Investigation on Energy Management for Air-Conditioning System in Electric Vehicle

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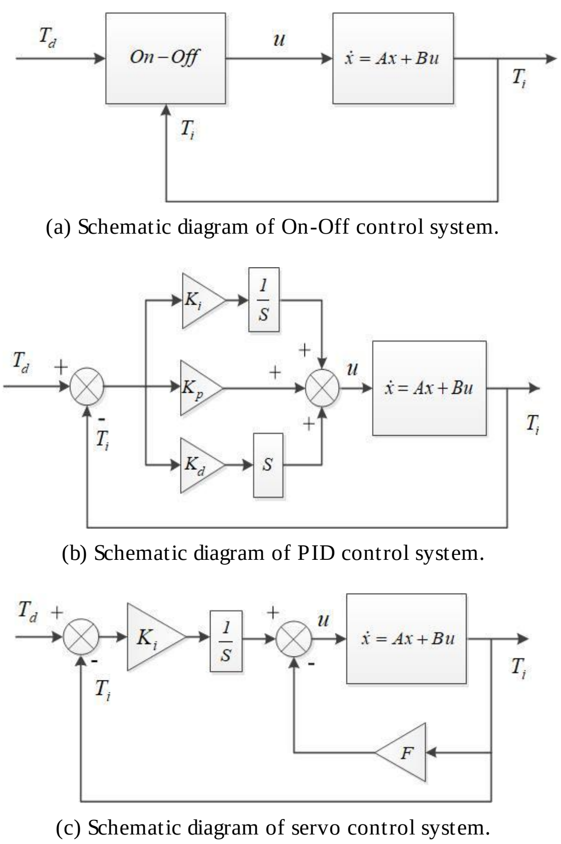
***Abstract*—This paper introduces servo control system. The servo control system is the optimization technique to reduce energy consumption for air-conditioning (A/C) system of battery electric vehicle (BEV). The system modeling of heat system in passenger room and battery pack are derived to represent in mathematic model. The characteristic of loss in Li-ion batteries during discharge are examined by experiment. The relationship between discharge rate and power loss in battery is tested by experiment kit. A new control system based on servo control system is presented to optimize the energy consumption. The simulation results exhibit that energy consumption and power loss of servo control system outperforms rather than PID and On-Off control systems and the energy loss of servo control system is 91,971 Wh, which is less than the PID and On-Off control systems about 0.1% and 0.25%, respectively.**

***Index Terms*—electric vehicle, air-conditioning, control system.**

I. INTRODUCTION

Nowadays, the amount of electric vehicle (EV) are increasing because it reduces pollution problem, which causes global warming as explained in the paper [1]. EV is powered by electric motor, energy of which is stored in the battery pack. The energy is consumed by two main systems such as powertrain system and air-conditioning system (A/C). It is a necessary system of electric vehicle in Thailand because the ambient temperature in Thailand is quite high.

According to papers [2-4], peak load was found in the air-conditioning system when it is operated with powertrain system. Ref. [2] introduced that energy consumption of A/C system reduces driving range about 36%. Power loss in battery pack is an important factor to indicate energy consumption. It depends on battery type, discharge rate, ambient and temperature of battery pack [5]. Battery pack type such as Li-Ion, Ni-MH and lead-acid, which have different characteristics and properties. Discharge ability will be reduced when discharge rate increases.



(a) Schematic diagram of On-Off control system.

(b) Schematic diagram of PID control system.

(c) Schematic diagram of servo control system.

Figure 1. Schematic diagram of control systems.

A/C system in battery electric vehicle concerns about energy consumption because the energy storage is limited and charging period requires a long period to fully charged. The conventional A/C control system is required working mode such as eco-mode and comfort mode. Eco-mode performs A/C system with limited power consumption. Then, the climate may be changed slowly.

On the other hands, A/C system will be operated with maximum performance in comfort mode, which concerns the passenger comfort. Then, the controller of A/C system should be designed by considering the efficiency of energy consumption such as efficiency of battery, battery assembly, and control technique.

To optimize energy consumption, control system is used to reduce discharge rate because the discharge rate should be proportional to the load. A/C system of internal combustion vehicle (ICV) and hybrid electric vehicle

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(HEV) are often controlled by On-Off control system. On the other hand, A/C system of present HEV, plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) are usually performed by PID control system, compressor of which are electric compressor such as Denso ES27, Denso ES34, and Delphi SP15. They can be controlled rotation speed relative to temperature in passenger room.

PID controller gains are usually designed by trial and error [6]. It is well-known as a classical control system. Linear quadratic regulator (LQR) method is presented as heuristic method in order to derive the optimal gains based on mathematical model of physical system. It is classified to modern control system. Ref. [6,7] presented LQR+PID control system, which are combined the solving method that LQR method is used to derive the state feedback gains and the output gains are designed by trial and error. The result of LQR+PID control system obtains the benefit from LQR and PID. It can improve time constant and settling time comparing with PID and LQR method. The trajectory tracking control system in the paper [8] is introduced that the feedback gains and the output gains are derived by LQR method. The feedback gains are multipliers of state feedback and the output gains are multipliers of output error. It is called servo control system.

Moreover, the desired input is adapted based on restriction so that the control system is nearly to the control system in the papers [6,7]. Fig. 1 present the schematic of On-Off, PID, and servo control system, respectively.

Therefore, this research investigates on heat balanced of automotive A/C system, characteristic of battery pack, servo control system with adaptive desired temperature, and comparison between conventional control system and the servo control system for optimizing energy consumption.

II. System Modeling Development

Heat transfer of passenger room describes variation of temperature in passenger room. Heat input of electric vehicle is contributed by battery, solar, and metabolism of passenger. Heat output is performed by air conditioning system. Then, passenger model describes the relationship between total heat input ($\sum \dot{Q}_{ip}$), heat output ($\dot{Q}_{op}$), and the variation heat in passenger room ($\dot{Q}_{p}$). It is given as

$$m_a c_{pa} \dot{T}_i = \dot{Q}_{mp} + \dot{Q}_{sp} + \dot{Q}_{bp} - \dot{Q}_{ac} \tag{1}$$

where, m_a is mass of air in passenger room. m_b is mass of battery. c_{pa} is specific heat of air

Heat input consists of heat from metabolic ($\dot{Q}_{mp}$), solar irradiation ($\dot{Q}_{sp}$), and battery pack ($\dot{Q}_{bp}$). Heat input by passenger ($\dot{Q}_{mp}$) occurs by human metabolism. It is given as

$$\dot{Q}_{mp} = \sum_{i=1}^{n} M_m A \tag{2}$$

where, M_m denotes metabolic heat generation. A is body's surface, which depends on weight and height. n is number of passengers.

Heat input by solar irradiation ($\dot{Q}_{sp}$) occurs by radiation from solar to passenger room. Average of solar irradiation ($\dot{Q}_{si}$) in Thailand is approximately about 1,000 W/m^2. The heat radiation enters to passenger room passing though roof and windshield surfaces. Then, it depends on heat transfer area and absorptivity of material. The solar heat input is expressed that

$$\dot{Q}_{sp} = \dot{Q}_{si} \left(A_r \beta_r + A_g \beta_g \right) \tag{3}$$

where, A_r is area of roof. A_g is area of windshield. β_r is absorptivity of roof. β_g is absorptivity of glass.

Heat input from battery ($\dot{Q}_{bp}$) is transferred from battery to passenger room. It can be computed by the relationship between temperature of battery and ambient temperature. The equation is given as

$$\dot{Q}_{bp} = U_p A_{bp} (T_b - T_i) \tag{4}$$

where, U_p is overall heat transfer coefficient between battery pack and passenger room. A_{bp} is top surface area of battery and T_i is temperature in passenger room.

To derive temperature of battery (T_b), it is increased by chemical process during discharge current and the battery is cooling by convection to ambient. Thus, temperature of battery can be computed as follows;

$$m_b c_{pb} \dot{T}_b = C_p P_s - U_b A_{bb} (T_b - T_a) - \dot{Q}_{bp} \tag{5}$$

$$C_p = \frac{1-\eta}{\eta_p} \tag{6}$$

where, U_b is the overall heat transfer coefficient of battery model. A_{bb} is area on bottom surface of battery pack. T_a is ambient temperature. P_s denote power supply from battery pack. C_p is coefficient of power loss. m_b is mass of battery. c_{pb} specific heat of battery pack. The value of parameters is measured from battery electric vehicle, which are expressed in Table I.

$$\dot{T}_i = \frac{U_p A_{bp}(T_b - T_i) + \dot{Q}_{sp} + \dot{Q}_{mp} - \eta_{COP} P_s}{m_a c_{pa}} \tag{7}$$

$$\dot{T}_b = \frac{-U_p A_{bp}(T_b - T_i) - U_b A_{bb}(T_b - T_a) + C_p P_s}{m_a c_{pb}} \tag{8}$$

Therefore, the heat in passenger room has an exchange with heat in battery pack. The equation (7) and (8) can be presented in matrix form as follows;

$$\dot{x} = Ax + Bu + Ev + Hw \tag{9}$$

where, $A = \begin{bmatrix} -\frac{U_p A_{bp}}{m_a c_{pa}} & \frac{U_p A_{bp}}{m_a c_{pa}} \\ \frac{U_p A_{bp}}{m_a c_{pb}} & -\frac{U_p A_{bp} + U_b A_{bb}}{m_a c_{pb}} \end{bmatrix}$, $B = \begin{bmatrix} -\frac{\eta_{COP}}{m_a c_{pa}} \\ \frac{C_P}{m_b c_{pb}} \end{bmatrix}$,

$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$, $E = \begin{bmatrix} \frac{1}{m_a c_{pa}} & 0 \end{bmatrix}^T$, $H = \begin{bmatrix} 0 & \frac{U_b A_{bb}}{m_a c_{pb}} \end{bmatrix}^T$,

$x = \begin{bmatrix} T_i & T_b \end{bmatrix}^T$, $u = P_s$, $v = \dot{Q}_{sp} + \dot{Q}_{mp}$, and $w = T_a$.

III. CONTROL SYSTEM

To design control system, the servo control system in the paper [8] is modified to control temperature as shown in Fig. 2. It obtains conventional servo control system with adaptive control temperature. The gain of servo controller is derived using Linear quadratic regulator (LQR) heuristic method. The equation (9) is linearized and it is arranged to state space equation that

$$\dot{\overline{X}} = \overline{A}\overline{X} + \overline{B}u \tag{10}$$

$$\overline{A} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \tag{11}$$

$$\overline{B} = \begin{bmatrix} B & 0 \end{bmatrix}^T \tag{12}$$

$$\overline{x} = \begin{bmatrix} x & 0 \end{bmatrix}^T \tag{13}$$

where, T_d is desired temperature in passenger room. ω is error between T_i and T_d. F and K_i denote proportional and integral gain.

Weighting matrix Q and R in (LQR) method is used to find F and K_i. The matrix is expressed in

$$Q = diag(5000, 0.0001, 2) \times 10^5$$

$$R = 6 \times 10^{10}$$

Therefore, the feedback gains are derived that

$$F = \begin{bmatrix} -0.9133 & -0.0015 \end{bmatrix}$$

$$K_i = \begin{bmatrix} -0.0018 \end{bmatrix}$$

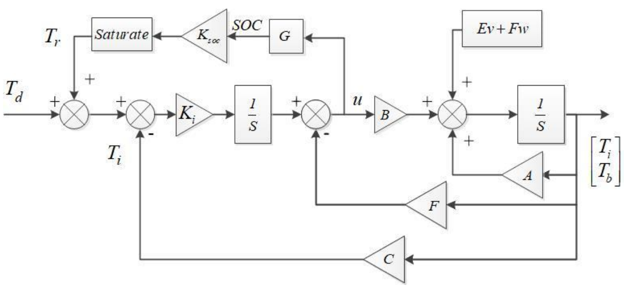


Figure 2. Servo control system with adaptive control temperature for A/C system.

TABLE I. PARAMETERS OF PASSENGER ELECTRIC VEHICLE.

Parameters	Value	Unit
Mass of battery (m_b)	208.8	kg
Mass of air (m_a)	1.8	kg
Area of battery on top surface (A_{bp})	0.9	m^2
Area of battery on bottom surface (A_{bb})	0.9	m^2
Are of roof (A_r)	2.2	m^2
Area of glass (A_g)	2.4	m^2
Absorptivity of roof (β_r)	0.8	-
Absorptivity of glass (β_g)	0.07	-
Specific heat of air (c_{pa})	1.0	kJ/kgC
Specific heat of battery pack (c_{pb})	0.9	kJ/kgC
Overall coefficient heat transfer of passenger model (U_p)	0.03	kw/m^2K
Overall coefficient heat transfer of battery model (U_b)	0.05	kw/m^2K
Coefficient of electric compressor (η_{COP})	2	-
Weight	65	kg
Height	1.7	m
Battery capacitor (E)	40	kWh

Adaptive control temperature is designed as proportional adjustment, which depends on state of charge (SOC) as shown in Fig. 5. SOC indicates remained energy in the battery pack. It can be derived as

$$G = SOC = 1 - \frac{1}{E}\int_0^t P_s(t)dt \tag{14}$$

$$T_r = K_{SOC}(1 - SOC) \tag{15}$$

where, E is maximum energy of battery pack. K_{SOC} denotes proportional temperature adaptive gain. Adaptive temperature (T_r) and the maximum of T_r should not exceed $\pm 2^o C$ from desired temperature so that K_{SOC} equals 2.

IV. CHRATERISTICS OF BATTERY

Li-ion battery may obtain dissimilar properties, which causes of chemical ingredients in the cell. NMC Li-ion cell is commonly used in electric vehicle and it has different capacity, which obtains specification as shown in Table II. They have different capacity such as 2,600 mAh, 3,000 mAh, and 3,200 mAh.

To demonstrate efficiency of discharge, the battery is connected to load and the discharge current and the voltage are measured using experiment system in Fig. 3. Discharge current is controlled by speed controller and it releases with constant current until empty. The battery pack is composed with four series and one parallel. The efficiency of discharge (η) can be derived as

$$\eta = \frac{\int_0^t P_s dt}{E_{\max}} \tag{16}$$

where, $E_{\max}$ is maximum energy in battery, which is defined by factory.

The result exhibits that the efficiency decreases when the discharge current is increased. The trend of efficiency as shown in Fig. 4 and it can be fitted by linear equation.

$$\eta = c_{dis}\, i_{dis} + e_{\max} \tag{17}$$

where, i_{dis} denotes discharge current. c_{dis} is coefficient of discharge current. $e_{\max}$ is maximum efficiency of battery pack in experiment. The efficiency and the coefficient of discharge current are presented as Table. III.

According to the results in Fig. 4, $e_{\max}$ affects to maximum energy of battery. c_{dis} seems reduction rate of battery's efficiency relative to discharge current. It can indicate power loss when discharge current is increased.

However, the 2,600 mAh battery has high efficiency than other cells during 1-3 A but the efficiency is reduced faster than others. The three batteries obtain similar efficiency when it is over than 5 A.

By the way, 3,000 mAh 3,200 mAh batteries have initial efficiency less than 2,600 mAh battery. Therefore, the battery's cell should be selected corresponding with total discharge rate of the system.

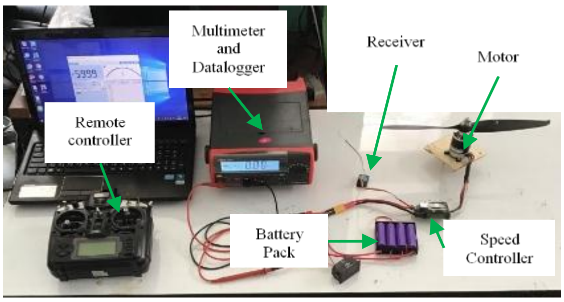


Figure 3. Setup of experiment to test properties of battery.

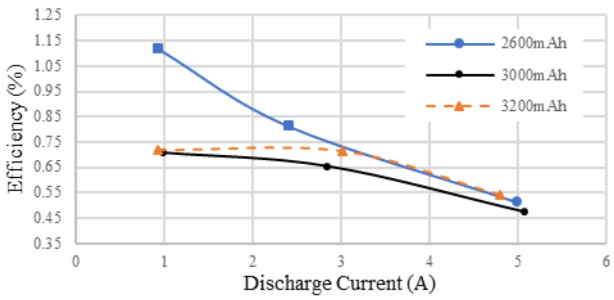


Figure 4. Efficiency with discharge current of battery.

TABLE II. SPECIFICATION OF BATTERY PACK FOR EACH CELL

	Cell		
	2600mAh	3000mAh	3200mAh
Maximum capacity (Ah)	2.6	3	3.2
Fully charged voltage (V)	4.2	4.2	4.2
Max. continuous discharge current (A)	10	20	10
Nominal discharge current (A)	2.2	2.5	2.7
Capacity (Ah) at nominal voltage	2.2	2.5	2.8
Nominal voltage (V)	3.65	3.6	3.7
Rated capacity (Ah)	2.6	3	3.2
Number of parallel (n_p)	22	19	18

TABLE III. EFFICIENCY OF 18650 LI-ION BATTERY AT SEVERAL DISCHARGE RATES

	Discharge Rate (A)	Discharge Current per cell (A)	η	C_p
2600Ah	1.0	0.94	1.10	0.024
	2.6	2.41	0.81	
	5.0	4.98	0.51	
3000Ah	1.0	0.93	0.72	0.029
	3.0	3.02	0.71	
	5.0	4.80	0.54	
3200Ah	1.0	0.99	0.70	0.026
	3.2	2.85	0.65	
	5.0	5.07	0.47	

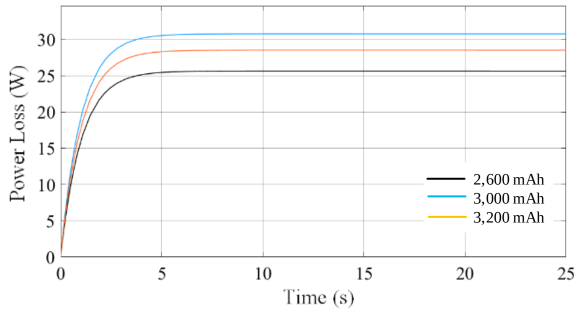


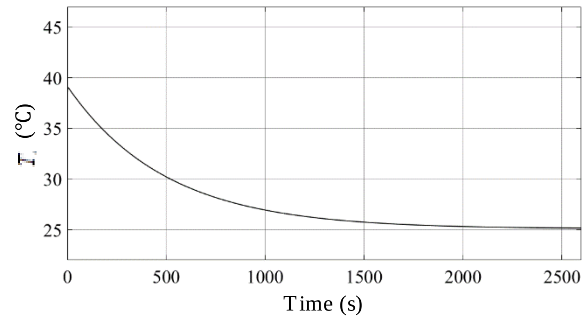
Figure 5. Power loss using servo control system for batteries

V. RESULT OF ENERGY CONSUMPTION

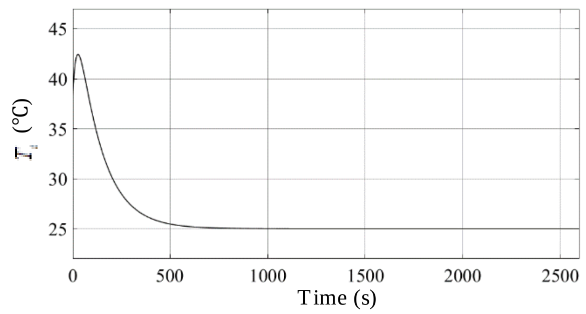
To simulate climate change in passenger room and design of battery pack, three battery models in Table III are stacked to similar capacity and they are supplied to the control system. The battery capacity is defined as 40 kWh and the number of parallel is 22, 19, and 18 parallels, respectively. The boundary condition is defined that the desired temperature is 25 °C, initial temperature of battery and passenger room are 38 °C, ambient temperature is 38 °C, the heat radiation from solar is 1.938 kW, and the heat from metabolic is 0.148 kW. The PID controller gain is defined as -0.0505, -0.0004, and 0.0098 for proportional, integral, derivative gains, respectively.

Fig. 5 shows the power loss of 2,600 mAh, 3,000 mAh, and 3,200 mAh batteries using servo control system. The gradient of 2,600 mAh battery is the least also the power loss of system. The discharge power is similar to certain the climate change as shown in Fig. 6. The temperature control using PID and Servo controllers are precisely than on-off controllers. It remains some temperature swing, which is limited at +/- 2 Celsius. The power loss of 2,600 mAh is lowest than others because each cell has specified continuous discharge current at 10 Amperes. Then, it means that the number of parallel is important to decrease discharge current of each cell.

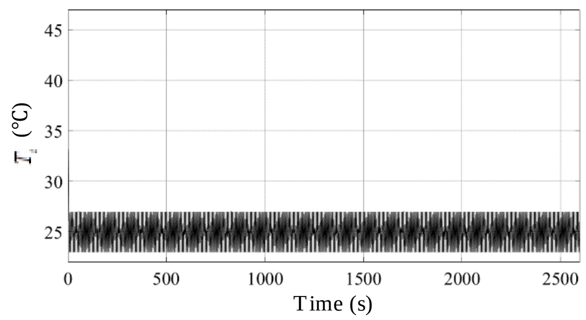
The simulation result of the energy loss in an hour, the energy loss of battery 2,600 mAh and 3,200 mAh are less than 3,000 mAh battery about 16.6% and 7.29%, respectively. Thus, the simulation of energy consumption of A/C system, temperature in passenger room, and power loss of battery are demonstrated based on 2,600 mAh battery.



(a) Temperature in passenger room of servo control system.



(b) Temperature in passenger room of PID control system.



(c) Temperature in passenger room of On-Off control system.

Figure 6. Temperature in passenger room using control systems.

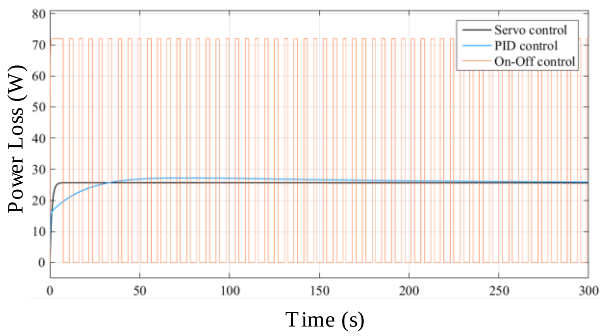


Figure 7. Power loss using 2600 mAh battery for servo, PID, and On-Off control systems.

Fig. 7 presents that the servo control system with adaptive temperature control has the large time constant. PID controller performs with the highest overshoot. The On-Of controller has fastest climate change because it executes with maximum power or no power, and 6 seconds for of cut-off power cycle.

TABLE IV. ENERGY LOSS USING 2,600 MAH FOR SERVO, PID, AND ON-OFF CONTROL SYSTEMS

	Servo	PID	On-Off
Energy Loss (Wh)	91,971	92,114	92,206

The result of power loss using control systems are presented in Fig. 7. The overshoot of servo control system is lower than PID control system because the settling time of servo control system is faster than PID control system. However, On-Off control system has the greatest power loss because it provides fully discharge from battery to the A/C system. Moreover, the energy loss of servo control system is 91,971 Wh, which is less than the PID and On-Off control systems about 0.1% and 0.25%, respectively. The result of energy loss using control systems is shown in Table IV.

VI. CONCLUSION

This paper describes the problem of A/C system in BEV, system modeling, the parameters affect to the efficiency of battery, and a new control system based on servo control system.

The characteristic of battery deals power loss during discharge and efficiency. The three battery models have similar continuous discharge rate but they have different capacity such as 2,600 mAh, 3,000 mAh, 3,200 mAh. The efficiency of 2,600 mAh performs highest efficiency during low discharge rate and the efficiency decreases to similar with other models when discharge rate is greater than 3 Amperes.

To optimize efficiency of battery pack, number of parallel and range of discharge current have been concerned. Range of discharge current depends on load of battery electric vehicle and number of parallel will splits the total discharge current to each parallel.

PID and the servo controllers can reduce energy consumption but on-off controller because the energy loss depends on discharge rate. On-off controller always perform with highest performance in a period and it is turn off A/C system. PID and servo controllers have almost similar but the feedback gain of the servo controller is designed based on LQR method in order to optimize energy consumption. Adaptive temperature control gain will increase the desired temperature based on state of charge, which causes to reduce some energy loss.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

This paper is a part of master thesis. P. Veerathanaporn has conducted the paper under vision of D. Phaoharuhansa. His research focuses on control system with hybrid rechargeable energy storage system for automotive air conditioning system. P. Veerathanaporn performs the results and he has been advised to adapt conventional control techniques by D. Phaoharuhansa.

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