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MODELLING, SIMULATION AND OPTIMAZATION OF DISCHARGE ULTRACAPACITOR FOR PLUG IN HYBRID ELECTRIC RECREACTIONAL BOAT

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ABSTRACT

Hybrid vehicles are one such alternative and an important part of them is the energy storage system. A series-parallel plug-in hybrid electric recreational boat (PHERB) is a new model for recreation boat innovation was introduced in this work. In PHERB power train, the main power source to drive the boat is electric machine and the primary energy source is an energy storage system (ESS). The ESS was consisted of ultracapacitor and battery. This paper presents modelling of ultra capacitor in MATLAB/SIMULINK environment based on mathematic equation, the design of a closed-loop feedback control system used proportional-integral controller and optimization. The control system is optimised by using genetic algorithm to provide the desired power with respect to the power reference curve. The optimal parameters obtained further improved the performance of PHERB powertrain control compared to non-optimal one.

Keywords: PHERB, powertrain, ESS, ultra capacitor, GA.

INTRODUCTION

Nowadays the increasing concerns on the environment and the use of non-renewable energy sources makes the importance of developing vehicles using alternative energy sources is recognized worldwide [1]. In addition, the fossil fuel depletion and global warming issues have changed the prospective of transportation mode from internal combustion engine vehicle into greener vehicular system. This matter is related to the transport sector which contributes for 19% of the global energy use and 23% of the energy related carbon dioxide (CO_2) emissions [2]. In PHERB powertrain, the main power source to drive the boat is electric machine (EM). The primary energy source of EM is energy storage system (ESS) during the regenerative reverse and delivers power for peak acceleration. The internal engine combustion (ICE) is set as a backup power source. The power converter is differs for both battery pack and ultracapacitor pack. It is only operated under certain conditions and will not be available all the time in order to minimize the fuel consumption and harmful emissions [3].

To achieve the minimum fuel consumption and emission, ESS has been one of the important features in the development of plug-in hybrid vehicle. Its characteristics such as specific energy and specific power greatly affect the performance of plug-in hybrid vehicle. ESS consists of two components which are battery and ultracapacitor. Batteries are the most common energy storage component for these vehicles because of their high energy density, compact size and reliability [4]. However, there are disadvantages of batteries that are poor properties of low temperature, low cycle life and specific power [5]. Ultracapacitor known as electric double layer capacitor [6-9] is a kind of novel energy storage element, which contains many advantages that battery and traditional capacitor have, such as fast charge and discharge time, large capacity, long cycle life and other characteristics. That is why the ESS has to be composed with batteries and ultracapacitor.

In this paper, discharged ultracapacitor is studied on detailed of ultracapacitor model in MATLAB/SIMULINK environment using mathematic equation. The model of ultracapacitor control by a closed-loop feedback control system. This system is built based on the proportional-integral (PI) controller. To optimize the control system, genetic algorithm (GA) is used to provide the desired power with respect to the power reference curve. The optimal parameters obtained further improved the performance of PHERB powertrain control compared to non-optimal one.

MODELLING OF THE ULTRACAPACITOR

The parameters and specifications of the ESS in PHERB powertrain is shown in Table-1 [10]. The data are essential in the selection of adequate ultracapacitor for modelling. In this case, Maxwell ultracapacitor is used with the specifications is given in Table-2.

Table-1. Parameters and specifications of the main component in PHERB powertrain.

Component	Parameters and specifications
ICE	20 kW @ 3000 rpm
EM	30 kW AC induction motor
ESS	Li, 5 kWh, 6 Ah

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Table-2. Specification of Maxwell ultracapacitor [11].

MOUNTING	BUS BAR
Capacitance, C (F)	2700
Voltage (V)	2.5
Internal resistance, DC (ohm)	0.001
Internal resistance, 1 kHz (ohm)	0.00055
Rated current, (A)	100
Operating temperature range, (C)	-40 to 65
Maximum energy, (mAh)	1800

Figure-1 demonstrates the input and outputs of the ultracapacitor model. The input of the ultracapacitor model is the power demand (*Pd*), and the output is actual power (*Puc*), voltage (*Vuc*), current (*Iuc*), and state of charge (*SOCuc*) of the ultracapacitor pack. Figure-2 displays the ultracapacitor model in MATLAB/SIMULINK environments.

The ultracapacitor model is built based on mathematic equation. The *Iuc* produced by the ultracapacitor pack can be calculated from *Vocpack* and *Pd*. By Kirchhoff's Law, ultracapacitor voltage calculation (*Vuc*) in equation 1 is the open circuit voltage of the ultracapacitor (*Voc*) minus the voltage drop to the internal resistance of the ultracapacitor, *Ruc* and multiple with current, *Iuc*.

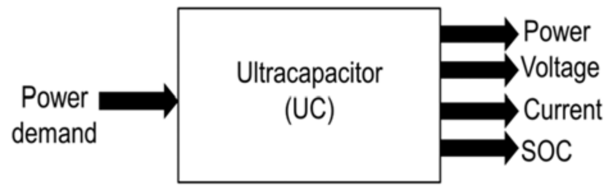

Figure-1. Basic block diagram of ultracapacitor model.

The corresponding output power of the ultracapacitor can then be calculated by

$$Vuc = Voc - Ruc.Iuc \quad (1)$$

$$Puc = Vuc.Iuc = Voc.Iuc\text{-}RIuc^2 \quad (2)$$

Under the condition that there is enough energy stored in the ultracapacitor, the output power should equal the power demand in equation 3. Therefore, the *Iuc* of the ultracapacitor can be obtained by solving equation (4)

$$Pd = Puc = Vuc\ Iuc = VocIuc\text{-}RIuc^2 \quad (3)$$

$$Iuc = (Voc \pm \sqrt{(Voc^2\text{-}4Ruc.Pd)})/2Ruc \quad (4)$$

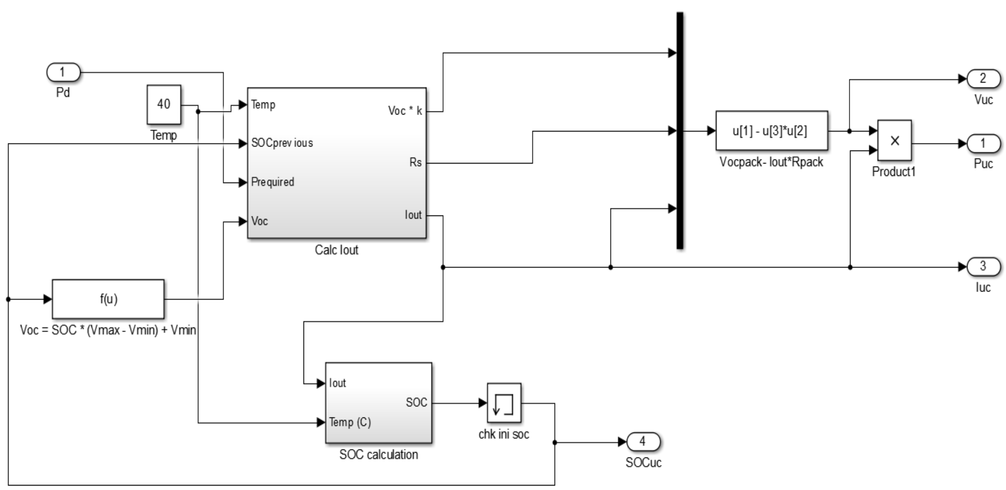

Figure-2. The ultracapacitor model in MATLAB/SIMULINK environment.

where *Voc* is open circuit voltage, *Ruc* is internal resistance of ultracapacitor and *Pd* is power demand. *Ruc* for ultracapacitor is different for discharging and charging. In this study, only discharging ultracapacitor determined. The *SOC* can be determined in terms of voltages in equation 5 where *Vmin* is the minimum voltage and *Vmax* the maximum voltage of the ultracapacitor. Open circuit voltage of the ultracapacitor (*Voc*) can be calculated using equation 6. From the mathematical equations presented in equations 1 - 6, the model has been developed in the MATLAB/SIMULINK environment. Figure-2 shows the ultracapacitor model in MATLAB/SIMULINK environment.

$$SOC = Voc\text{-}Vmin/Vmax\text{-}Vmin \quad (5)$$

$$Voc = SOC\ [(Vmax\text{-}Vmin)]+Vmin \quad (6)$$

DESIGN AND OPTIMIZATION OF THE POWERTRAIN CONTROL SYSTEM

After the ultracapacitor model is developed and validated, the closed-loop feedback control system of the

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model is designed as shown in Figure-3. The PI controller is used so that the power of the ultracapacitor can be controlled according the load demand. In other words, it is necessary to provide an optimal tuning of the PI control parameters in order to improve the response of the ultracapacitor model, that is, the power output of the ultracapacitor is based on the power demand. PI controller in the closed-loop feedback system is used to process the error value that is the difference between a reference power set point and the actual output power from the ultracapacitor. In this case, a proportional gain (*Kp*) had the effect of reducing the rise time but never eliminate, the steady-state error. By adjusting *Kp* and integral gain (Ki) the dynamic properties of the controller can be modified. An integral control, *Ki* had the effect of eliminating the steady-state error for a constant or step input, but it may make the transient response slower.

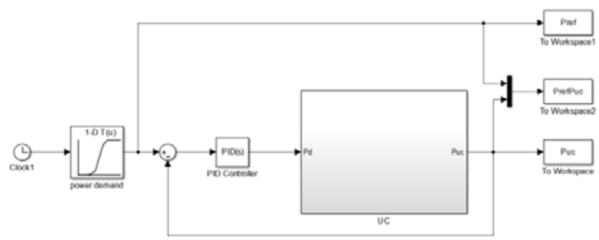

Figure-3. Closed-loop feedback control system.

For the purpose of optimization, the initial population of the PI parameters were chosen by trial and error method. Then, tuning of controller using GA is carried out with the GA parameters as shown in Table-3. In this case, 40 chromosomes in one population have been chosen because the chances of better performances are higher with high chromosomes number. The selection method determines how individuals are selected for mating. In this research, Roulette Wheel selection method is used because it allows the weaker chromosomes to be selected many times. Crossover probability controls the frequency of crossover. A larger crossover probability enhances the probability that the GA opens up new search areas, but it destroyed excellent chromosomes if it is too large. Here, the chosen crossover probability value is 0.95. For mutation, it is the occasional random alteration of a value of a string position. Low frequency mutations prevent the possible loss of a single and important gene in the population, the high frequency mutations enables heredity and tends to be a purely random search [12]. Usually, the mutation probability is 0.05 but in this simulation, the mutation probability used is 0.085. The selected maximum number of generations is 200 in order to terminate the continuous evolution procedure. For the fitness function, Integral of Time Multiply by Absolute Error is used. The flowchart of GA process is as shown in Figure-4.

Table-3. GA parameters.

GA parameters	Value/Method
Population Size	40
Number of Generations	200
Crossover Probability	0.95
Mutation Rate	0.085
Selection Method	Roulette Wheel Selection
Fitness Function	Integral of Time Multiply by Absolute Error
Variable bound [*Kp Ki*]	[-100 250; -100;250]

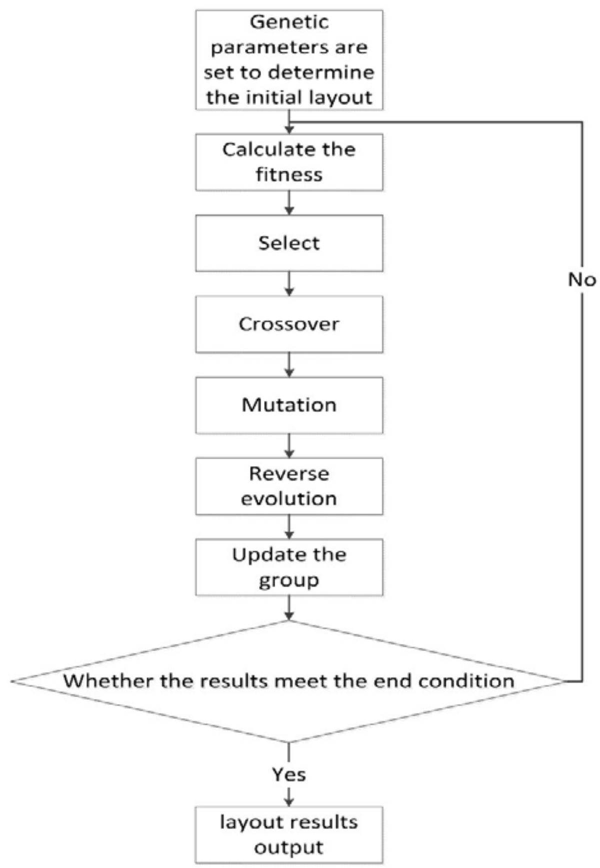

Figure-4. Flowchart of GA process [12].

RESULTS AND DISCUSSIONS

Once the ultracapacitor model is developed, the power demand for 2060 s is used in the simulation that is based on the Kuala Terengganu driving cycle used [13]. The graph of power, voltage discharge, current and state of charge of ultracapacitor, can be seen in Figures 5-8, respectively. The current for PHERB reached its peak because of the high input power demand and it has to give out the high power out. The current and the power out for PHERB are proportional. The voltage discharge and state of charge shows that it is decreasing over time.

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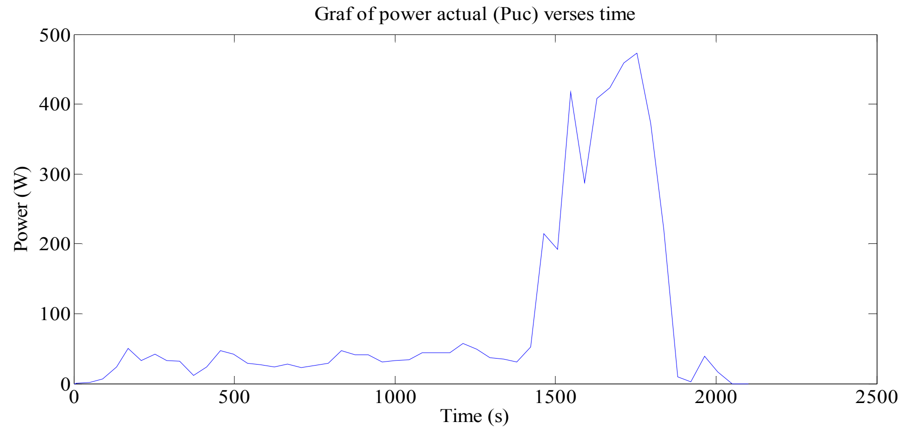

Figure-5. P_{UC} versus time.

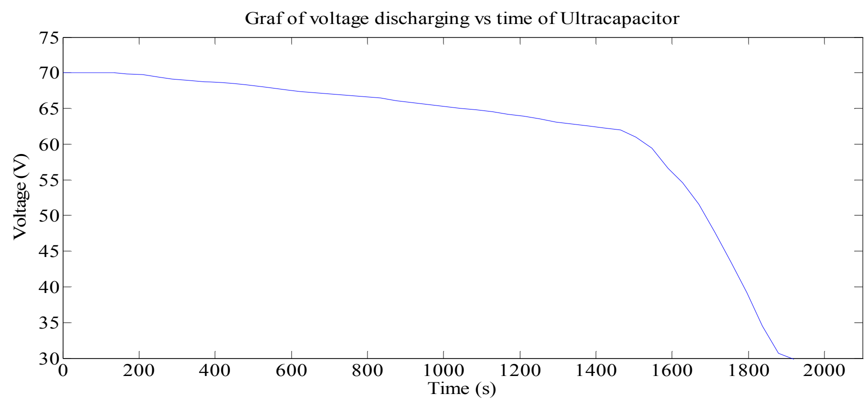

Figure-6. Voltage discharge versus time.

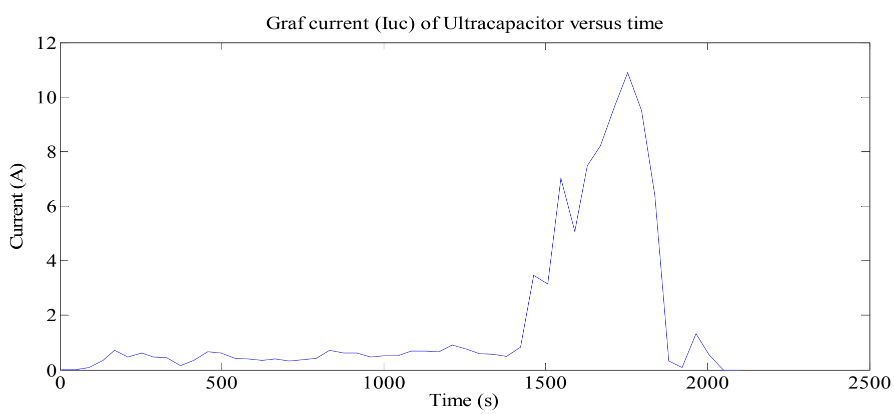

Figure-7. Current versus time.

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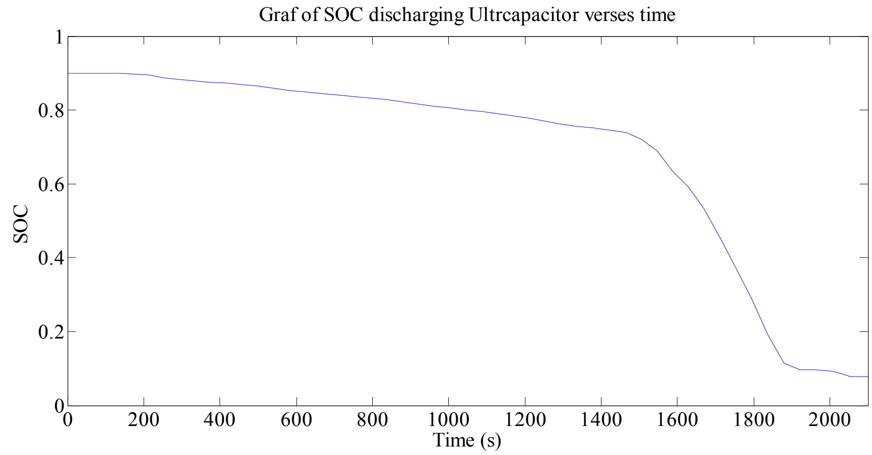

Figure-8. SOC versus time.

For GA optimization, the performance of the developed system is firstly tuned by trial-and-error of the PI control gains. The *Kp* and *Ki* value is set to 1. Figure-9 shows the results of power system response before GA optimization. The system is then optimized by adjusting the PI parameters using GA with the lower bound of -100 and upper bound of 250. Figure-10 shows the result of power response of the system that has been tuned with GA.

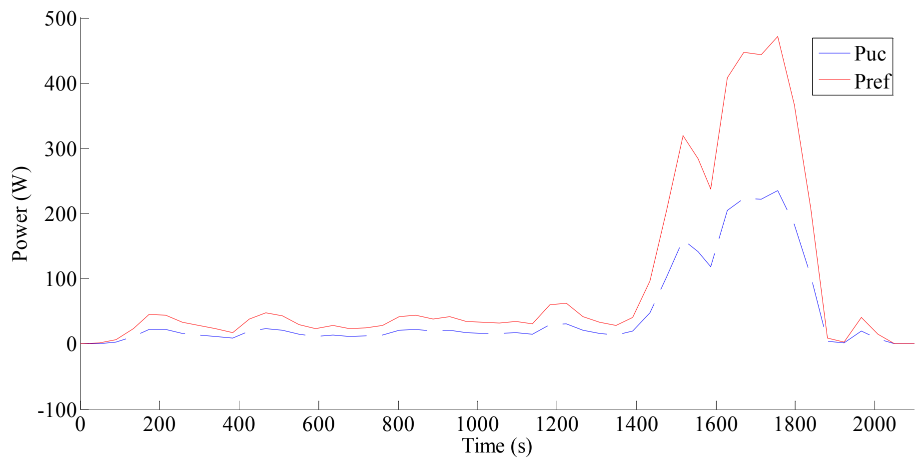

Figure-9. Power response before GA optimization.

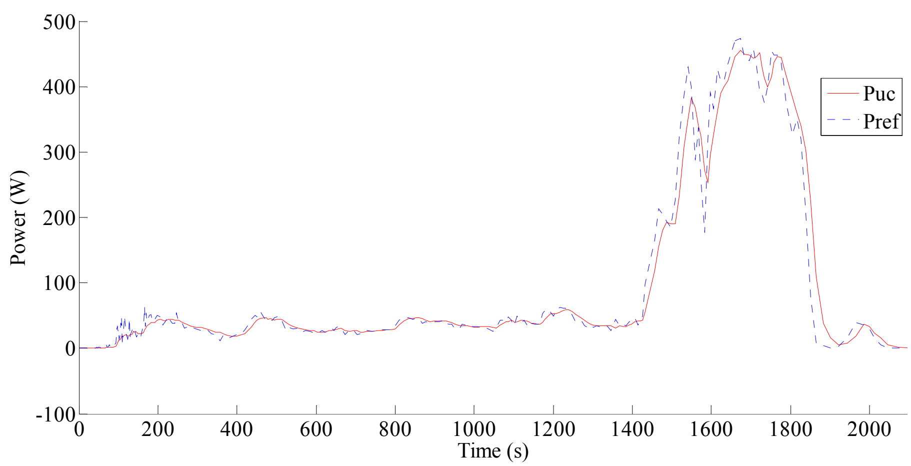

Figure-10. Power response after using GA.

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CONCLUSIONS

A power flow model of PHERB is presented using ultracapacitor which is the crucial part of the ESS. The ultracapacitor specification and parameters have been obtained based on the specification in the data sheet. The ultracapacitor discharge model is used to provide power to the PHERB. The reference load curve has been designed based on fluctuated power that represents acceleration and deceleration at a specific time. With the developed closed-loop feedback control system for the PHEB drive train, optimization of the PI control parameters has been carried out using GA. The results show that the ultracapacitor can track the power reference closely with the minimum error. It shows that use of ultracapacitor with the optimal control system can generally improve the performance of the PHERB.

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