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Charging and Discharging Process Analysis of Energy Management System Strategy Towards Battery Aging in Series Configuration Hybrid Vehicle

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Abstract

Batteries, crucial for hybrid and electric vehicles, inevitably experience capacity loss over time due to regular usage, known as battery aging. The degradation is influenced by factors like the C-rate, depth of discharge (DOD), and temperature variations. This study delves into a hybrid series-configured vehicle that integrates both a battery and an engine generator as primary energy source. The primary objective revolves around determining an optimal energy management system (EMS) that mitigates battery aging effects. Testing was conducted across varying speeds: 17 km/hour, 30 km/hour, and 50 km/hour, involving two operational modes—full electric and hybrid. The engine-generator activation was contingent upon the battery's state of charge (SOC) set at 40% and 60%, operating consistently at 7000 RPM and 7500 RPM. Data collected from these experiments facilitated the assessment of battery aging, simulated through MATLAB Simulink software. The findings highlighted that the most favorable battery aging occurred at 50 km/hour when the engine generator was engaged at 60% SOC and operated at an engine speed of 7500 RPM. Notably, the hybrid mode showcased superior battery longevity, particularly at higher speeds.

Keywords: Battery aging, energy management system, electric vehicle, life cycle

1. Introduction

Vehicles can't be separated from supporting human activities. The vehicle population currently reaches around 1.14 billion and 99% of them are dominated by internal combustion engines (ICE) [1]. [2] predicted, that in the next 20 years, human activities will still be dependent heavily on ICE vehicles. The usage of fossil fuels can't be separated from the threat of global warming. Combustion of fossil fuel becomes the main contributor to CO2 gas production [3].

Utilization of Battery Electric Vehicle (BEV) and Hybrid Electric Vehicle (HEV) will be an alternative for decreasing fossil fuel consumption [4]. HEV uses 2 sources of energy to energize the vehicle, i.e. ICE and a battery with an electric motor [5]. With this technology, the travel range extends while maintaining lower fuel consumption [6]. Hybrid vehicles can be classified as series systems, series-parallel systems, and parallel systems [7]. In a series system, vehicle propulsion is only provided by an electric motor, and ICE is used to charge the battery [8,9].

The ICE will drive a generator, whose output current is directed to the battery and electric motor. The battery will supply the electrical power required by the electric motor according to the power needed for vehicle propulsion. Therefore, the battery becomes a critical component in a series hybrid vehicle that relies solely on the electric motor as its main source of propulsion. The battery must be capable of storing sufficient energy, possessing high energy efficiency, good discharge capability, effective charging acceptance, and a long cycle life [10].

During the charging and discharging phases, the battery undergoes degradation due to the reversible processes experienced by its electrochemistry, consequently reducing its maximum capacity. This phenomenon is known as battery aging. The primary stress factors contributing to battery aging include C-rate (current rate index value), depth of discharge (DOD), and temperature [11].

The amount of energy either being expelled or retained by the battery depends on both the driving cycle and the charging system. The high amperage charging/discharging process will affect linearly the temperature generated by the battery. Rising battery temperature leads to a decrease in battery lifespan [12]. Higher temperatures accelerate and intensify the chemical reactions within the battery, consequently enhancing its capacity. Nevertheless, in elevated temperatures, excessively active battery elements can adversely affect the battery's health.

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Fundamentally, the cathode material forms a passive layer by reacting with the anode, but under higher temperatures, it interacts with salts and metal oxides originating from the cathode material [13].

This study involves observing the current flow during the charging and discharging processes while varying the vehicle's speed, aiming to assess its impact on battery life by considering the primary stress factors affecting the battery. The engine generator and battery performance will be optimized using an EMS algorithm. By combining a 100Ah capacity battery with an Internal Combustion Engine (ICE), the goal is for the vehicle to cover a 50 km distance, mirroring the average daily vehicle usage in the Surabaya region as observed in previous tests by Hasoloan, 2019. The research will implement 15 EMS algorithms that adjust the vehicle's speed, battery SOC levels triggering the engine generator, and ICE speeds.

These tests will measure battery temperature, SOC, amperage, capacity, and the time taken to reach the 50 km distance. Subsequently, an analysis of battery aging and life cycles will be conducted. The acquired data aims to determine the most optimal EMS algorithm for the series hybrid vehicle.

2. Experimental Method

This research employs two methods: experimentation and simulation. Experiments are conducted to determine the battery characteristics under varying speed loads and engine-generator activation. These battery characteristics serve as input parameters for simulating battery aging using MATLAB Simulink. The simulation aims to assess battery degradation and predict the vehicle battery's lifespan under aging conditions, considering C-rate, DOD, and temperature. This method of analyzing battery life is known as the in-vehicle aging test.

Figure 1. PHEV ITS car

2.1. Vehicle Specification

In this research, the research subject used is the PHEV ITS car. This car features a series of hybrid powertrain configurations. The car has three driving modes: full electric driving mode, hybrid driving mode, and charging mode. This car utilizes $LiFePO_4$ batteries arranged in a series of 15 and 2 in parallel, resulting in a battery pack with a capacity of 100Ah 48V. The battery pack is equipped with an Orion Jr2-type Battery Management System (BMS). Table 1 shows vehicle specifications and main components of the PHEV ITS car.

2.2. Experiment Method

The testing was carried out using various tools to facilitate data collection as shown in Figure 2. Data was gathered at one-minute intervals. The current data per time interval will be used to estimate battery usage cycles. Battery voltage and SOC data will help understand battery characteristics, while temperature data will be used to calculate the thermal time constant and thermal resistance.

Table 2 illustrates the experimental design for the Rule-Based energy management system, indicating the different levels of variation. In Figure 2, U, V, and W denote the three phases of a BLDC motor. The experiments involved combining various levels of each parameter. The gathered data will unveil how the current rate affects temperature and DOD during charging and discharging processes after a 50 km distance.

The test results will be used to ascertain the actual condition of the battery in each applied mode on the vehicle. These results will then be processed to serve as input parameters for simulating battery aging using MATLAB Simulink.

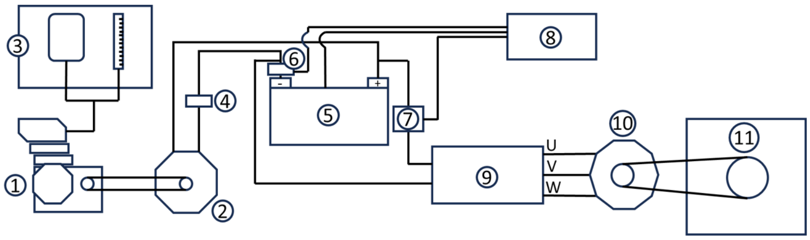
2.3. Thermal Time Constant and Thermal Resistance

The cell temperature measurements during testing will be averaged and used as the film temperature for calculating the thermal time constant and thermal resistance. To determine the thermal resistance value, equation 1 and equation 2 are used.

$$R_{t,conv} = \frac{1}{hA_s} \quad (1)$$

Table 1. PHEV ITS component specification

Component	Specification		
Electric Motor: Golden Motor 10 kW 48V	Maximum Power (Pm)	Kw	10
	Maximum Torque	Nm	29.2 @3442 RPM
	Speed	RPM	3442-4733
ICE: Honda CB150R 149cc 4-stroke	Maximum Power (Pe)	kW	12.4
	Maximum Torque	Nm	13.8 @ 5468 RPM
	Speed	RPM	2750-9500
Battery cell: LiFePO4 GB System Prismatic Battery 50Ah	Cell Voltage	V	3.2
	Capacity	Ah	50
	Standart charge current	A	12.5
	Max. charge current	A	50
	Max. continuous discharge rate	A	150
	Internal resistance	mΩ	≦0.6
	Cycle life	Cycle	3000 @ 0.5C
	Working temperature	^{o}C	-80
Alternator: Werner DC F60AD	Efficiency	%	95
	Output voltage	V	48-57
	Rated power	kW	5
	Peak power	kW	7.5



Note :
1. ICE
2. Alternator
3. Fuelflow meter
4. Clampmeter
5. Battery
6. Current sensor
7. Contactor
8. Battery Management System
9. Controller
10. Electric Motor
11. Dynamometer

Figure 2. Vehicle performance test schematic

Table 2. Experimental design

EMS Rule Parameter	Unit	Level 1	Level 2	Level 3
Vehicle Speed	Km/hour	17	30	50
Engine RPM	RPM	7000	7500	-
Battery SOC	%	40	60	-

$$R_{t,cond} = \frac{1}{kA_s} \quad (2)$$

$R_{t,cond}$ represents the thermal resistance of conduction, whereas $R_{t,conv}$ represents the thermal resistance of convection. h denotes the convective coefficient, and k denotes the conduction coefficient. The surface area for heat transfer is symbolized by A_s. Equation 3 is used to find the thermal time constant τ_t.

$$\tau_t = \frac{1}{hA_s}(\rho V c) \quad (3)$$

Completing equation 1, equation 3 are characterized by ρ denoting the object's density, V representing the object's volume, and c signifying the object's specific heat capacity.

2.4. Battery Aging Simulation Model

The battery datasheet, as well as voltage and SOC during testing, are input into the generic battery model block (LFP battery). The discharge/charge current for each driving mode (T_1 to T_{15}) from the test will be used as input, representing the current profile passing through the battery during its lifecycle. The temperature, processed into thermal resistance and thermal time constant, is input into the heat generation parameter in the generic battery model block. The block diagram in MATLAB Simulink is formed using several components available in the library as shown in figure 3. The generic battery model is used to model the *LiFePO*$_4$ battery utilized in the PHEV ITS vehicle.

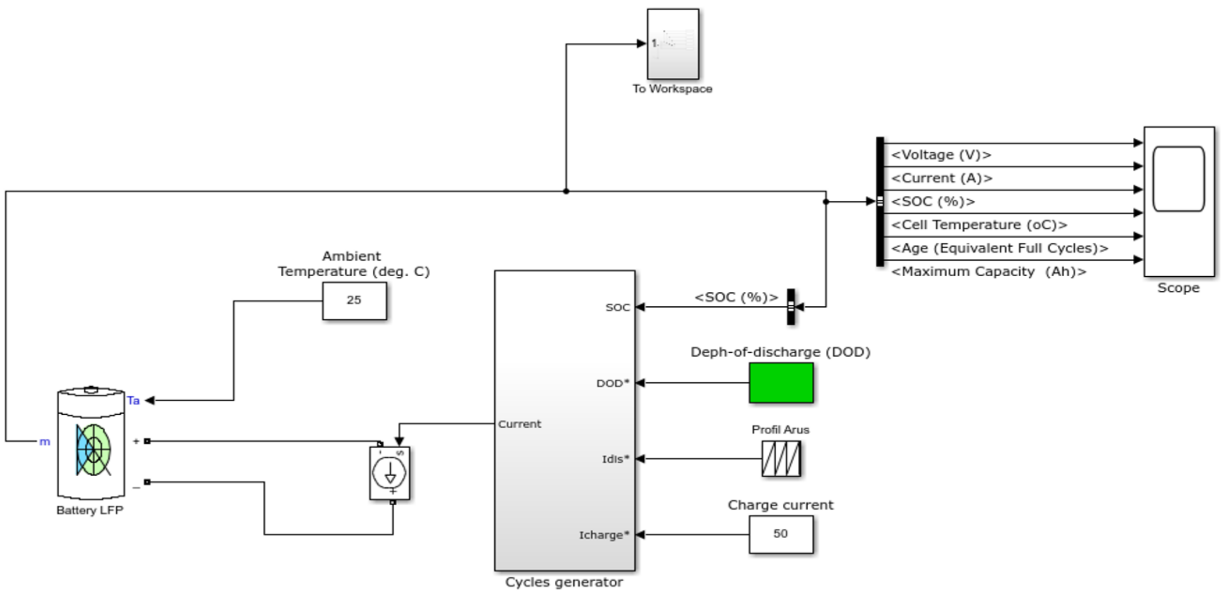


Figure 3. Battery aging prediction MATLAB modeling

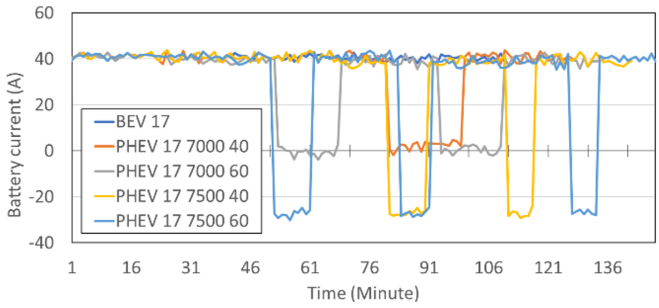


Figure 4. Battery current rate at a speed of 17 km/h

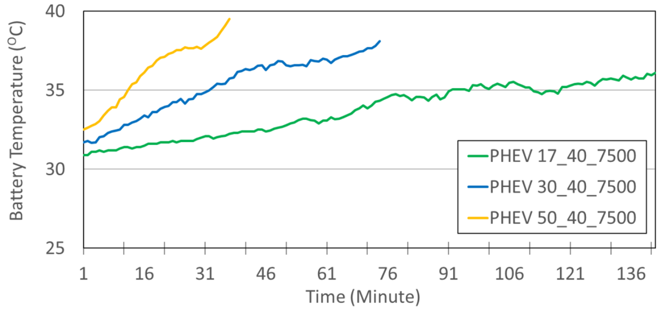


Figure 5. Rate of temperature increase in the battery at each speed in PHEV hybrid mode

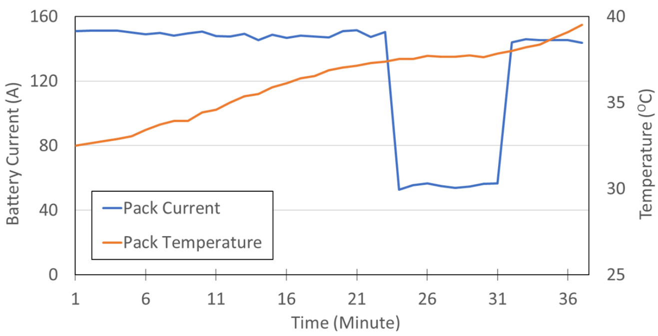


Figure 6. Comparison of current rate and temperature increase in battery cells over time in the PHEV 50_40_7500 test

The simulation results represent a type of battery cycle life test using the in-vehicle aging test method. This method is employed to assess the battery's performance after undergoing the same driving cycle for days and compare it with other driving cycles. From this data, the rate of battery aging until reaching End of Life (EOL) due to the provided driving cycle conditions and temperature can be estimated. The results of this simulation will serve as recommendations and be applied to the PHEV ITS car.

3. Result and Discussion

3.1. Analysis of Test Result

The variations in the speed load and generator RPM applied to the PHEV ITS car affect the rate of current imposed on the battery to meet the power requirements of the electric motor.

In Figure 44, at 17 km/h, the battery discharges at 40 A (0.4C) to the electric motor. In hybrid mode at 7000 RPM, the engine generator provides power (1.8 kW) with a current ranging from 34 A to 38 A, occasionally leading to a charging phase (-0.42 A to 4.7 A). At 7500 RPM, generator power increases to 3.2 kW with a current range of 63 A to 66 A, causing the battery to enter a full charging phase (-24 A to -28 A). The higher voltage of the generator compared to the battery enables it to easily meet the power demand from the electric motor [14].

3.2. Heat Generation in the PHEV ITS Battery

Variations in the speed and generator rpm provided to the PHEV ITS car influence the rate of current loaded into the battery to meet the power needs of the electric motor for vehicle propulsion. Different current rates will affect the temperature changes in the battery [14].

In Figure 5, initial and final temperature differences are shown for the PHEV hybrid mode (engine-generator on, SOC 40%, engine rpm 7500) at different speeds. Notably, at 50 km/h, temperature increases more than at 30 km/h and 17 km/h. The temperature rise with speed loading is non-linear over time. When the engine generator is activated, there are observable changes in the temperature trend: at 50 km/h (minutes 23-30), 30 km/h (minutes 47-56), and 17 km/h (minutes 80-90). This occurs as the battery's current rate decreases with the generator assisting the power supply to the motor.

In a PHEV 50_40_7500 test case (Figure 6), at minute 23, the battery's SOC touches 40%, activating the engine generator. The discharge current drops from ±150A to ±54A, leading to a smoother temperature increase. In hybrid mode, cell temperature reaches 37.5°C and slowly rises to 37.8°C by minute 30. To prevent engine overheating as the temperature approaches 100°C, the engine generator is turned off again at minute 31.

Figure 7 illustrates temperature changes in different driving modes, with higher currents causing larger temperature variations. Temperature changes are influenced by PHEV driving time and speed, as higher speeds result in greater power output and faster heat growth in the battery. Theory suggests that an increased discharge rate and high charging current can generate more heat due to energy losses from internal resistance within the battery cells. Tests confirm that adding an engine generator as an additional power supply significantly reduces the battery workload. This helps maintain an ideal temperature condition, lowering the risk of battery damage.

3.3. Battery Aging Analysis

Simulation testing of PHEV ITS hybrid mode with the engine generator active at SOC 40%, engine rpm 7000, and speed of 30 km/h for one year (figure 8) showed a battery capacity decrease of 1.6% from the initial 100 Ah. The PHEV ITS full electric mode at 30 km/h has a capacity of 98.4 Ah. In this scenario, reaching End of Life (EOL) would take approximately 12 years and 6 months, suggesting a slight slowdown in battery aging. The engine generator reduces current load, lessening stress on battery cells, and the Depth of Discharge (DOD) is lower compared to PHEV 30 km/h in full electric mode.

Simulation testing of PHEV ITS hybrid mode with the engine-generator active at SOC 40%, engine rpm 7000, and speed 30 km/h for one year (figure 9) resulted in a 1.5% decrease in battery capacity, reaching 98.5 Ah in full electric mode at 50 km/h. With an initial 100 Ah capacity, reaching EOL is estimated at approximately 13 years and 3 months. Engine-generator activation at SOC 60% allowed two starts before overheating, providing slight additional travel time. In terms of battery aging, the extra power at SOC 60% delays reaching SOC by 9 months compared to activation at SOC 40%, aligning with the theory that a lower DOD during battery cycling slows down aging, including the formation of the Solid Electrolyte Interface (SEI) layer.

Table 3 displays MATLAB Simulink simulation results for battery aging in the PHEV ITS. Predictions for time to End of Life (EOL) and distance to EOL under ideal conditions show battery life and capacity. This in-vehicle aging test method considers cycles, current rate, operational temperature, and Depth of Discharge (DOD). It compares battery capacity reduction, indicating that PHEV hybrid mode at 17 km/h with engine-generator activated at SOC 60% and engine rpm of 7500 exhibits the most favorable battery aging rate. In summary, hybrid driving modes significantly improve battery performance percentages.

Table 4 illustrates how the PHEV ITS car battery lifespan improves with the hybrid mode. The most significant enhancement is seen when comparing PHEV full electric and PHEV hybrid modes at 50 km/h. Higher discharge currents show slightly larger generator-supplied power at the same rpm compared to lower speeds. This is due to increased voltage drop across the battery, creating a higher potential difference between the generator and the battery, benefiting battery performance.

In line with theory, battery stress factors include C-rate, temperature, and DOD. Test and simulation results confirm that the PHEV ITS driving mode effectively slows down battery aging and maximizes total distance traveled. Using the engine generator as an additional power supply proves quite effective in preventing faster battery damage.

In comparison to adding an ICE to the Mitsubishi iMiev, this study shows similar results to the iMiev [15]. Adding an ICE can increase the vehicle's range, but using an ICE with high charging power may speed up battery aging. A strategic approach to ICE utilization with the appropriate output power can slow down battery aging, leading to a longer lifespan [15].

The difference in how batteries age between our study and the iMiev lies in the iMiev's more frequent use of its ICE, which consistently produces high power. In contrast to the PHEV ITS, the iMiev's ICE speeds up the battery charging process, completing cycles more quickly. The PHEV ITS, with its maximum ICE power, has a smaller C-rate charging value compared to the iMiev, resulting in a longer time to complete a battery cycle. However, it's important to note that the PHEV ITS has a shorter driving range compared to the iMiev.

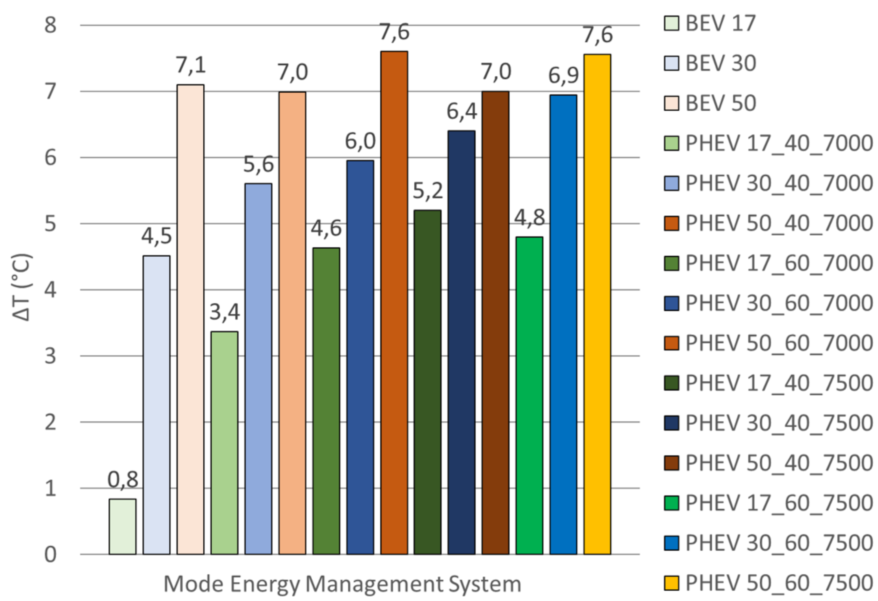


Figure 7. Magnitude of temperature changes for each driving mode

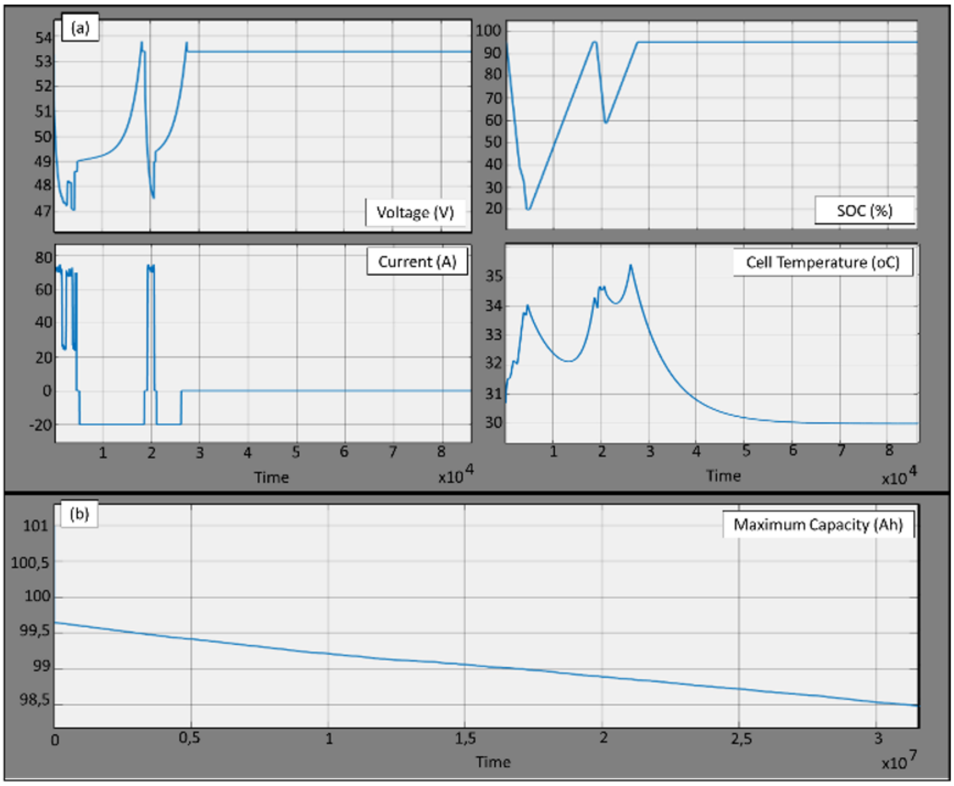


Figure 8. (a) battery current, voltage, SOC, and temperature conditions of PHEV 30_40_7000 within a day. (b) decrease in battery capacity of PHEV 30_40_7000 over a year.

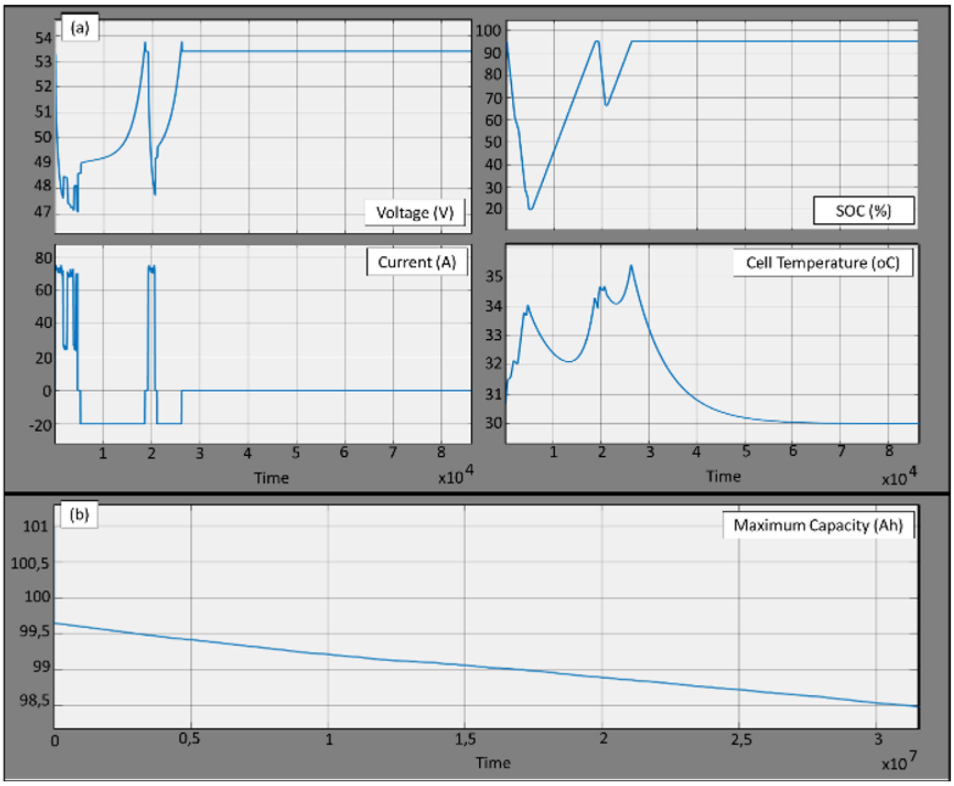


Figure 9. (a) battery current, voltage, SOC, and temperature conditions of PHEV 30_60_7000 within a day. (b) decrease in battery capacity of PHEV 30_60_7000 over a year.

Table 3. Comparison of battery performance until reaching End of Life (EOL)

EMS	Capacity (Ah)	Time to EOL (years)	Distance to EOL (km)
PHEV 17 full electric	98,34	12 years	220103,2
PHEV 30 full electric	98,29	11 years 9 months	214017,5
PHEV 50 full electric	96,64	5 years 10 months	108631,0
PHEV 17_40_7000	98,73	15 years 9 months	287837,8
PHEV 30_40_7000	98,39	12 years 6 months	227050,1
PHEV 50_40_7000	98,11	10 years 7 months	192618,0
PHEV 17_60_7000	98,71	15 years 6 months	283833,8
PHEV 30_60_7000	98,49	13 years 3 months	241737,8
PHEV 50_60_7000	98,20	11 years 1 months	203313,5
PHEV 17_40_7500	98,71	15 years 6 months	282733,3
PHEV 30_40_7500	98,37	12 years 3 months	223738,4
PHEV 50_40_7500	98,21	11 years 1 months	203349,2
PHEV 17_60_7500	98,72	15 years 7 months	285273,9
PHEV 30_60_7500	98,55	13 years 10 months	252568,4
PHEV 50_60_7500	98,32	11 years 11 months	217850,8

Table 4. Percentage increase in battery life of PHEV hybrid mode compared to PHEV full electric mode

Speed	EMS	Percentage increase in battery life (%)
17 km/h	PHEV 17 full electric	-
	PHEV 17_40_7000	30,77
	PHEV 17_60_7000	28,95
	PHEV 17_40_7500	28,45
	PHEV 17_60_7500	29,61
30 km/h	PHEV 30 full electric	-
	PHEV 30_40_7000	6,09
	PHEV 30_60_7000	12,95
	PHEV 30_40_7500	4,54
	PHEV 30_60_7500	18,01
50 km/h	PHEV 50 full electric	-
	PHEV 50_40_7000	77,31
	PHEV 50_60_7000	87,16
	PHEV 50_40_7500	87,19
	PHEV 50_60_7500	100,54

4. Conclusions

Higher speeds lead to increased current use, causing a rise in battery cell temperature and damaging cells, shortening battery life. Matlab simulations show PHEV ITS hybrid mode delays aging by providing extra power through the engine generator and maintaining a low battery temperature. Using the ICE in a series hybrid boosts battery capacity and extends battery life. At lower speeds and discharge currents within the battery's range (0.5C-1C), hybrid mode slows SOC decline with minimal aging impact. Yet, at higher discharge power (1.5C or more), engine-generator power significantly slows battery aging. In PHEV hybrid mode at 60% SOC and 7500 rpm, the engine-generator supplies up to $\pm$85 A, reducing battery load in full electric mode, lowering DOD and battery temperature, improving range, and minimizing aging, making it a superior EMS choice.

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