

A study on optimizing the characteristics of lithium-ion battery power source and operating cost for hybrid motorcycle

Nguyen Van Trang¹, Nguyen Duy Tan^{2,*}, Pham Tuan Anh³



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ABSTRACT

This study presents a research related to a Plug-in Hybrid Electric Motorcycle (HEM) which renovated from a Honda Lead 110cc with rear wheel is driven by original internal combustion engine and continuously variable transmission, while front wheel is directly-driven by a 48V – 1,000W BLDC Hub-Motor. The research focuses on optimal calculating, designing, prototyping and testing an electric power supply using Lithium-ion (Li-ion) battery pack to replace the lead-acid battery. The simulation and experimental results are able to evaluate the dynamic characteristics and operating cost of HEM. The study has been designed and prototyped a 48V – 33Ah Li-ion battery pack with a Battery Management System (BMS) circuit embeded on the vehicle. The battery pack is 10.84 (kg) weight and 8.11 (l) volume, reduced 30 (kg) and 12.89 liters compared to the lead-acid battery where battery life is greater than 2,000 cycles.

In only electric motor mode, the longest distance of the HEM is 78.77 (km) for a half load, only driver, and 65.83 (km) for full load, one driver, and one passenger. Maximum speed is 52.67 (km/h) for a half load and 48.42 (km/h) for full load. In hybrid mode until SOC reduce to 50%, HEM can travel 64.366 (km) for a half load and 54.477 (km) for full load. The fuel consumption in the each case is 2.162 and 2.425 (l/100km), 0.5 liter lower than the original one and 0.3 liter lower than lead-acid battery. The cost of investment in HEM is 56 million VND and the operating cost is 1,106 VND/km, while the original vehicles are 40 million VND and 1,352 (VND/km). For every 1km using hybrid vehicles, 246.88 VND will be saved, after about 3.1 years, it will recoup the spending on investment. At the end of the motorcycle life cycle is about 200,000 km, and 43 million VND will be saved.

Key words: Lithium-ion battery, hybrid electric motorcycle, hybrid vehicle, battery management system (BMS)

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INTRODUCTION

Currently, people on the world is facing increasingly exhausted fossil fuel sources and global climate change, the urgent requirement is to reduce greenhouse gas emissions and use energy resources effectively¹⁻³. In the previous studies, the authors presented the current situation of the number and growth trend of motorcycles in Ho Chi Minh City⁴⁻⁶ as well as the impact of motorcycles using internal combustion engines on environmental pollution and its fuel economy⁷⁻¹⁰. From there, the authors proposed a plan to renovate the 110cc Honda Lead into a gasoline-electric hybrid motorcycle. The main issues have been solved such as: Selecting a general layout schematic; choose electric motors, generators, batteries; propose principles and operating mechanisms of the power management system¹¹; Modeling and simulating the operation of vehicles after renovation with Matlab/Simulink software¹²; Researching overview of Lithium-ion battery and its applicability on hybrid motorbikes, proposing a design solution for

Lithium-ion battery pack for renovated hybrid electric motorcycles¹³.

In this study, the authors continue to solve the following outstanding issues: Manufacturing and testing of Li-ion battery pack; Model the Li-ion battery pack and simulate vehicle operating modes when installing the Li-ion battery pack; Assessing the dynamic characteristics of the vehicle and optimizing the operating characteristics of the battery pack; Calculate the cost of renovation and operating of the vehicle. Raise issues that need further study to conduct wide-ranging application.

PROBLEM IDENTIFICATION AND METHODOLOGY

The prototype of Lithium-ion battery pack must be conducted to test some specifications such as function of battery management system, SOC, etc.

Pair the Li-ion cells into a battery pack

In previous study¹³, authors calculated and proposed a plan to design a Li-ion battery pack that is paired

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from 180 Li-ion cells type SANYO UR18650F-SCUD-3¹⁴ to get a 48V-33Ah battery pack. As seen in Figure 1, 180 cells are paired into 12 serial blocks, each block consists of 15 cells in parallel.

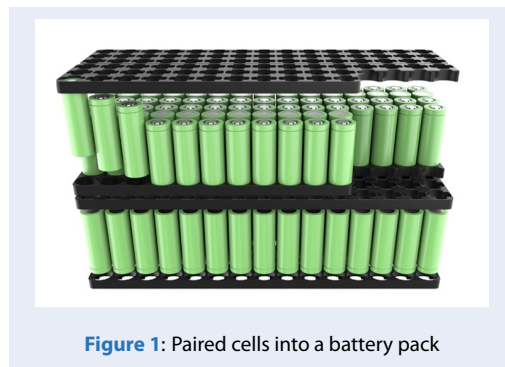


Figure 1: Paired cells into a battery pack

This option gives the advantage of good cell self-balance¹⁵, simple pairing, just need to use only one BMS 48V-33Ah circuit for the battery pack. The downside is the battery pack connected to one unit, so it is difficult to disperse to take advantage of the vehicle free space. After pairing (excluding the box), the battery pack weighs 8.64kg and has dimensions (L x W x H) = 240mm x 200mm x 136mm. The volume is 6,528 (l). This volume accounted for 17.6% of the vehicle's U-Box, meeting the size requirements

Prototype BMS, Battery Management System

The requirements and features have to be achieved of battery pack mentioned in the previous study¹³. In Figure 2, the authors designed and manufactured a BMS 48V-33Ah circuit for the battery pack consists of following blocks:

- Cells-balancing and multiplexer voltage signal block;
- Regulator and power supply block
- Central control unit;
- Communication block
- Protection block such as: overcurrent, overvoltage and overheat, short circuit...

Cells balancing block is using 2 cell-balancing control ICs LTC3300 from Linear Technology. Each IC receives signal and controls 6 serial nodes. 12 cell voltage sensor to get signal and 12 executive structure to balance cell.

Central control unit is using a programmable MCU to control charge-discharge cycles, read-write battery logs and communicate with external interface... In this circuit, authors have chosen MCU PIC18F47J53.

Regulator and power supply block, 3.3V power is supplied by a regulating IC named LT1761ES5-3.3.

Communication block: BMS circuit communicate with external interface by USSB protocol through a transceiver LTM2884CY.

Charge-discharge controller and protection block: To monitor charge-discharge current and voltage, authors used a pair of LTC 6804 and LTC 6802.

Power amplifier block: to control cell balancing, consist of 12 MOSFET RQJ3003PGDQALT, rate voltage is 30V, rate current is 3A. Added an RC type Low-pass filter to filter the cell voltage signal.

In addition, to ensure operational and safety features, BMS circuit is included other auxiliary components such as: current sensors, self-healing fuse, power filters, and temperature sensor in Figure 3.

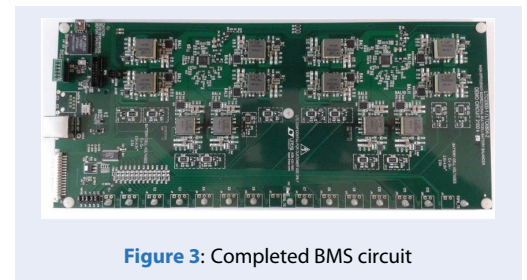


Figure 3: Completed BMS circuit

Connection of the BMS circuit to battery pack and solder power connector, communication jack and battery capacity level indicators. Then pack the battery pack with electrical insulation papers. Choose a plastic toolbox that fits a laptop size, fits the battery pack, and reprocess the case. Because the battery pack and BMS circuitry need heat dissipation, the cover is made of aluminum, thickness 3mm, screwed in holes, hand-held holes and milling the power connector plug holes. Then insert the battery pack into the box. Completed battery pack has a weight of 10.84kg and dimensions of 308 x 183 x 144 mm (L x W x H), volume of 8.11 liters accounted for 21.9% of the U-Box that illustrated in Figure 4.

Testing battery pack

The power source of DC60V – 40A can be used to adjust the power supply, an adjustable Tungsten resistor set to create the load. Testing to figure out charge-discharge characteristics, cell balancing, life-time cycle, temperature rising test with high current. Because the experimental conditions could not keep the room temperature fixed at 25⁰C, authors chose a closed room and adjust the air conditioner at 25⁰C for testing.

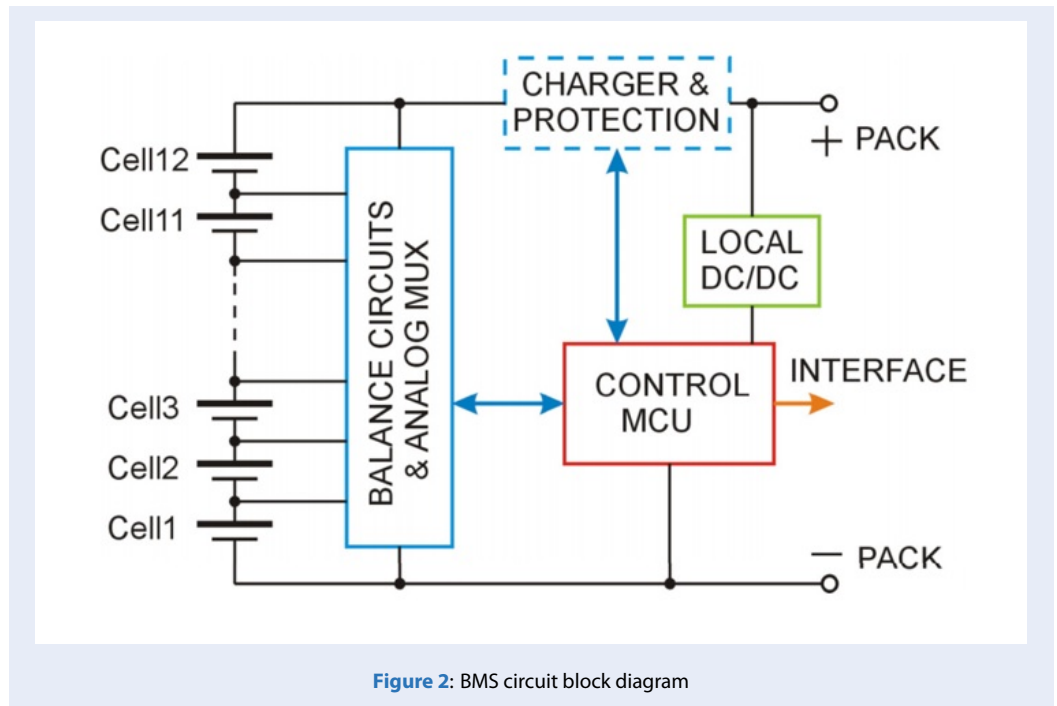


Figure 2: BMS circuit block diagram



Figure 4: Completed battery pack

if the discharge with mode C_5 or C_{10} , and stop discharge at SOC = 50%, the longevity of the battery pack can reach over 2000 cycles while the capacity still over 60% original capacity.

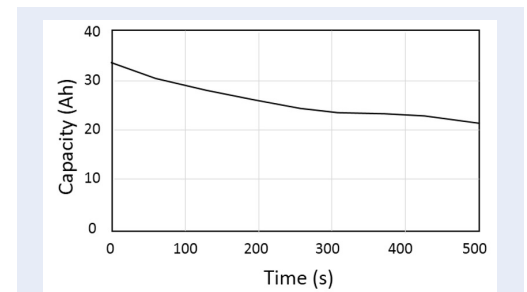


Figure 5: Battery pack lifetime characteristics

The results include:

- Cell over-voltage protection at $4.25 \pm 0.025V$.
 - Balance the cell automatically in two states of charge and discharge with the maximum difference of 0.03V.
- Charge the battery pack in CC-CV method (Constant Current – Constant Voltage) constant current $I_n = 21A$, constant voltage $U_n = 50.4 V$, stop when $I_n \leq 1.5A$, room temperature at 25^0C . As seen in Figure 5, battery pack capacity reaches 98-99% in about 2 hours. Then discharge in C_1 mode ($I_p = 33A$) and stop discharge when SOC = 20%, repeat in 500 cycles, battery pack capacity falls down to 23Ah (69.7% original capacity). This result is not much different when compared with the cell charge-discharge test mentioned in the previous study. So we can conclude,

BATTERY PACK MODELING AND SIMULATION OF OPERATING MODES IN MATLAB/SIMULINK

Li-ion battery pack modeling

In the study¹², authors modeled HEM assemblies and systems including:

- Modeling the gasoline engine and power train systems;
- Modeling the driver;
- Modeling electric motors

- Modeling the vehicle dynamics

In this study, authors model Li-ion battery pack to predict the state of charge level (SOC), capacity, voltage and current when testing.

For designing battery pack and doing simulating of vehicle performance, the SOC is calculated from the following current integration:

$$SOC(t) = SOC_0 - \frac{1}{3600} \int_{t_0}^t \frac{I(\tau) \eta_{bat}}{Q_i} d\tau \quad (1)$$

$$SOC(t_0) = SOC_0; \quad (2)$$

Where Q_i is battery pack capacity (Ah)

The relationship between terminal voltage and current can be expressed following equation:

$$U_{HV} = U_{OC} - U_r \quad (3)$$

Where U_r is dropped voltage caused by internal resistance of battery pack

$$U_r = I.R \quad (4)$$

Where R is internal resistance of battery

Modeling controller

Rule-based algorithms are used to control the power management system of the HEM. There are two important rules in this controller:

- Internal combustion engine has to operate in optimal performance area;
- The battery pack has to be optimized SOC, SOC is kept in:

$$SOC_{min} \leq SOC \leq SOC_{max}$$

Controller has three input signals: Demand power of driver; state of charge of battery pack; actual speed of HEM. Two output elements are demand power of gasoline engine and demand power of electric motor.

Simulating HEM operation

To evaluate dynamic characteristics and fuel consumption of HEM when mounted Li-ion battery pack. Models of parts in system are concreted to blocks in Matlab/Simulink as shown in Fig 6. Then simulated HEM under some motorcycle basic testing cycles such as: Japan 10-15 Mode, WVUCITY, FTP75, ECE-R15.

SIMULATION RESULTS AND DISCUSSION

In order to compare the results of HEM using lead-acid battery with previous study¹⁰⁻¹². In this paper, authors focused on the results of HEM simulation under the Japan 10-15 Mode cycle from $t = 0$ with the step increase time of 0.1 to the end of the cycle (660 seconds) and then repeat until SOC = 50%. The typical simulation results are shown as in Figure 7.

In simulation cycle, the HEM's response speed is very close to the required speed of the cycle, at the points that speed changes suddenly, the vehicle's speed is still late or overshoot, but the level of deviation is less than 0.5%, better than the deviation when the HEM mounted lead - acid battery is ~ 2%. The reason may be the weight of the power supply unit was reduced and reduces the vehicle's weight 30kg, leading to a decrease in HEM's inertia.

As seen in Figure 8, when the required power (P_{k_demand}) stays in the optimal efficiency area of internal combustion engine, the internal combustion engine will drive rear wheel, the electric motor will be turned off. In case P_{k_demand} smaller than the minimum limited point of high efficiency zone, the electric motor will drive front wheel, the gasoline engine will be turned off. In case P_{k_demand} higher than the maximum limited point of efficiency zone, both engines work together, electric motor supplies power to bring internal combustion engine work in the optimal area. In simulation cycle, total consumed electrical energy accounts for 32% of total vehicle demand energy. The remaining energy (68%) is provided by gasoline engine. Electrical energy is equivalent to 48.15% of the energy from gasoline engines as shown in Figures 9 and 10 and Figure 11.

Fuel consumption of HEM is 2.162 (l/100km) for a half load, and 2.425 (l/100km) for full load. Estimated range until SOC reduced to 50% is 64.36 km for a half load and 54.47 km for full load given in Table 1.

Renovating cost

The investment on buying and renovating include:

- Cost of buying new scooter: \$1,709
- Battery pack: \$414
- Other supplies and costs: \$275.2

Details shown in Table 2.

Operating cost

In order to calculate the operating costs of base scooter and renovated HEM, authors choose the calculation method and conversion all of depreciation and basic operating costs per 1 kilometer.

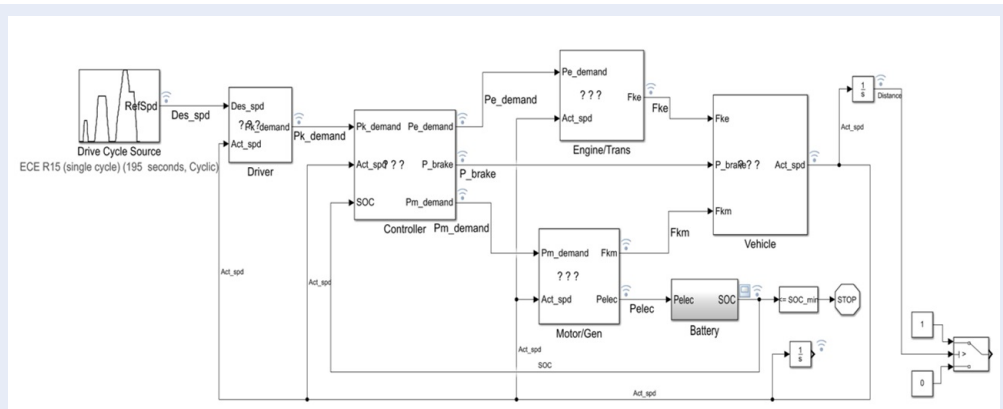


Figure 6: HEM block diagram in Matlab/Simulink

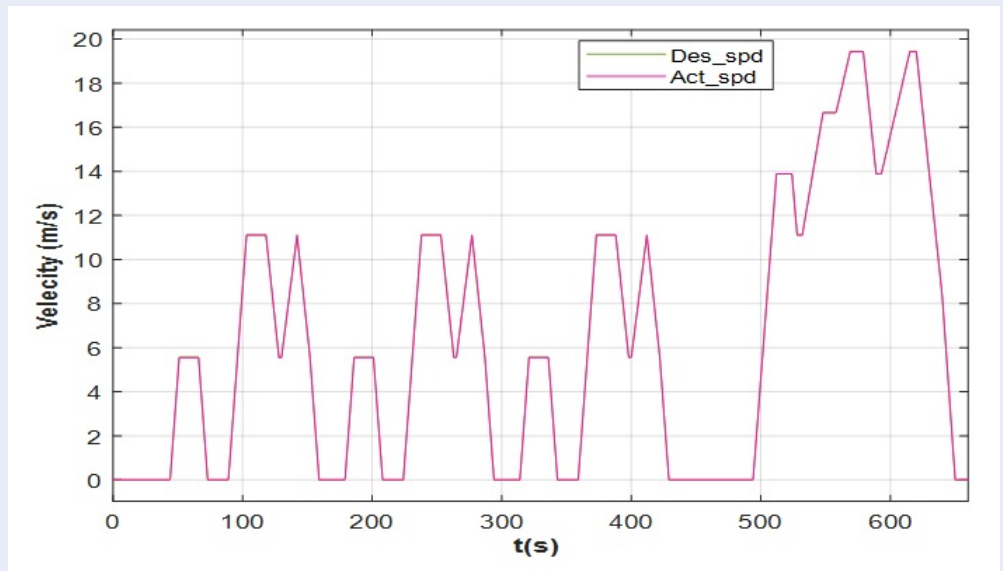


Figure 7: Velocity response

According to H. D. Tung’s research¹⁶, motorbike life depends on many factors such as production quality, environment, usage terrain, maintenanc, and usage habits. But on average, motorcycles in Vietnam have a life expectancy of about 200,000 km with two major repairs at 100,000 km and at 150,000 km.

Based on the simulation results in section 4, when operating in hybrid mode with Japan 10-15 Mode cycle, the generated power by the electric motor around 48.15% of the total HEM demand power. To calculate the operating cost, authors accept the assumption that all the details of the internal combustion engine and powertrain of the HEM have a lower operating frequency than the original vehicle and all services of the vehicle are also extended by 48.15%. Thus, the life

of the HEM is about 296,300 km.

- Depreciation of base scooter: 40,000,000VND/200,000km = 200 (VND/km)
 - Depreciation of renovated supplies: 6,439,000 VND/296,300km = 21.73 (VND/km)
 - Depreciation of base scooter in hybrid mode: 40,000,000 VND/296,300km = 135 (VND/km)
- In half-load mode, HEM consumed 2.162 (l/100km), the original one consumed 2.693 (l/100km) while in full-load mode are 2.425 and 3.012 (l/100km). In particular, used ratio of motorcycles in HCM city is 1.25¹⁶. There will be 1 motorcycle to carry 2 people. From there, we calculate the average consumption of HEM and original vehicle:
- Average fuel consumption of original vehicle:

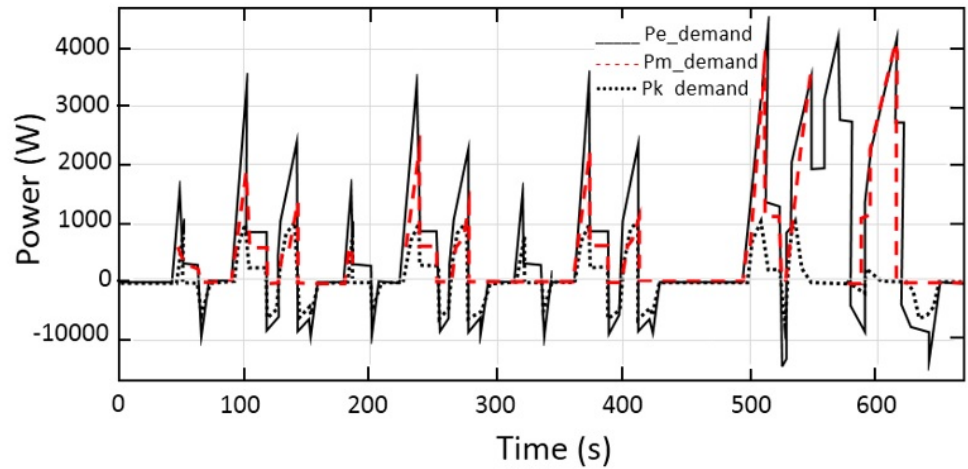


Figure 8: Demand power distribution

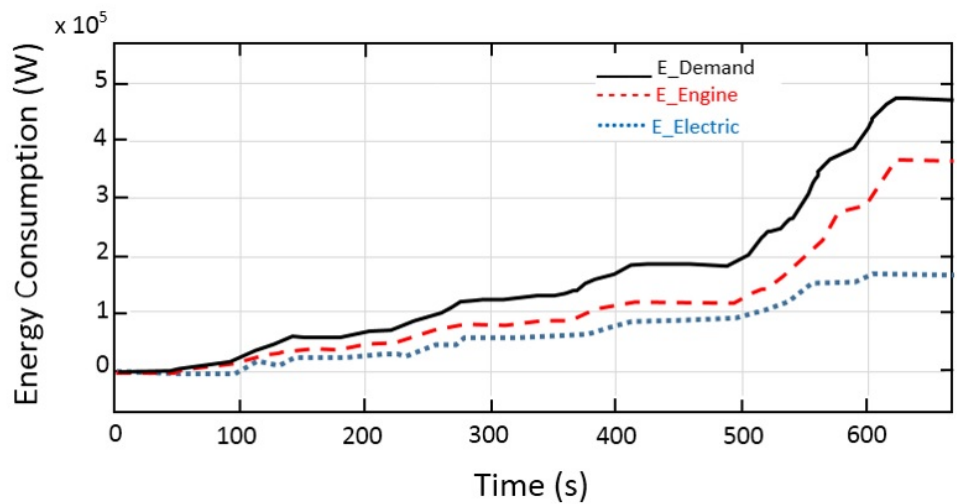


Figure 9: Energy distribution ratio

$$(2.693 \times 3 + 3.012)/4 = 2.77 \text{ (l/100km)}$$

- Average fuel consumption of HEM:

$$(2.162 \times 3 + 2.425)/4 = 2.228 \text{ (l/100km)}$$

- MogasA95 price in HCM City in Jun/2019: 20,000 (VND/l)

- Fuel cost of original vehicle: $2.77 \times 20,000/100 = 554.55$ (VND/km)

- Fuel cost of HEM: $2.228 \times 20,000/100 = 445.55$ (VND/km)

With the operation cycle stopped discharging at SOC = 50%, according to the characteristics of Li-ion cell and the Li-ion battery pack mentioned in section 2,

the battery life is greater than 2,000 cycles while ensuring the battery capacity does not fall below 50%. Each cycle of charging and discharging 50% capacity, the HEM get 64.336 km, we calculate the battery life is 128,672 km.

Depreciation of battery pack:

$$9,687,000/128,672 = 75.284 \text{ (VND/km)}$$

Power of battery pack: $12V \times 33Ah = 1584Wh$

Each charge cycle of 50% of power consumption consumes 0.792 kWh with an estimated electricity price of 2,000 (VND/kWh)

The cost of electricity: $0.792 \times 2,000 / 64.336 = 24.62$ VND/km. According to the Honda Lead 110cc oper-

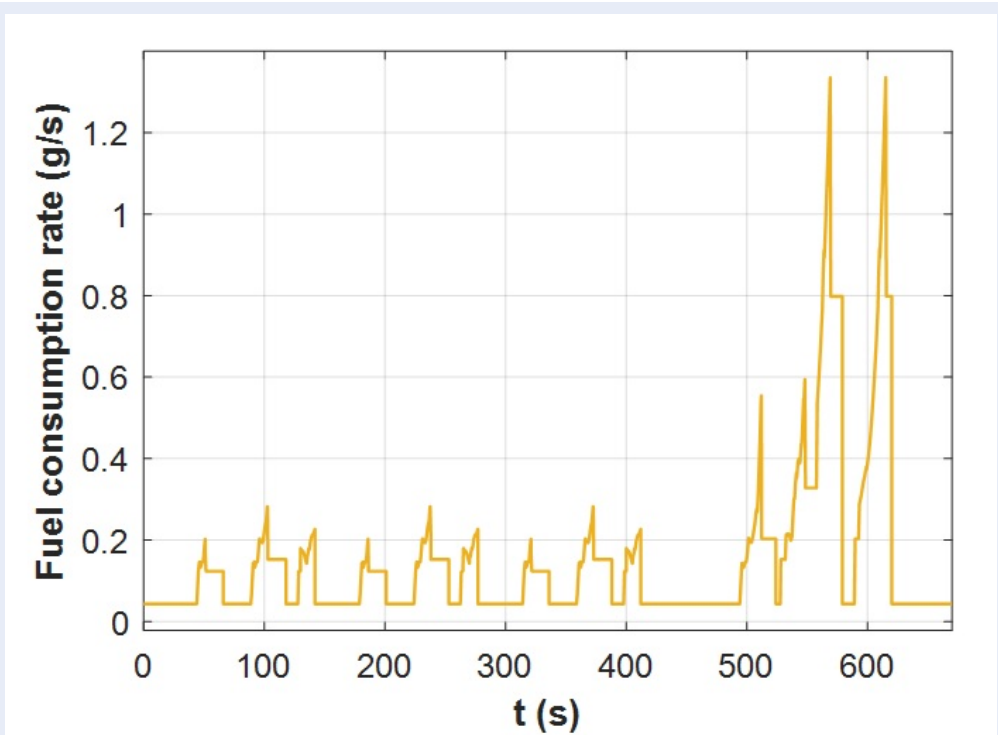


Figure 10: Fuel consumption rate

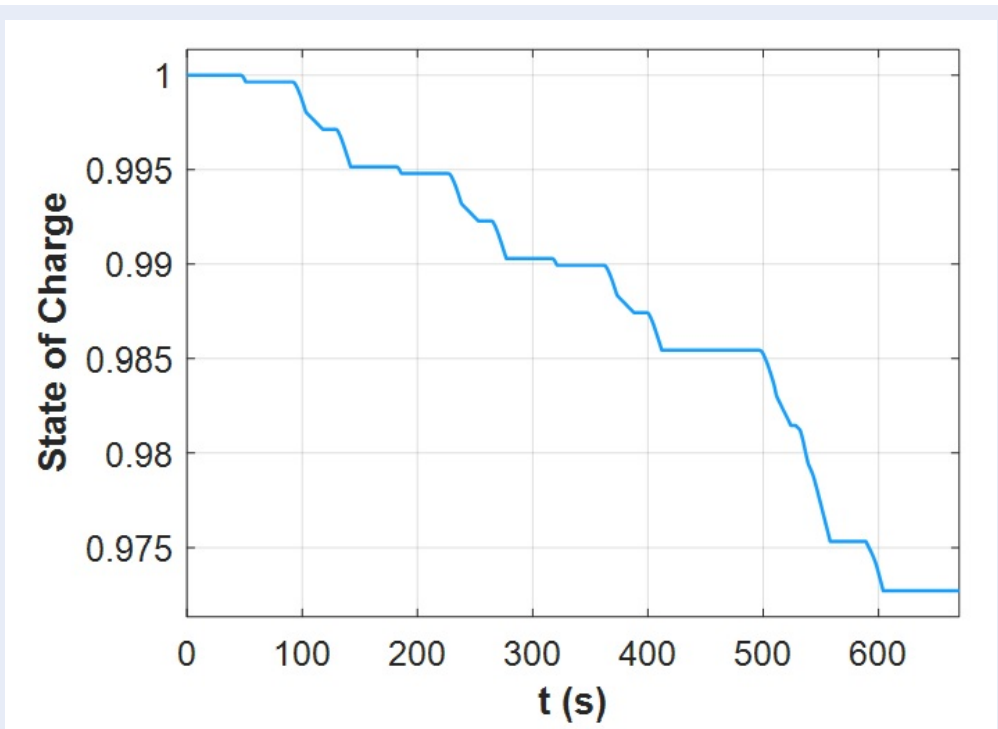


Figure 11: State of charge (SOC) vs. time

Table 1: Dynamic characteristics comparison

Characteristics	Lead-acid battery HEM		Li-ion battery HEM	
	Half load	Full load	Half load	Full load
Fuel consumption (l/100km)	2.521	2.866	2.162	2.425
Estimated range in hybrid mode until SOC reduced to 50% (km)	43.43	36.48	64.36	54.47
Estimated range in electric mode (km)	47.6	42.4	78.77	65.83
Maximum speed in electric mode (km/h)	44.75	41.3	52.67	48.42
Maximum slope in electric mode (%)	3.54	2.39	4	2.54
Renovated HEM weight (kg)	238	303	208	273
Battery pack weight (kg)		41.6		10.84
Battery pack volume (l)		14.5		6.53
Battery pack volume including box (l)		21		8.11

Table 2: The cost for renovating to hem

Contents	Quantity	Unit price (\$)	Amount (\$)	Amount (x1,000 VNĐ)
New Honda Lead scooter	1	1,709	1,709	40,000
BLDC motor 48V-1000W	1	117	117	2,737.8
BLDC controller	1	24	24	561.6
Handle with Hall sensor	1	8.2	8.2	191.88
Li-ion cell 18650	180	2.3	414	9,687.6
Battery management system	1	14	14	327.6
Power management system	1	12	12	280.8
Machining and assembling	1	100	100	2,340
Total			2,398.2	56,127.28

Exchange rate: 23,400VNĐ/\$

ation and maintenance manual¹⁷, stipulating the cycle of maintenance, repair and longevity of some spare parts of natural wear and tear of the vehicle. Combination with the quotation of services and spare parts supplies of Honda Vietnam’s authorized dealer in Ho Chi Minh City, we calculate other cost and depreciation.

Evaluation of renovating and operating cost

According to the calculation results above, we set up a table to calculate the cost, figure out the break-point when renovating and operating vehicles given in Table 3.

The initial investment of the renovated HEM is nearly VNĐ 16 million higher than the original vehicle. However, in the operating life, every 1 km of operation,

246.88 VNĐ will be saved by the HEM. Break-point when investing in renovating and operating HEM with Li-ion battery pack is about 26,000 km.

According to the research results of Mr. Tung¹⁶ too, the average distance traveled by motorbike of people in Ho Chi Minh City is 23 km per day, equivalent to 8,395 km/year. Thus, if investing in renovation of Honda Lead to a HEM, after about 3.1 years, it will recoup the spending on investment.

After 3.1 years, for every additional 1 km of operation, 246.88 VNĐ will be saved. So by the end of life of the original vehicle (200,000km), equivalent to 23.8 years, 43 million VNĐ will be saved by the HEM, equivalent to the money to buy a new motorcycle as in Figure 12. In Ho Chi Minh City with about 8.6 million motorcycles, if investing to renovate traditional gasoline motorbikes into HEM, it will cost 137,600 billion VNĐ,

Table 3: Evaluation of renovating & operating cost

Contents	Investment (x 1,000VND)		Distance (km)		Cost (VND/km)	
	Original scooter	HEM	Original scooter	HEM	Original scooter	HEM scooter
Depreciation of original vehicle	40,000	40,000	200,000	296,300	200	135
Depreciation of renovating	0	6,439	0	296,300	0	21.73
Fuel	55.455	44.55	100	100	554.55	445.55
Electricity	0	1.584	0	64.336	0	24.62
Li-ion battery	0	9,687	0	128,672	0	75.28
Lead-acid battery	450	450	30,000	44,445	15	10.125
The 1 st maintenance	600	600	2,000	2,963	300	202.5
The 2 nd maintenance	1,100	1,100	5,000	7,407.5	220	148.5
The 1 st major repair	3,000	3,000	100,000	148,150	30	20.25
The 2 nd major repair	5,000	5,000	150,000	222,225	33.33	22.5
Total					1,353	1,106

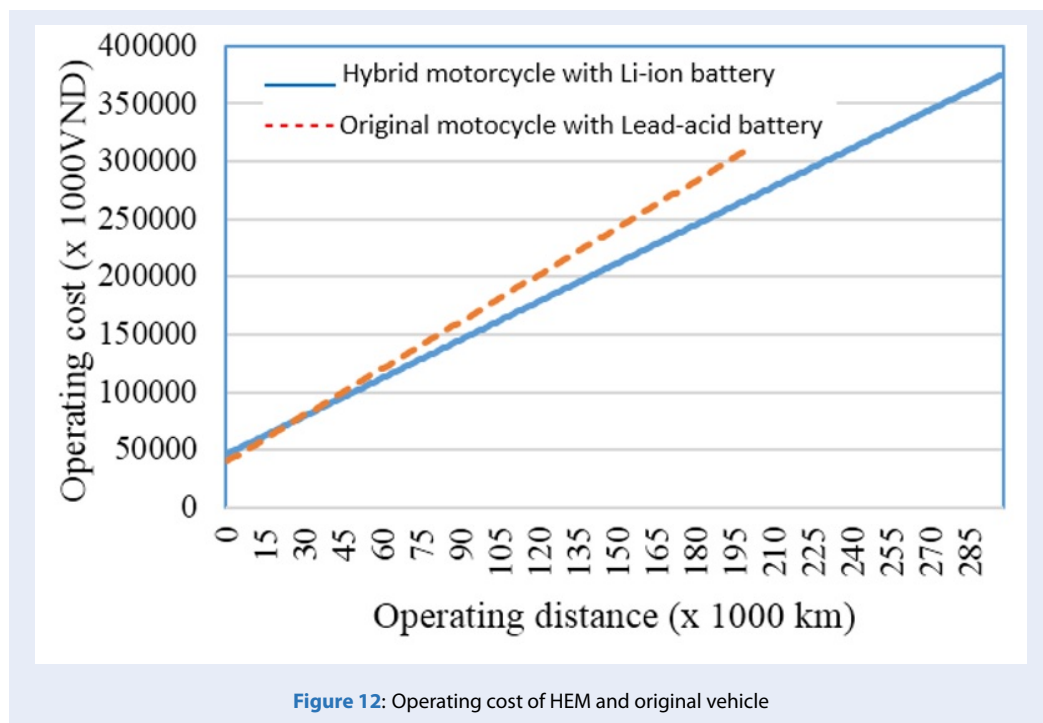


Figure 12: Operating cost of HEM and original vehicle

but after 23.8 years, the operating cost will be reduced by 369,800 billion VND, the saved amount is 232,200 billion VND. If compared to the cost of Ho Chi Minh City - Long Thanh - Dau Giay express way is 375 billion VND/km (20,630 billion in total for 55km), this amount can build transport infrastructure equivalent to about 600 km of express way. At the same time, the demand for A95 gasoline will decrease by nearly 9.4 million m³. Compared with the country's gasoline consumption in the first 6 months of 2018, it was 4.43 million m³¹⁸. The amount of gasoline saved is enough to supply gasoline for the whole country in about 1 year.

Thus, the renovating motorbikes using internal combustion engines with gasoline fuel into HEM has been achieved the expectations in terms of reducing fuel consumption to ensure energy security while reducing emitting 50% of CO and HC into the environment¹⁹.

CONCLUSIONS

In this study, the calculation and experiment have been conducted to:

- Analyze advantages and disadvantages of energy storage systems used in hybrid vehicles, design, prototype, and testing for the 48V - 33Ah Li-ion battery pack and BMS circuit to meet the requirements of dynamic characteristics and appropriate operating conditions of the vehicle.
- Calculate, test the HEM in many operation modes, and simulate HEM in Matlab/Simulink, the evaluation of the dynamic characteristics and fuel economy of the renovated HEM have been compared to original vehicles.
- Calculate the cost of investing, renovating and operating of renovated HEM, compare to the original vehicle, and give assessments.

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CONFLICT OF INTEREST

The authors hereby guarantee that there is no conflict of interest in the publication of the article.

AUTHORS' CONTRIBUTION

Nguyen Van Trang: analysis and interpretation of results; approved the final version of the manuscript.

Nguyen Duy Tan: draft manuscript preparation; data collection.

Pham Tuan Anh: study conception; correction of the draft manuscript.

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Nghiên cứu tối ưu tính năng bộ nguồn pin Lithium-ion và chi phí vận hành cho xe gắn máy tích hợp truyền động lai

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TÓM TẮT

Nghiên cứu này thực hiện trên xe máy lai xăng điện được cải tạo từ xe nền Honda Lead 110cc với bánh sau được dẫn động bằng động cơ đốt trong thông qua hệ thống truyền lực nguyên bản của xe, bánh trước được dẫn động trực tiếp bằng động cơ điện một chiều không chổi than 48V – 1000W. Nội dung chính của nghiên cứu là chế tạo, thử nghiệm bộ nguồn điện sử dụng pin Lithium-ion thay thế cho bộ nguồn ắc quy axit – chì. Mô phỏng hoạt động, đánh giá tính năng động lực học đồng thời tính toán chi phí cải tạo và vận hành xe.

Nghiên cứu đã tính toán thiết kế, chế tạo một bộ nguồn pin Li-ion 48V – 33Ah với mạch BMS để lắp lên xe. Bộ pin có khối lượng 10.84 kg và thể tích 8.11 lít, giảm được 30kg và 12.89 lít so với ắc quy axit – chì. Tuổi thọ của bộ pin lớn hơn 2,000 chu kỳ.

Ở chế độ chỉ hoạt động với mình động cơ điện, xe có thể di chuyển được quãng đường dài nhất là 78.77km cho $\frac{1}{2}$ tải và 65.83km cho trường hợp đầy tải. Vận tốc lớn nhất là 52.67km/h cho $\frac{1}{2}$ tải và 48.42 km/h cho trường hợp đầy tải. Ở chế độ hybrid đến khi SOC = 50%, xe đi được quãng đường 64.366 km cho $\frac{1}{2}$ tải và 54.477 km cho trường hợp đầy tải. Tiêu hao nhiên liệu tương ứng trong hai trường hợp là 2.162 và 2.425 lít/100km, giảm hơn 0.5 lít so với xe nền và 0.3 lít so với xe dùng bộ nguồn ắc quy axit – chì.

Chi phí cho xe đầu tư cho xe hybrid là 56 triệu đồng còn chi phí khai thác là 1,106 đ/km, trong khi xe nền là 40 triệu đồng và 1,352đ/km. Cứ mỗi km khai thác xe hybrid tiết kiệm được 246.88đ, sau khoảng 3,1 năm sẽ hòa vốn chi phí đầu tư. Nếu khai thác hết vòng đời xe khoảng 200,000km, xe hybrid tiết sẽ kiệm được khoảng 43 triệu đồng.

Từ khoá: Pin Lithium-ion, xe máy lai, xe hybrid, mạch quản lý pin

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