RESEARCH ON CONTROLLING OF EXPERIMENT MODEL TO EVALUATE OF KINETIC ENERGY RECOVERY SYSTEM BASED ON DRIVING CYCLES

NGHIÊN CỨU ĐIỀU KHIỂN MÔ HÌNH THỰC NGHIỆM ĐỂ ĐÁNH GIÁ HỆ THỐNG THU HỒI NĂNG LƯỢNG QUÁN TÍNH CỦA Ô TÔ THEO CÁC CHU TRÌNH LÁI XE

Duong Tuan Tung, Do Van Dung, Nguyen Truong Thinh
Ho Chi Minh City University of Technology and Education, Vietmam

Received 13/3/2018, Peer reviewed 27/03/2018, Accepted for publication 06/04/2018

ABSTRACT

The inertia of the automobile during braking and deceleration is enormous. In a conventional vehicle, this energy has not been recovered but is converted into heat at the braking mechanism. In this study, an experimential model will be built to calculate the energy recovered during braking or deceleration in a vehicle with the conventional powertrain. This study model includes: A motor-driven an axle; a magnetic brake and torque measuring device at the drive wheel to control the traction and braking force in the vehicle; a double planetary gear set to change the ratio paralleled to the propeller shaft to rotate the flywheel whenever braking or deceleration is performed; a generator is coaxial with the flywheel to convert the mechanical energy into electricity rechargeable for battery. Moreover, the PID controller is built to control the energy kinetic energy recovery system during braking or deceleration according to the driving cycles such as FTP75, NEDC, EUDC and ECE R15. Experimental results show that the energy recovery efficiency can achieve about 27.87% to 38.25% depending on the driving cycle.

***Keywords:** Regenerative Braking System (RBS); Kinetic Energy Recovery Storage (KERS), Planetary Gear Unit; Conventional Powertrain System; PID Controller.*

TÓM TẮT

Năng lượng quán tính của ô tô trong quá trình phanh và giảm tốc là rất lớn. Trên xe ô tô truyền thống năng lượng này chưa được thu hồi mà bị biến thành nhiệt năng tại cơ cấu phanh mỗi khi quá trình phanh xảy ra. Trong nghiên cứu này sẽ đi xây dựng mô hình thực nghiệm để tính toán năng lượng thu hồi được trong quá trình phanh hoặc giảm tốc của một chiếc ô tô có kiểu hệ thống truyền lực truyền thống. Mô hình hệ thống bao gồm: Một mô tơ điện dẫn động cầu xe; một bộ hãm từ và thiết bị đo mô men tại bánh xe chủ động để điều khiển lực kéo và lực phanh của xe; một bộ bánh răng hành tinh kép nhằm thay đổi tỷ số truyền được mắc song song với trục các đăng của xe để làm quay bánh đà mỗi khi quá trình phanh hay giảm tốc được thực hiện; một máy phát điện được nối đồng trục với bánh đà nhằm biến cơ năng thành điện năng nạp lại cho ắc quy và một bộ CVT thay đổi tỷ số truyền để duy trì tốc độ máy phát trong dải hoạt động tối ưu nhất. Bộ điều khiển PID được xây dựng để điều khiển thu hồi năng lượng mỗi khi xe phanh hoặc giảm tốc theo các chu trình lái xe như FTP75, NEDC, EUDC and ECE R15. Kết quả thực nghiệm cho thấy hiệu suất bộ thu hồi năng lượng có thể đạt từ 27,87% tới 38,25% tùy theo chu trình thử nghiệm

***Từ khóa:** Hệ thống phanh tái sinh (RBS); Tích trữ năng lượng quán tính (KERS), Bộ ánh răng hành tinh kép; Hệ thống truyền lực truyền thống; Bộ điều khiển PID.*

1. INTRODUCTION

The braking process in automotive is an energy conversion from mechanical energy into heat. This transformation is a waste of energy and it causes damage to components in the braking system. However, the traditional braking system is still used because of the safety reasons, although the dissipated energy during braking is not small. Regenerative Braking System (RBS) is designed for recovery to reuse inertial energy of the vehicle during braking or deceleration. It saves fuel consumption and increases durability of braking mechanism. Currently, the RBS is applied to Electric Vehicles (EV); Hybrid Electric Vehicle (HEV) and Conventional Vehicle with Internal Combustion Engines (ICEs). According to recently researchers [1]; [3] who have developed a recoverable energy equation of a vehicle of the conventional powertrain system in the formula (1)

$$[i_{rbs} \times \frac{1}{4.3} \times r_b (m \frac{dv}{dt} \delta_i - fmg\cos\theta - 0.5\rho A C_D . V_{(t)}^2 + mg\sin\theta)] - \frac{P_{ton\_hao}}{\omega_{mp}} = \frac{3 E_S I_S \cos\phi}{\omega_{mp}} \qquad (1)$$

Where: $E_s = K_M I_s \omega_{mp}$

i_{rbs} is the ratio of recovery energy unit; r_b is wheel radius; δ_i: coefficient of rotation mass components; P_{ton_hao} is the loss power including the mechanical loss and electrical loss; E_s and I_s are voltage and current of the generator.

The study results [1]; [2], a simulation model of the RBS system were developed and a PID controller was used to control the simulation model in Matlab Simulink based on the driving cycle. An emperiment study is needed to evaluate the overall efficiency of the inertial energy recovery system. In the studies [1] and [2] the research had set up an experimental model on a Toyota Hiace to test on road. However, these experimental results only assess the energy recovery efficiency at each speed range of the vehicle, it hasn't tested with whole cycle. In order to test the system on different driving cycles, the experimental model will be built on a test band with the diagram shown in Figure 1.

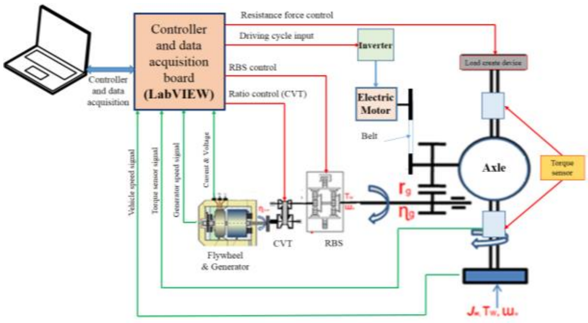

Figure 1. *Research model diagram*

General description of the experimental model: From the actual model of the vehicle with the vehicle speed signal is controlled based on the frequency converter to control electric motor. Electric motors will drive the axle to rotate the drive wheel. There are load generating devices and torque sensors mounted on the half shaft to determine the torque applied to the drive wheels and control the traction of the motor so that the velocity of the vehicle in the experiment model match to standard driving cycle.

The driving axle is connected to the RBS unit via a double planetary gear that allows the inertial to be delivered to the flywheel during braking or deceleration. The flywheel and generator are coaxial to convert mechanical energy into electricity. In addition, the CVT is added to maintain the generator speed within the optimum range [2]. The PID controller controls the vehicle speed match to driving cycles. Load create device and torque sensor has used to control and measure the braking force at the drive wheels. At deceleration state, the controller will control activation of the energy recovery system; change ratio of CVT; controls the current and voltage generated by the generator to balance the mechanical braking force and regenerative braking force [3].

2. DRIVING CYCLES ANALYSIS

To simulate and calculate the energy recovery efficiency, FTP-75, NEDC, EUDC and ECE R15 driving cycles are used for simulating. In this section, the study analyzes the FTP-75 cycle to model first, then other cycles are performed similarly and analyzed the results only. The FTP-75 is a driving cycle used by the U.S. Environmental Protection Agency (EPA) for testing in city conditions with a travel distance of 17.77 km. Time Period: 1874s. Average speed: 34.1 km/h is shown in Figure 2 [2].

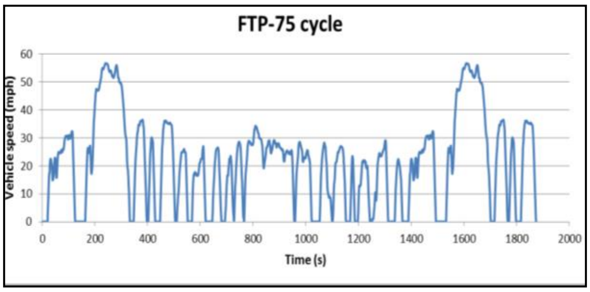

Figure 2. *FTP75 driving cycle [4]*

As shown in Figure 2, the velocity of the vehicle changes according to driving conditions. As the vehicle accelerates, power from the engine is transmitted to the driving wheel. At this time the energy recovery assembly does not work. When the vehicle decelerates, the energy recovery unit is activated and energy recovery begins. To control the velocity of the vehicle meeting to the speed of the standard driving cycle, the PID controller used in this study is shown in Figure 3.

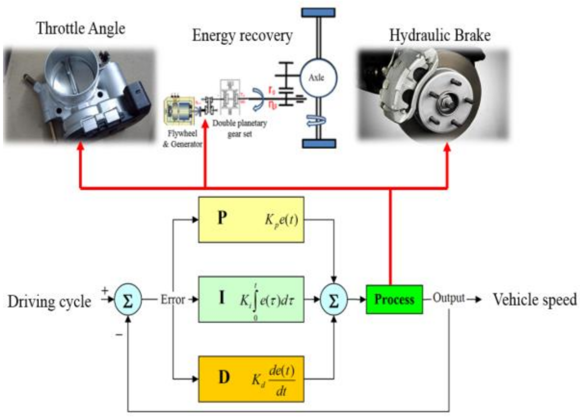

Figure 3. *Block diagram of simulation*

During the driving cycle test, the deceleration of the vehicle is detected by vehicle speed so that the controller will act on the energy recovery assembly, controls the engine power, and adjusts the hydraulic braking force to ensure the actual speed of vehicle matching to the vehicle speed of standard driving cycle. Thus, to perform simulated control of the energy recovery system the input signals including the standard driving cycle (velocity and acceleration of the vehicle) are controlled by accelerator pedal. Based on the velocity and acceleration measured signals, the controller is designed to control the clutch engage/disengage for acting recovery energy unit, controlling the CVT to maintain the generator speed in the speed range that gets high performance. The current and voltage are collected to calculate the power and energy recovered over the full cycle.

3. SIMULATION MODEL

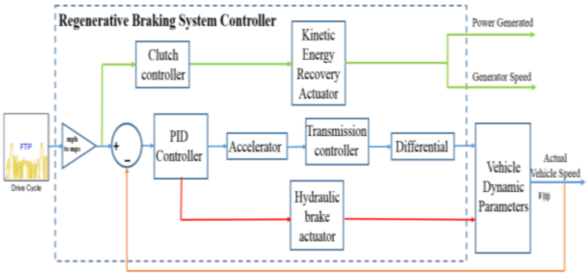

Figure 4. *Block diagram of simulation controller*

The simulation process description: At the beginning of simulation, the standard driving cycle is loaded into the system. The controller will control the output engine power in accordance with the acceleration graph of the standard driving cycle. When deceleration signal is recorded, the controller activates the energy recovery assembly and the hydraulic braking system operates to ensure that the actual speed of the vehicle match to the vehicle speed in the standard driving cycle. To control the torque changing of the vehicle a PID controller is set up to control the transmission ratio. While the recovery energy unit operating, the generator speed is controlled in the range with optimum performance by the CVT controller

Power loss: The power of generator in this system can be determined by the following equation:

$$P_{out} = P_{Generator\_shaft} - P_{Mechenical\_loss} - P_{Generator\_loss} - P_{Converter\_device} \quad (2)$$

***Table 1**: Mechanical & Electrical Loss [6]*

Electrical loss	
Stator winding loss	$P_{cu,S} = 3I_S^2 R_S$
Rotor winding loss	$P_{cu,R} = 3I_f^2 R_f$
Rectifier diode voltage drop loss	$P_{Rect} = 3V_d I_s$
Power converter device loss	$P_{Conv} = I_{dc}^2 R_{on} D$ $+0.5V_{dc} I_{dc} f_S (t_{c(on)} + t_{c(off)})$
Brush loss	$P_{Brush} = I_f^2 R_{Brush}$
Magnetic	
Eddy current	$P_{Eddy} = K_{Ed} t^2 \omega_{mp}^2 B^2$
Hysteresis	$P_{Hyst} = K_{Hyst} \omega_{mp} B^2$
Mechanical loss	
Bearing friction	$P_{Be} = K_{Be} \omega_{mp}$
Windage	$P_{Win} = K_{Win} \omega_{mp}^3$
Planetary gear and chain	$P_{Mech,loss} = 0.03 P_{truc\_mp}$

Where: K_{Ed}: Eddy current loss constant coefficient; t: thickness or length of magnetic path in iron; ω_{mp}: alternator rotational speed (rad/s); B: flux density of the iron cross-section; K_{Hyst}: hysteresis loss constant coefficient; K_{Be}: bearing loss constant coefficient; K_{Win}: windage loss constant coefficient; V_d: rectifier diode finite on-voltage; I_s: stator phase current; f_S: switching frequency $t_{c(on)} + t_{c(off)}$ = hard switching conduction on & off time.

Based on the simulation results of the full driving cycle, the energy recovered is calculated. From the result of the power curve, the energy generated can be determined by the equation (3) [6], [7].

$$E = \int_{t_0}^{t_n} P(t)dt \quad (3)$$

If the obtained power is a line parallel to the time axis, the energy obtained is calculated as equation (4)[8].

$$E = P.\triangle t = P.(t_n - t_0) \quad (4)$$

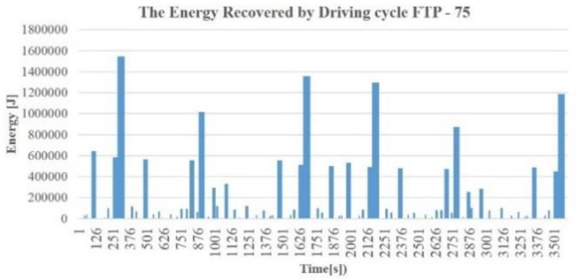

***Figure 5**. Chart of energy recovered by FTP-75 driving cycle*

The total energy recovered by FTP-75 driving cycle: $\sum E = 18038407.8\ (J)$ with full driving cycle duration 3748(s) and active duration of RBS 1145(s)

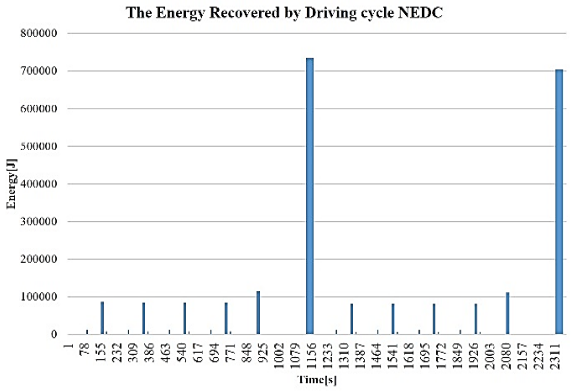

***Figure 6**. Chart of energy recovered by NEDC driving cycle*

The total energy recovered by NEDC driving cycle: $\sum E = 2478085.01(J)$ with full driving cycle duration 180(s) and active duration of RBS 238 (s)

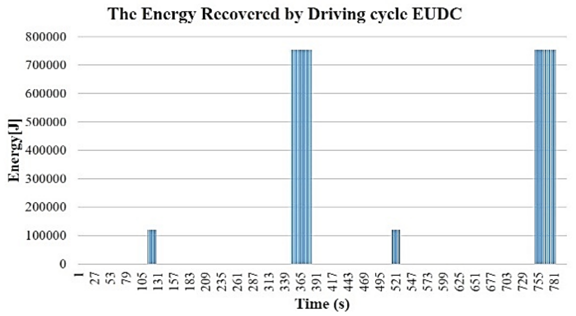

***Figure 7**. Chart of energy recovered by EUDC driving cycle*

The total energy recovered by EUDC driving cycle: $\sum E = 1745521.455\ (J)$ with full driving cycle duration 400(s) and active duration of RBS 94 (s)

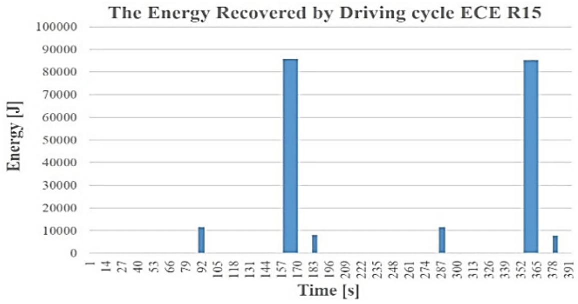

***Figure 8**. Chart of energy recovered by ECE R15 driving cycle*

The total energy recovered by ECE R15 driving cycle: $\sum E = 209022.28\ (J)$ with full driving cycle duration 195(s) and active duration of RBS 36 (s)

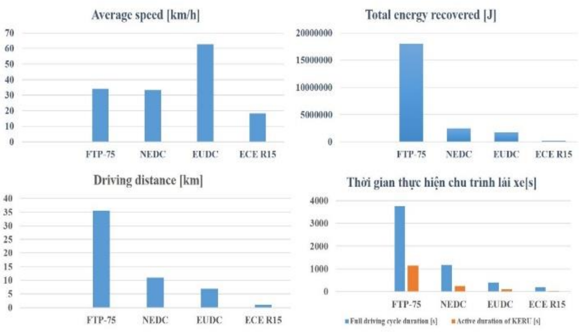

***Figure 9.** Chart of comparing simulation results between cycles*

Thus the energy recovered depend on the velocity at the beginning of deceleration process, the variation of acceleration, the time and distance of the driving cycle as well. In addition, energy recovery also depends on many factors such as system control algorithms, energy storage devices... Therefore, it is necessary for experimentally control the system by using different standard driving cycles for evaluating results.

4. EXPERIMENT AND EVALUATION

In order to experimentally evaluate the efficiency of the recovery system, experimentation will be conducted with full driving cycles. Specifications of the components in the experimental model are shown in Table 2

***Table 2.** Parameters of the experimental model.*

Name	Parameters
Motor	Toshiba 3 pharses -220V ; 7.5kW
Inverter	Toshiba VF-FS1 ; 3 pharses -220V ; 7.5kW
Magnetic braking	VSED ; 80V- 4.7A ; 1800rpm
Torque sensor	Burster Torque sensor 85646 ; 0-500Nm ; 2.34mV/Nm
Controller and data acquisition	Card NI Aduino-uno LabVIEW 2014 Magnetic sensor are used to measure vehicle speed and generator speed
RBS Ratio	0.1< i<0.6
Generator	2HP
Load device	I_{max} 50A ; U 20V

***Figure 10**. Experimental model*

The experiment was carried out with 4 different driving cycles: FTP-75, NEDC, EUDC and ECE R15. Each cycle is installed to the inverter that drives the motor through the PID controller. During vehicle speed sensor operation, the feedback signal allows the PID controller to continuosly control the actual speed of the vehicle match with the standard speed of the driving cycle. In addition, the magnetic brakes are activated which act on the wheel to make slow down vehicle speed. Whenever a deceleration signal occurs, the controller activates the energy recovery system through a double planetary gear set, which makes the flywheel and generator spin. The energy recovery process is started. The energy generated by the generator will be run through an adjustable load. During operation, the data acquisition system through LabVIEW software always records the values such as vehicle velocity, generator speed, voltage and current through the load.

Figure 11. *Data acquisition using LabVIEW*

The data obtained from the system in the experimental model is the voltage and current that are generated whenever the energy recovery unit operating. Based on these data, the energy recovered was calculated as shown in Figure 12.

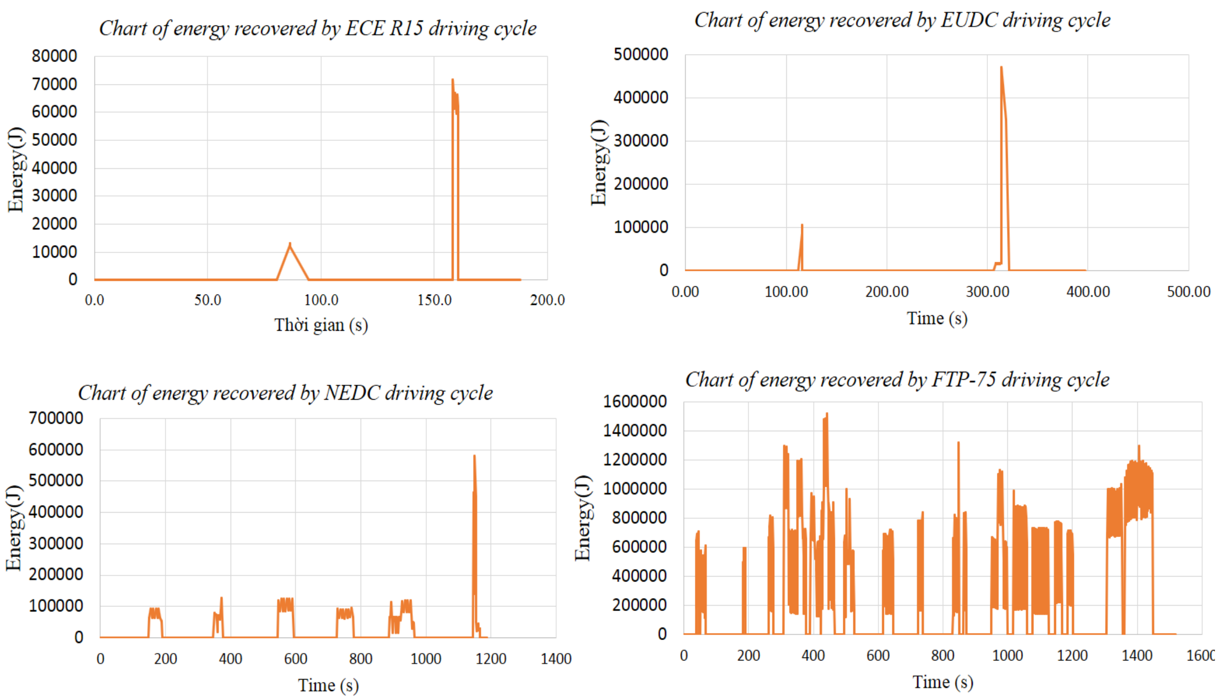

Figure 12. *Experimental energy graphs*

Discussion: According to the graph is built from the experimental results, the energy recovery time is less than the simulation result. Because of electrical latency phenomenon, when the system detects the deceleration of the vehicle through the speed sensor, the controller immediately activates the RBS. However, due to the mechanical can cause energy recovered increasing slowly. In addition, deceleration stages often occur shortly about 2 to 3 seconds and afterward acceleration mode are performed. In these situations, are often controlled without recovering energy during the experiment.

Table 4. *The results of energy recovered in driving cycles.*

Driving cycle		FTP-75	NEDC	EUDC	ECE R15
Driving distance [km]		35,54	109,314	69,549	0,9941
Full driving cycle duration [s]		3748	1180	400	195
Active duration of RBS [s]		1145	238	94	36
Percentage of active duration (%)		30,5%	20,2%	23,5%	18,5%
Average speed [km/h]		34,1	33,35	62,59	18,35
Total energy recovered [J]	**Simulation**	18038407.85	2478085.01	1745521.46	209022.28
	Experiment	5050754.198	792987.2032	792987.2032	45984.9016
Effeciency		0.28	0.32	0.38	0.22

5. CONCLUSION

This paper has modeled the simulation of the inertial energy recovery system of the automobile during deceleration process. The PID controller was built to control the simulation and experimental models through the inverter to control the vehicle speed according to the standard driving cycle. The results show that actual recovered energy range can reach from 22% to 38% comparison to simulation and theory calculations. The results of this study are fundamental for experimental calculation and the application of energy recovery in braking for vehicles with conventional powertrain systems.

REFERENCES

[1] Duong Tuan Tung, Do Van Dung, Nguyen Truong Thinh "An overview of research and proposed experiment model of regenerative braking system based on the conventional vehicle powertrain", the International Conference of Green Technology and Sustainable Development 2^{nd}, HCMUTE, 2014

[2] Duong Tuan Tung, Do Van Dung, Nguyen Truong Thinh, "Research on kinetic energy recovery of conventional vehicle based on regenerative braking system" The Fifth International Multi Conference on Engineering and Technology Innovation 2016 (IMETI2016), Taichung Taiwan, November, 2016

[3] Duong Tuan Tung, Do Van Dung, Nguyen Truong Thinh "Research on using PID algorithm to control simulation model of regenerative braking system based on driving cycles" IEEE International Conference on Systems Science and Engineering, HCMUTE, July 21-23, 2017.

[4] http://www.car-engineer.com/the-different-driving-cycles/

[5] F. J. Thoolen, "Development of an advanced high speed flywheel energy storage system," Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 1993.

[6] O.A. Ajayi "Application of automotive alternators in small wind turbines" Delft University of Technology, July 2012

[7] S. Shen, A. Serrarens, M. Steinbuch, and F. Veldpaus, "Coordinated control of a mechanical hybrid driveline with a continuously variable transmission," JSAE Review, vol. 22, pp. 453-461, 2001

[8] N. A. Schilke, A. O. DeHart, L. O. Hewko, C. C. Matthews, D. J. Pozniak, and S. M. Rohde, "The Design of an Engine-Flywheel Hybrid Drive System for a Passenger Car," Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 200, pp. 231-248, October 1, 1986 1986.

Corresponding author:
Duong Tuan Tung
Ho Chi Minh City University of Technology and Education, Vietnam
Email: tungdt@hcmute.edu.vn