEDC) and 25726 seconds (Japan 10-15). For the basic model with full HVAC load and based on the NEDC driving cycle, the automobile can travel for 193.9 km within 5.77 hours in an average speed of 33.6 km/h. For the basic model with full HVAC load and based on the Japan 10-15 driving cycle, the automobile can travel for 162.2 km within 7.15 hours in an average speed of 22.7 km/h. Figures 9 and 10 show the related SoC scores.

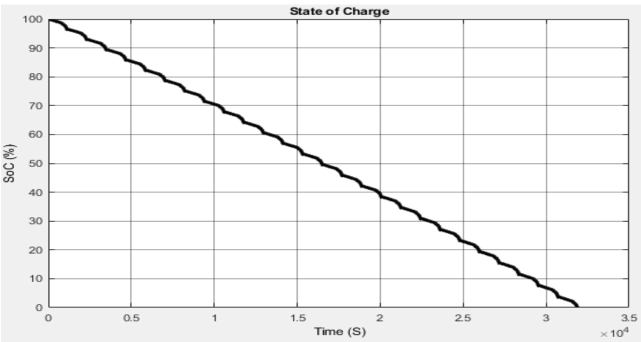

Fig. 7 - SoC of the Basic Model with No HVAC Load (NEDC)

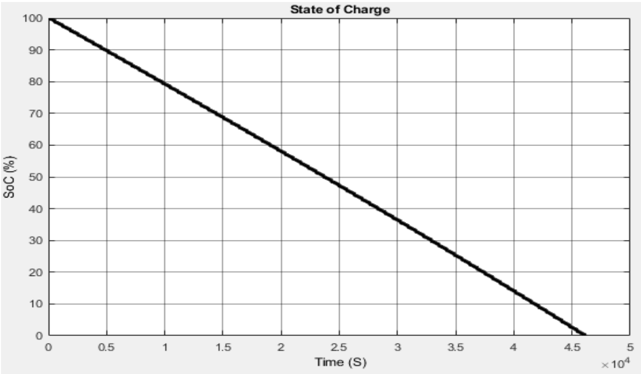

Fig. 8 - SoC of the Basic Model with No HVAC Load (Japan 10-15)

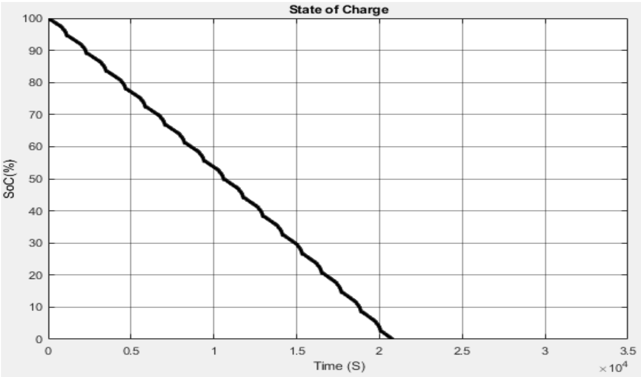

Fig. 9 - Soc of the Basic Model with HVAC Full-Unmanaged Load (NEDC)

Fig. 10 - SoC of the Basic Model with HVAC Full-Unmanaged Load (Japan 10-15)

4.3 Simulation Results of Fuzzy Controller Integrated Model with Controlled HVAC Load

The fuzzy logic integrated model with controlled HVAC load is essential, as it is the outcome measure which must be improved compared with the control status. With the assumption of a maximum accumulative load of 3000 watt for HVAC system, but controlled by a fuzzy logic strategy, the travel range must be significantly increased. For this study, the travel range is 25013 seconds (NEDC) and 28255 seconds (Japan 10-15). For fuzzy logic integrated model with controlled HVAC load and based on the NEDC driving cycle, the automobile can travel for 233.5 km within 6.95 hours in an average speed of 33.6 km/h. For fuzzy logic integrated model with controlled HVAC load and based on the Japan 10-15 driving cycle, the automobile can travel for 178.2 km within 7.85 hours in an average speed of 22.7 km/h. Figures 11 and 12 show the related SoC scores.

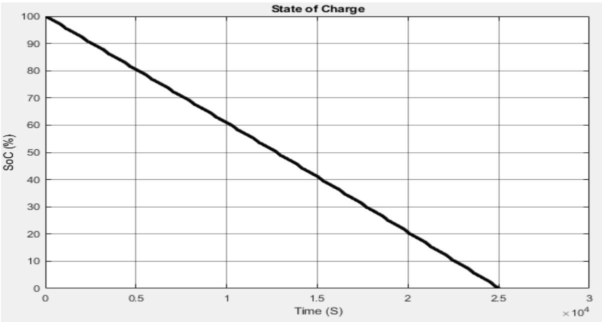

Fig. 11 - SoC of the Fuzzy Logic Integrated Model with HVAC Controlled Load (NEDC)

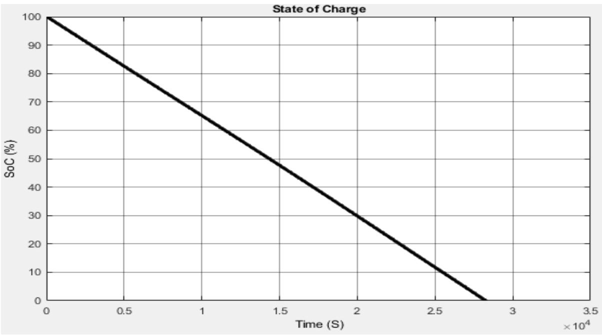

Fig. 12 - SoC of the Fuzzy Logic Integrated Model with HVAC Controlled Load (Japan 10-15)

5. Discussions

It is clear that implementing the fuzzy logic strategy can improve the power consumption of HVAC system and retain the power capacity for motor torque and speed. Based on NEDC driving cycle, the maximum SoC is 31884 seconds, which is dramatically reduced by 34.8% with HVAC full load to reach 20774 seconds. However, integrating fuzzy logic strategy can recover 20.4% of the power and the SoC can reach 25013 seconds. Figure 13 shows an integrated comparison diagram of the three scenarios. In addition, based on Japan 10-15 driving cycle, the maximum SoC is 46098 seconds, which is dramatically reduced by 44.2% with HVAC full load to reach 25726 seconds. However, integrating fuzzy logic strategy can recover 9.8% of the power and the SoC can reach 28255 seconds. Figure 14 shows an integrated comparison diagram of the three scenarios.

Both figures indicate that the proposed fuzzy logic integrated model is working properly. The Fuzzy Logic Controller situation shows a rational variance of power capacity that is increasing up as time passes (SOC). As a result of the smart power degradation of the HVAC components, the discharging rate is becoming significantly better with a percentage of 9.8-20.4%. The driving cycle of Japan 10-15 has less average speed and more travelling time when compared with NEDC, so it is rational to have a higher power consumption as well and a higher enhancement rate for integrating the fuzzy logic system. Comparing the rational cross tabulation results between the two driving cycles and the three scenarios supports the validity of the simulation behaviour and the results as well. Table 5 shows the summary of the results.

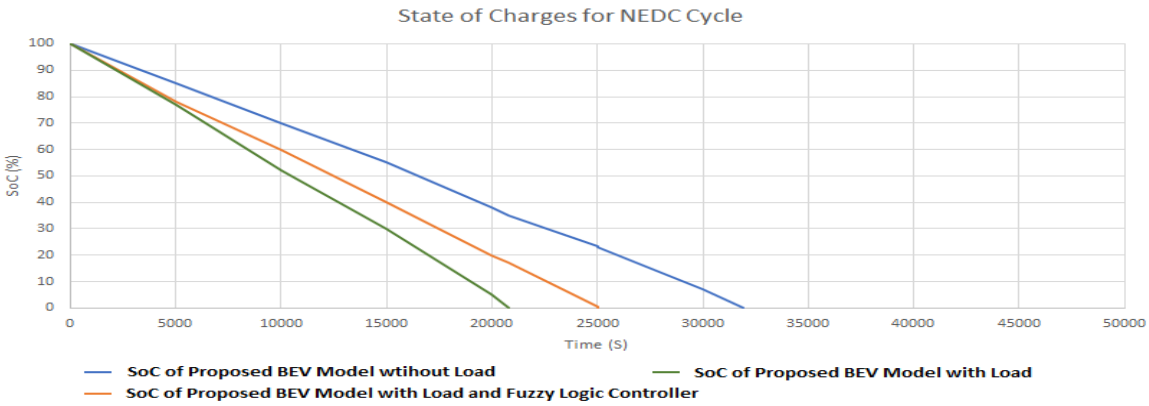

Fig. 13 - SoC Comparison Diagram Between the Three Scenarios (NEDC)

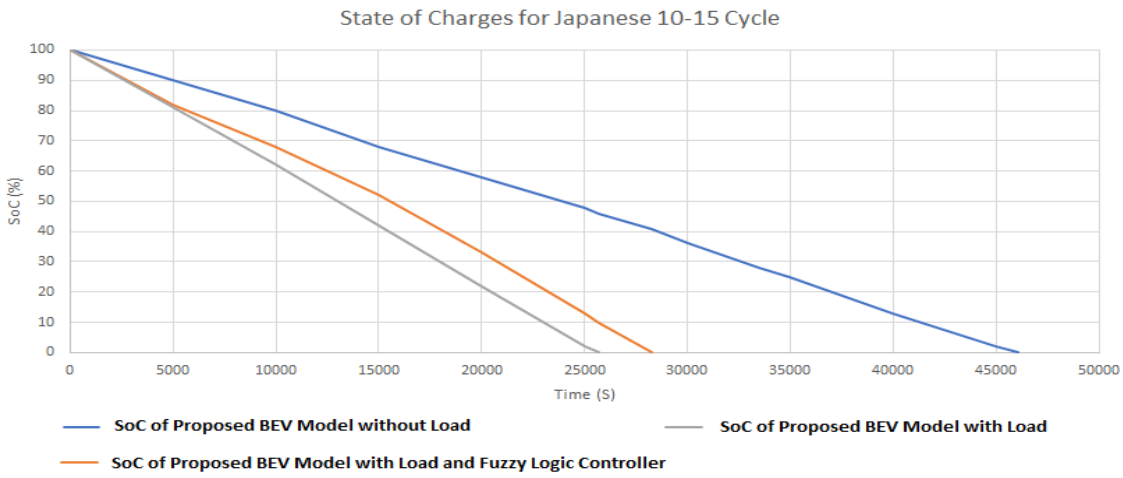

Fig. 14 - SoC Comparison Diagram Between the Three Scenarios (Japan 10-15)

Table 5 - SoC Comparison Between the Three Scenarios

Driving Cycle	SoC Measures			Full Consumption Rate (%)	Fuzzy Enhancement Rate (%)
	Basic Model	Basic Model with HVAC	Integrated Fuzzy Model with HVAC		
NEDC	31884	20774	25013	34.8%	20.4%
Japan 10-15	46098	25726	28255	44.2%	9.8%

6. Conclusion

In this particular research, a fuzzy logic integrated model is proposed to intelligently control and manage the behavior of HVAC power consumption. The fuzzy logic strategy has nine possible statuses based of two variables, SoC and Speed. The proposed design is a MATLAB-Simulink model, which is found to be valid based on the ration behavior and comparisons between different scenarios.

The study is performed with the assumption that fuzzy logic controller with proper strategy can significantly save power capacity and increase the travel range in BEVs. Findings for NEDC driving cycle proved the success the research assumption as the enhancement rate reached 20.4%. In addition, finding for Japan 10-15 driving cycle have a similar confirmation with 9.8% of enhancement rate.

The study is limited to the configuration of the LG-Proton IRIZ specification, therefore examining the model with different specification is proposed for future work. Examining the proposed design by using different driving cycles and maybe designated driving cycles is also proposed for future work. In addition, integrating more variables to the fuzzy logic strategy can provide different results, which are also proposed for future work. Finally, integrating different artificial intelligent techniques are a main objective for the upcoming proceeding work of this in-going research.

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