Jurnal
Teknologi

Full Paper

MODELING, SIMULATION AND MODEL OPTIMIZATION OF INTERNAL COMBUSTION ENGINE FOR PHERB POWERTRAIN

Article history
Received
28 June 2016
Received in revised form
21 April 2017
Accepted
31 May 2017

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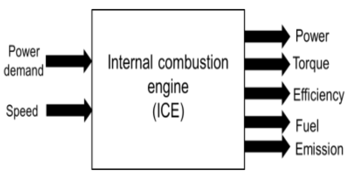
Graphical abstract



Abstract

Internal combustion engine (ICE) is the most important part in vehicle. Generally, the combustion of ICE is facilitated by petrol and exhaust gas emission from vehicles is a primary contributor to the environmental pollution problem. In this research, Plug-in hybrid electric recreational boat (PHERB) is introduced and PHERB has a combination of energy storage system, ICE and electric machine. The objective of this work is to derive a detailed model of ICE in MATLAB/SIMULINK environment, develop proportional-integral (PI) controller for ICE and optimize ICE using a Genetic Algorithm (GA) based on PI controller. The efficiency of ICE for PHERB obtained was 40 % at rotational speed 4000 rpm of the engine. Via using the GA, the optimal performance of ICE is found by power demand curve, as a reference for the model with mutation probability used is 0.085. In terms of the performance results, the optimal tuning parameters of ICE for PHERB had a significantly improved performance towards green and clean technology.

Keywords: PHEV, PHERB, Powertrain, ICE, GA

Abstrak

Enjin pembakaran dalaman (ICE) adalah bahagian yang paling penting dalam kenderaan. Secara umumnya, pembakaran ICE oleh petrol dan pencemaran dari kenderaan merupakan penyumbang utama kepada masalah pencemaran alam sekitar. Dalam kajian ini, *plug-in hybrid electric recreational boat* (PHERB) diperkenalkan dan PHERB mempunyai gabungan sistem penyimpanan tenaga, ICE dan mesin elektrik. Objektif kajian ini adalah untuk mendapatkan satu model terperinci bagi ICE dalam persekitaran MATLAB/SIMULINK, membina pengawalan berkadar-integral (PI) untuk ICE dan mengoptimumkan prestasi ICE menggunakan algoritma genetik (GA) berdasarkan pengawalan PI. Kecekapan ICE untuk PHERB diperolehi adalah 40% pada kelajuan putaran 4000 rpm enjin. Via menggunakan GA, prestasi optimum ICE didapati oleh keluk permintaan kuasa, sebagai rujukan untuk model dengan mutasi kebarangkalian digunakan ialah 0.085. Dari segi keputusan prestasi, parameter penalaan optimum ICE untuk PHERB mempunyai prestasi yang ketara lebih baik ke arah teknologi hijau dan bersih.

Kata kunci: PHEV, PHERB, rangkaian kuasa, ICE, GA

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1.0 INTRODUCTION

Every vehicle has an own engine. Engine have are two types which are external combustion engine and internal combustion engine (ICE). ICE has two types, which is 2-stroke engine where a piston moves one time up and down while 4-stroke engine piston moves two times inside the cylinder and complete one crankshaft revolution during single time of fuel burn. In automobile, truck and buses, the 4-stroke ICE used petrol or gasoline to run the vehicle, the emission exit can effect environmental pollution [1], and for marine transportation, engines contribute to the total exhaust gas emissions. This contribution to air emissions is particularly significant for cruise ships [2]. According to Miola *et al*., 2011, emissions from the maritime transport sector represent a significant and increasing air pollution source. The amount of gases emitted from marine engines into the atmosphere is directly related to total fuel oil consumption of marine transportation. Thus, a worldwide towards cleaner and greener technology is observed nowadays to solve this delinquent.

One of the methods to realize this move is acceptance of alternate transportation solution; plug in hybrid electric vehicles (PHEVs). PHEVs provide one of the most promising solutions of the clean technology. PHEVs reduce the fuel consumption by using electrical energy stored in batteries along with ICE. This system must be applied to marine transportation to reduce emission from it. Consequently, Plug-in hybrid Electric Recreational Boat (PHERB) was introduced.

PHERB was built to reduce the fuel consumption and emissions for marine transportation. Figure 1 shows a schematic illustration of the series-parallel PHERB powertrain [3-6]. According to Salisa *et al.*, 2015, the main power source to drive the boat is the electric machine (EM). The primary energy source of the EM is the battery pack to supply continuous power to the boat and the secondary energy source is the ultra-capacitor pack which is used to absorb the power pulses during reverse and deliver power for peak acceleration. The ICE is set as a backup power source [7].

Before the ICE prototype was build, modelling and simulation is a main concern on the development model [8-12]. So, this paper presents the modeling of ICE for PHERB using mathematical equation and simulation in MATLAB/SIMULINK environment. After that, the closed loop feedback system is developed and the optimization using Genetic Algorithm (GA) method to find the best tuning parameters for the Proportional Integral (PI) controller. The results of the model development and verification as well as the performance of the proposed system are comparing with the conventional trial and error method.

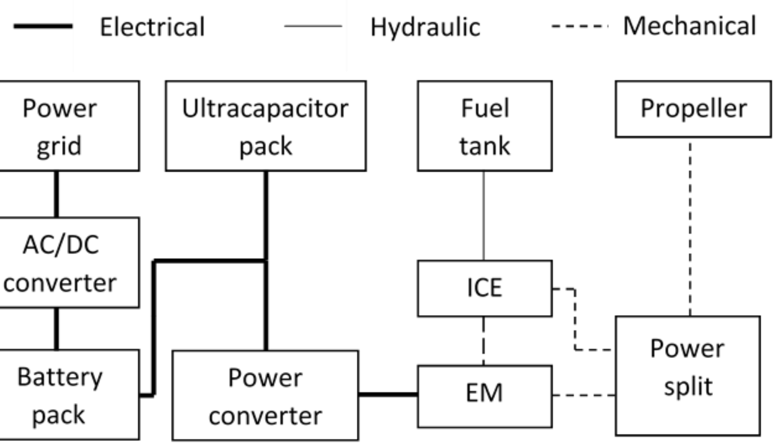

Figure 1 A schematic illustration of PHERB [3-6]

2.0 METHODOLOGY

There are 4 stages in conducting this research which are determines ICE parameter and specification, ICE modelling stage, developing a closed loop feedback control system and optimization stage.

2.1 ICE Parameters and Specifications

The preliminary step before starting the modelling stage is to determine the parameters and specifications of ICE which is listed in Table 1. Once the parameters and specifications of ICE are determined, the model is constructed using MATLAB/SIMULINK environment as shown in Figure 2.

Table 1 Parameters and Specifications of ICE model

Parameters	Specification
Maximum Power	43 kW
Maximum Rotation Speed	4000 RPM
Peak Torque	101.69 Nm
Engine displacement	1.5 L
Maximum Efficiency	36%
Heating value of the fuel	42.6 J/kg
Density of the fuel	0.749 kg/L
Fuel-to-air ratio	14.5

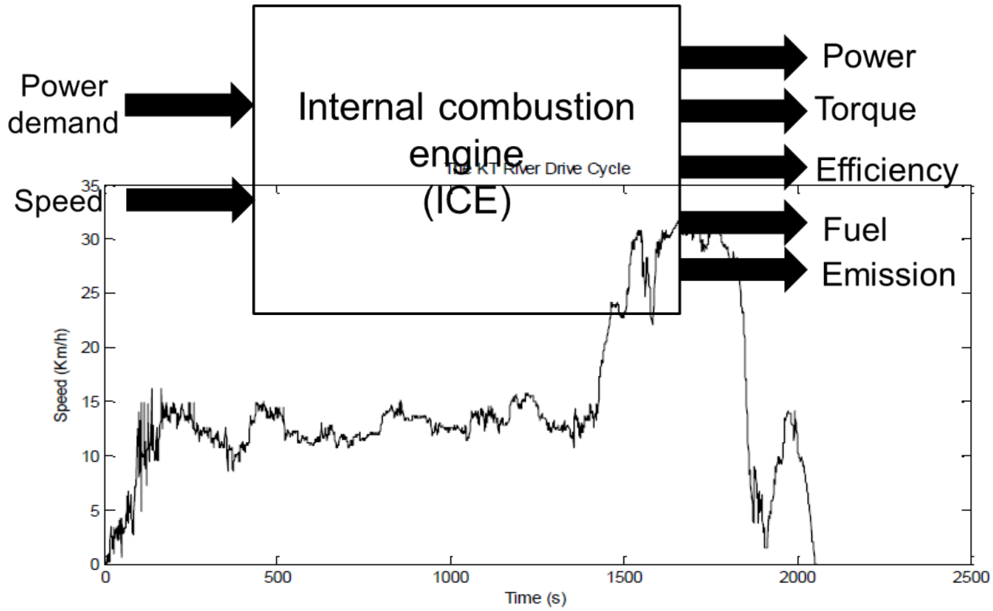

Figure 2 Basic block diagram for ICE

The desired input and output variables are calculated. The ICE model was built based on the basic operating characteristics of an ICE particularly on a 4-stroke engine type. The input speed and power was getting from the Kuala Terengganu (KT) driving cycle [13] using dynamic boat equation [14-18] shown in Figures 3 and 4. The equations involved in this model were shown from Eq 1 - 9.

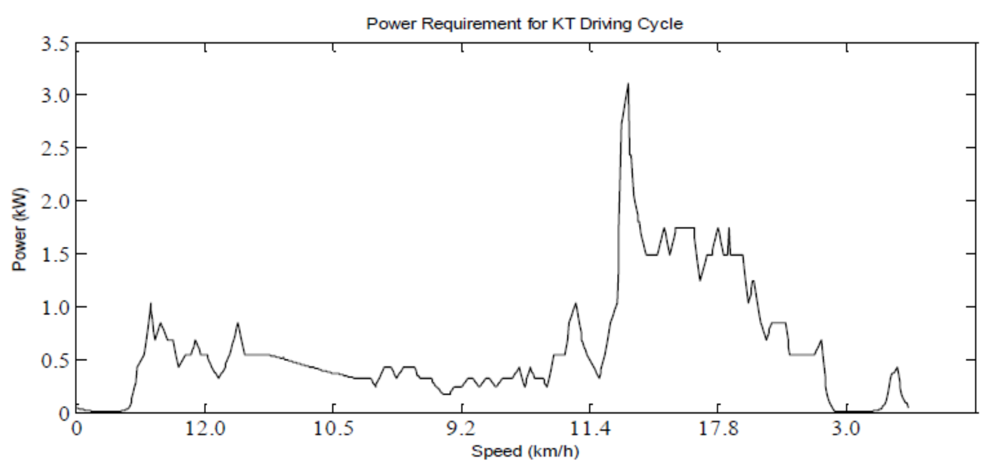

Figure 3 KT driving cycle [13]

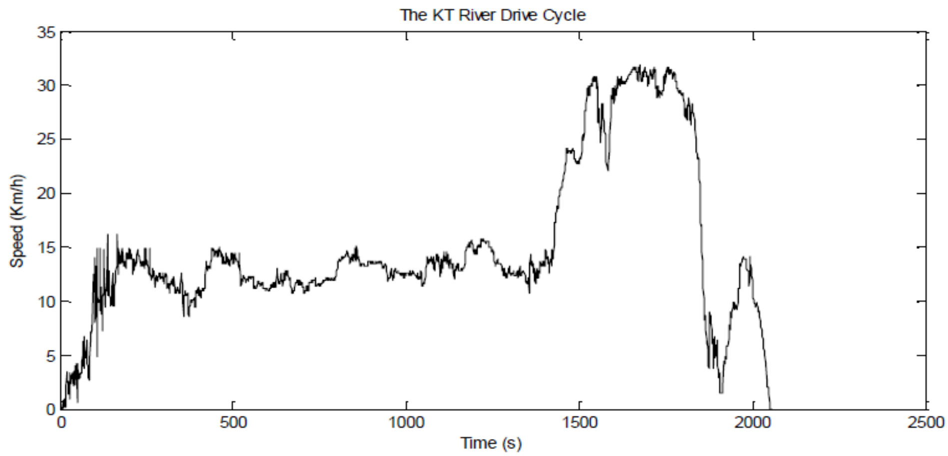

Figure 4 Power requirement using KT driving cycle [13]

2.2 ICE Modeling

The torque, Q required can be calculated using Eq 1 where P is power output and ω is rotational speed

$$Q = P/\omega \quad \text{(Eq 1)}$$

Fuel conversion efficiency (η_f) also known as, the engine's efficiency is the effectiveness of an ICE to convert chemical energy to mechanical energy. The fuel conversion efficiency are calculated by heating value (Q_{hv}) that is the amount of thermal energy released by the fuel during combustion and the specific fuel consumption (SFC) is the efficiency of an engine as shown in equation Eq 2,

$$\eta_f = \frac{1}{SFC.\,Q_{hv}} \quad \text{(Eq 2)}$$

SFC is calculated from fuel flow rate (mf) and *P* as shown in Eq 3.

$$SFC = \frac{mf}{P} \quad \text{(Eq 3)}$$

Eq 4 shows the engine's performance at a more useful relative performance that is measured using mean effective pressure (MEP). MEP of an engine is its work per cycle as in power (P) and number of crank revolution for each power stroke per cylinder (n_R) divided by the volume displaced (V_d) and the rotational speed of crankshaft (N). Eq 5 shows the MEP for four-stroke cycle engines where ($\frac{F}{A}$)the fuel-to-air ratio is, $P_{a.i}$ is the inlet air density.

$$MEP = \frac{Pn_R}{V_d N} \quad \text{(Eq 4)}$$

$$MEP = \eta_f \eta_v Q_{hv} P_{a.i}(\frac{F}{A}) \quad \text{(Eq 5)}$$

As for the volumetric efficiency (η_v) as shown in Eq 6, the effectiveness of an engine's induction process where the mass of air inducted into cylinder per cycle (m_a) divided by inlet air density ($P_{a.i}$) and volume displaced (V_d)

$$\eta_v = \frac{m_a}{P_{a.i}.V_d} \quad \text{(Eq 6)}$$

The Eq 7 and Eq 8 is the expression of engine's power, *P* and torque, *Q* in terms of MEP.

$$P = \frac{V_d.N.MEP}{2} \quad \text{(Eq 7)}$$

$$Q = \frac{V_d.MEP}{4\pi} \quad \text{(Eq 8)}$$

Eq 9 shows the specific emission of oxides of nitrogen, carbon monoxide and hydrocarbon where it is the mass flow rate of the pollutant (m) divided by the power output (P).

$$SNO_x = \frac{mNO_x}{P}$$

$$SCO = \frac{mCO}{P}$$

$$SHC = \frac{mHC}{P}$$

$$SPM = \frac{mPM}{P}$$

$$SO_2 = \frac{mO_2}{P} \quad \text{(Eq 9)}$$

From the mathematical equations presented in equation 1 – 9, the model has been developed in the MATLAB/SIMULINK environment. Figure 5 shows the ICE model with the consistent input and output variables representing the 4-stroke ICE.

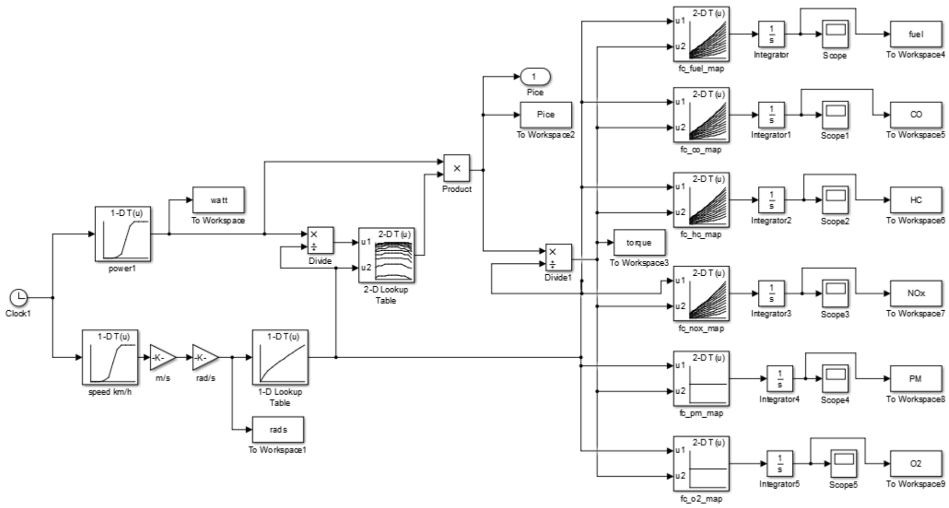

Figure 5 ICE model in MATLAB/SIMULINK environment

2.3 ICE Close Loop Feedback System

Once the model is developed, the next stage is constructed a closed loop feedback system as shown in Figure 6. The PI controller used in a way that power of the ICE can be controlled according load demand. It mean to deliver an optimal tuning of the PI control parameter in order to increase the response of ICE is essential. The power output of the ICE based on power demand curve that characterized typical motion of PHERB.

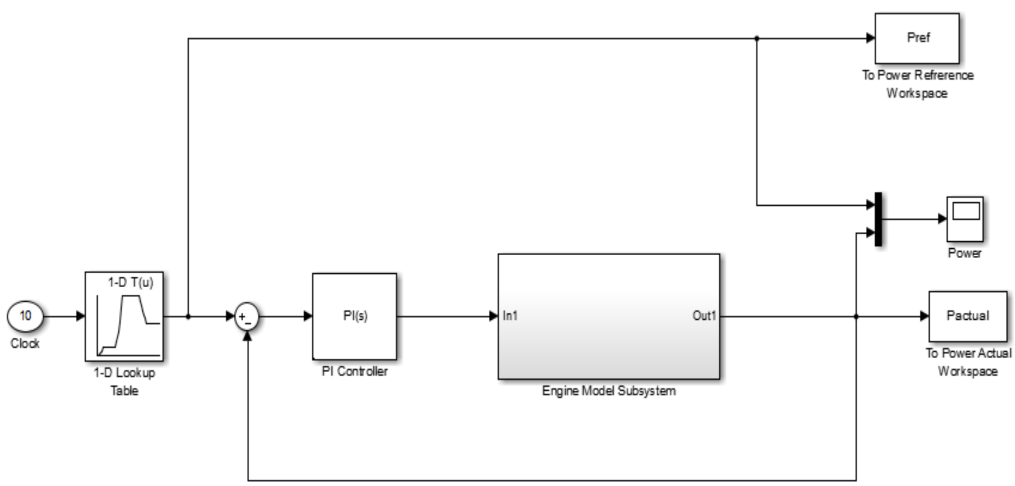

Figure 6 Closed Loop Feedback Control System

2.4 ICE Optimization using GA

According to Pratibha Bajpai *et al.*, 2010, the GA is used to generate useful solutions to optimization and search problems. It generates solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. GA are one of the best ways to solve a problem for which little is known. They are a very general algorithm and so work well in any search space [19]. In this study, GA and PI controller usage together when optimize the model. The block diagram of PI controller and GA are shown in Figure 7. Thus, in optimization the initial population of the PI parameters is chosen by trial and error method. Then, tuning of controller using GA is carried out with the GA parameters as shown in Table 2. 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. 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 [20]. 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 8.

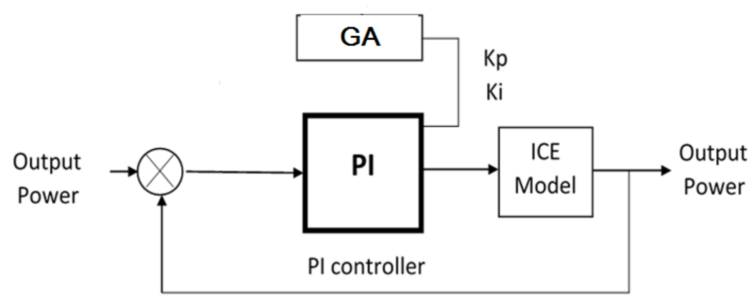

Figure 7 Block Diagram of PI Controller with Genetic Algorithm

Table 2 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]

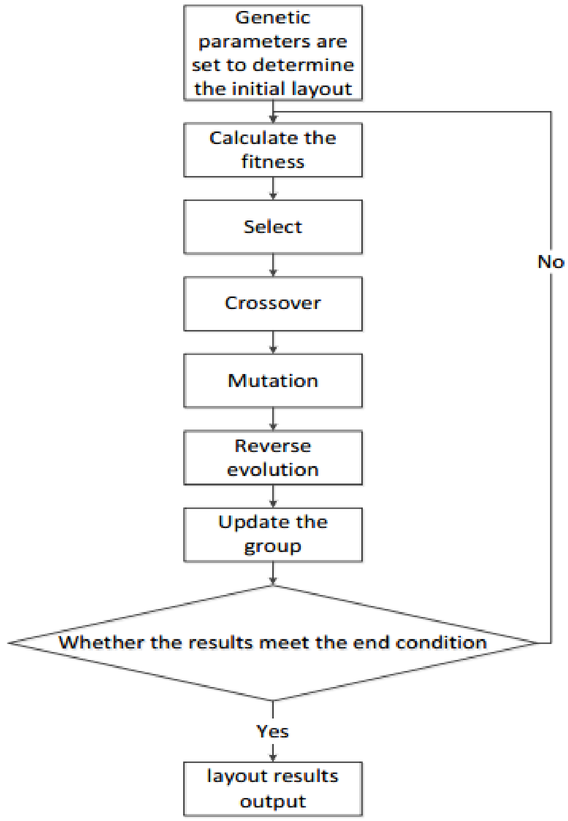

Figure 8 The flowchart of GA [20]

3.0 RESULTS AND DISCUSSIONS

3.1 Power, Fuel Consumption and Efficiency of ICE

The power map of the ICE as a function of rotation speed and torque was shown in Figure 9. The line on the power map indicates the range of power in kilowatts based on the input of engine rotational speed and the torque. So, the power map at the red zone is at its maximum power area where the torque and rotational speed of the engine is at its peak [21]. Figure 10 shows the characteristic of the fuel consumption of ICE as function of N and Q. This map allows the identification of the fuel consumption when referring to N and Q [16]. The ICE efficiency map as function of N and Q shown in Figure 11. The efficiency is high when engine speed in high position and torque of engine decreased.

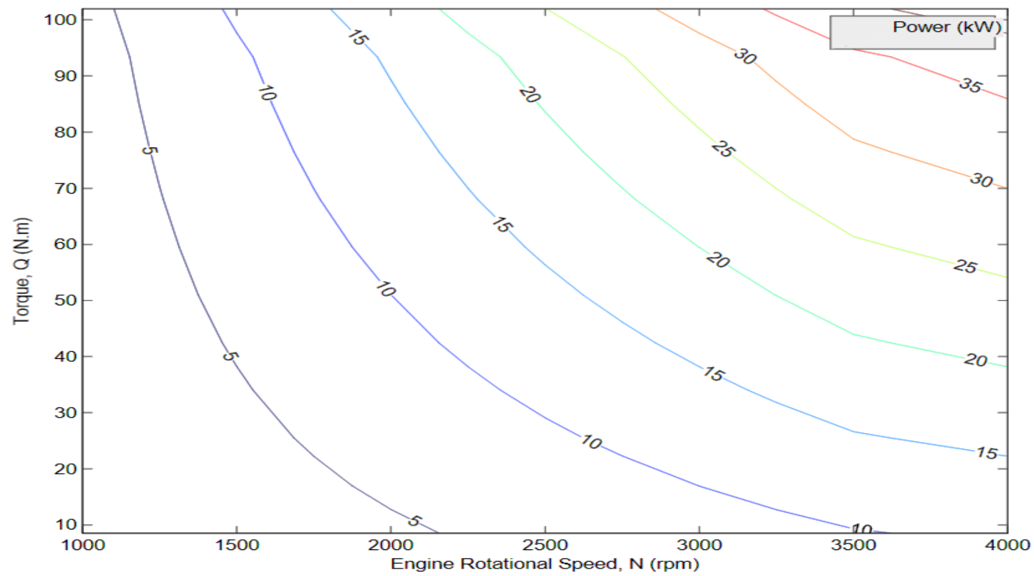

Figure 9 Engine Power Map

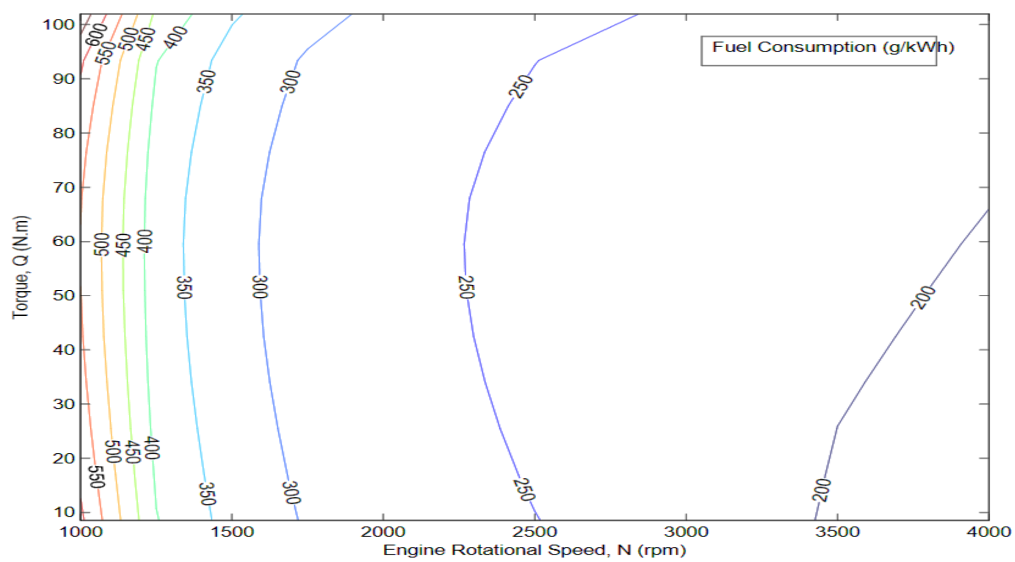

Figure 10 Engine Fuel Consumption Map

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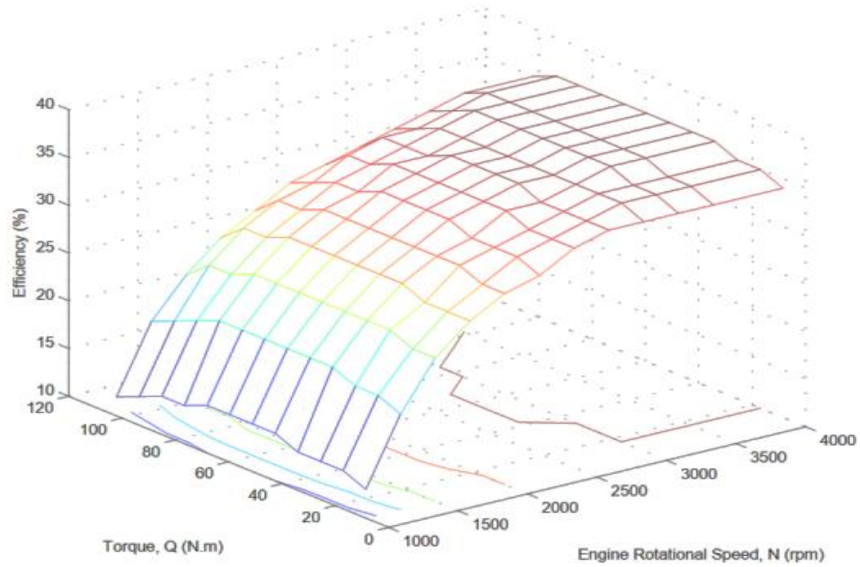

Figure 11 ICE Efficiency Map

3.2 Power, Speed and Torque of ICE

With the characteristic of the engine described is validated, the ICE model is then inserted with the data input which were extracted from the power requirement based KT driving cycle done by Norbakyah *et al.*, 2015. The ICE model generates the output power, torque and rotational speed that used to obtain the final output of the model. Figures 12 – 14 show the output power, torque and rotational speed data of ICE after going through the engine is characteristic.

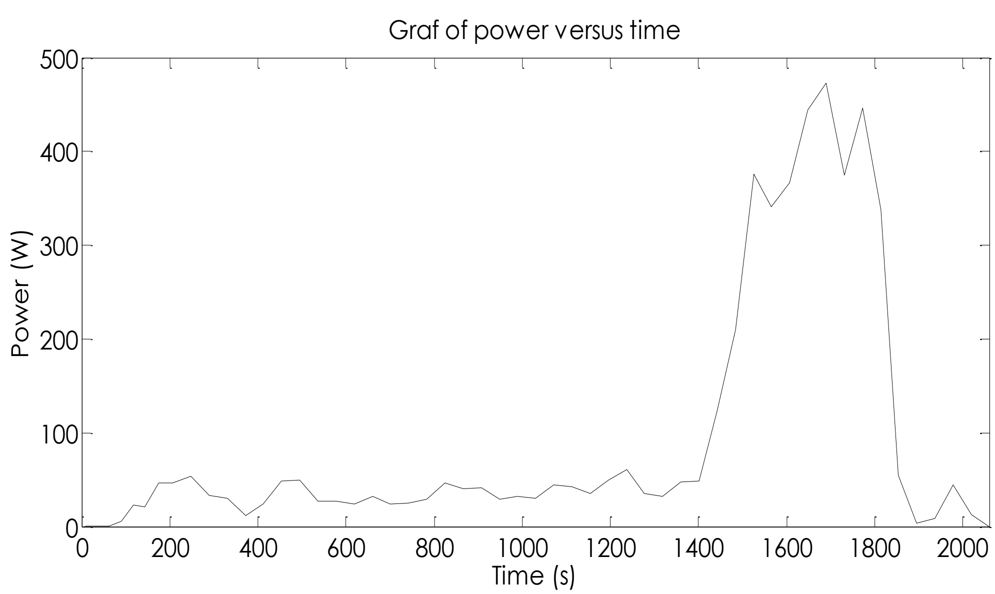

Figure 12 Power versus simulation time

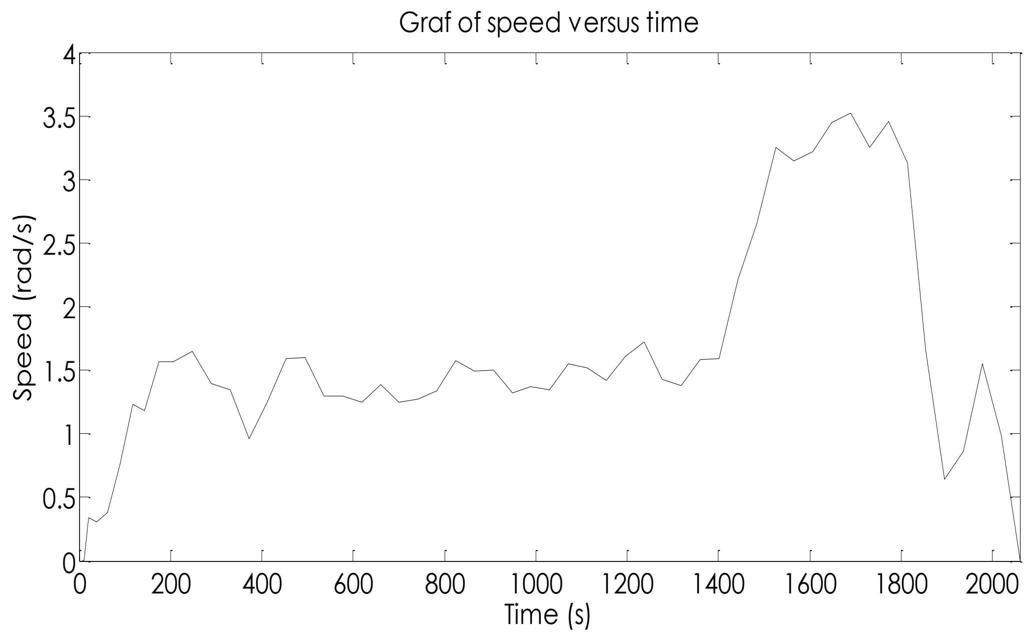

Figure 13 Speed versus simulation time

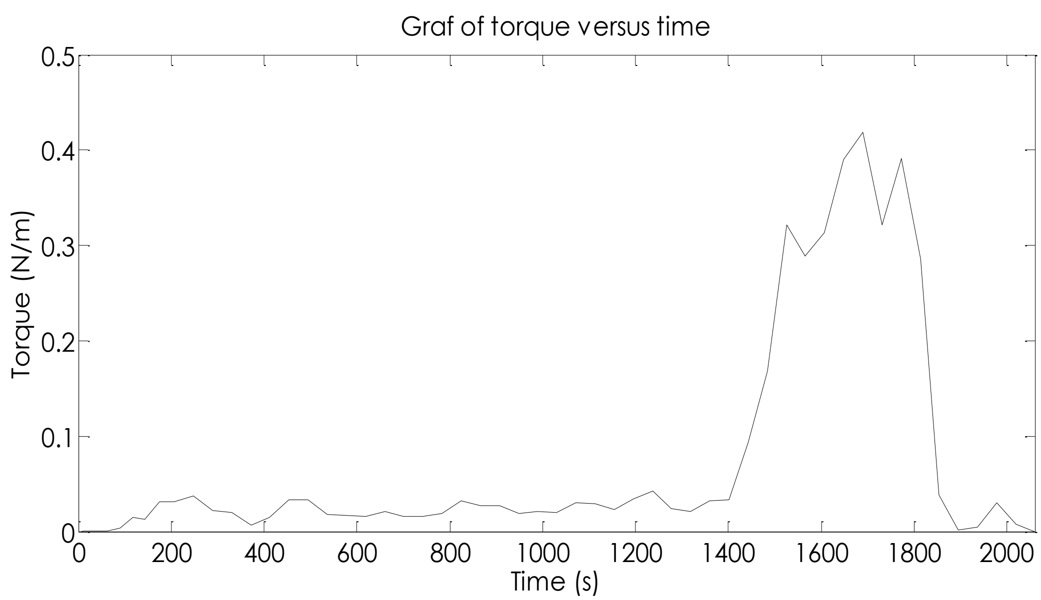

Figure 14 Torque versus simulation time

3.3 Emissions and Fuel Consumption

With the output power, torque and rotational speed, the final output is obtained after going through the model, which is the fuel consumption and the emissions of oxides of nitrogen (NOx), carbon monoxide (CO), and hydrocarbon (HC).

Figure 15 illustrates the results of the output of the ICE model where the final output data has the cumulative values reference to the inputs data. Based on the results, the emission of NO_x, CO and HC was increasing by time. Thus, fuel consumption also increase when time increase.

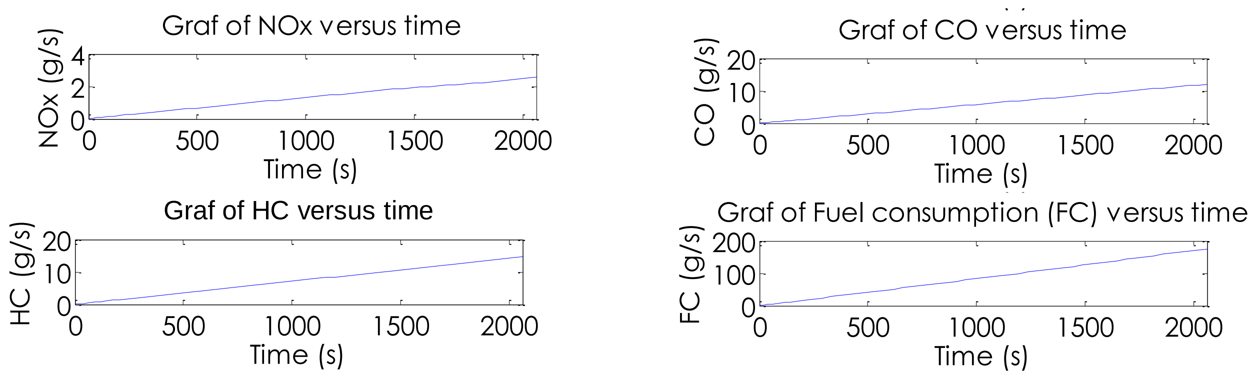

Figure 15 Emission and fuel consumption versus time

3.4 Optimization using GA

The optimization algorithm, GA, is looped with the ICE model and the optimization is carried out. For this step, the initial or default and the bounds for the design variables are considered were state in Table 2. The GA algorithm is allowed to run for 200 function evaluations. For this research, a power demand was designed as a reference power. The reference power compromised acceleration, deceleration and constant speed at 2060 seconds. The performance of the developed system was first tuning by trial-and-error with the PI controller. The Kp and Ki value were set to 1. Figure 16 shows the result of power response of the system that tuned by PI controller. The system is optimizing by adjusting the PI parameters via GA with the SIMULINK model with the lower bound of -100 and upper bound of 250. Figure 17 illustrates the result of power response of the system that tuned with GA. The different between before and after GA optimization can see in Figure 16 and Figure 17. The sizes of error become smaller and decrease. The performance of ICE of PHERB powertrain improved.

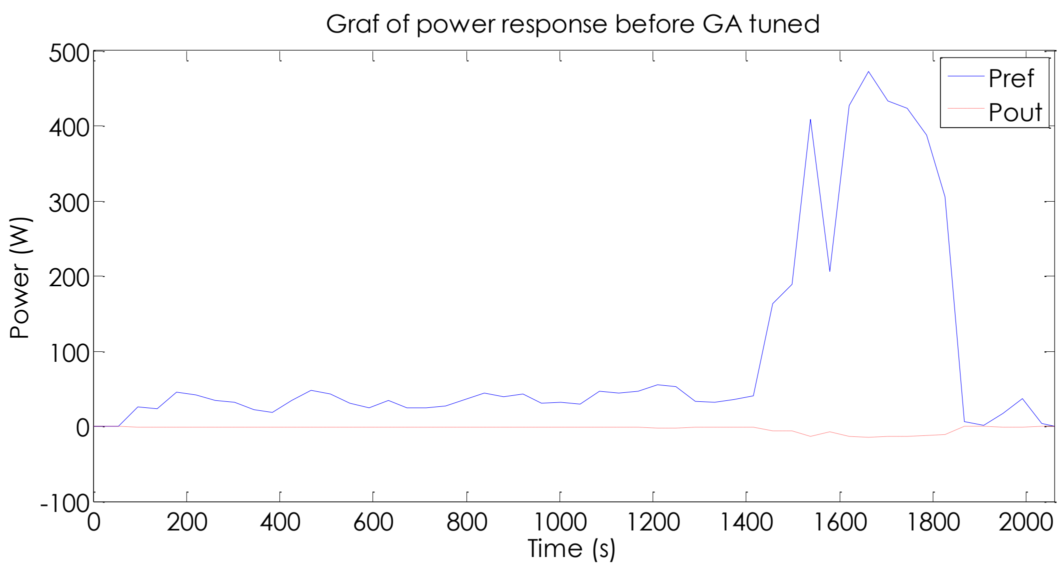

Figure 16 Power response tuned using PI controller

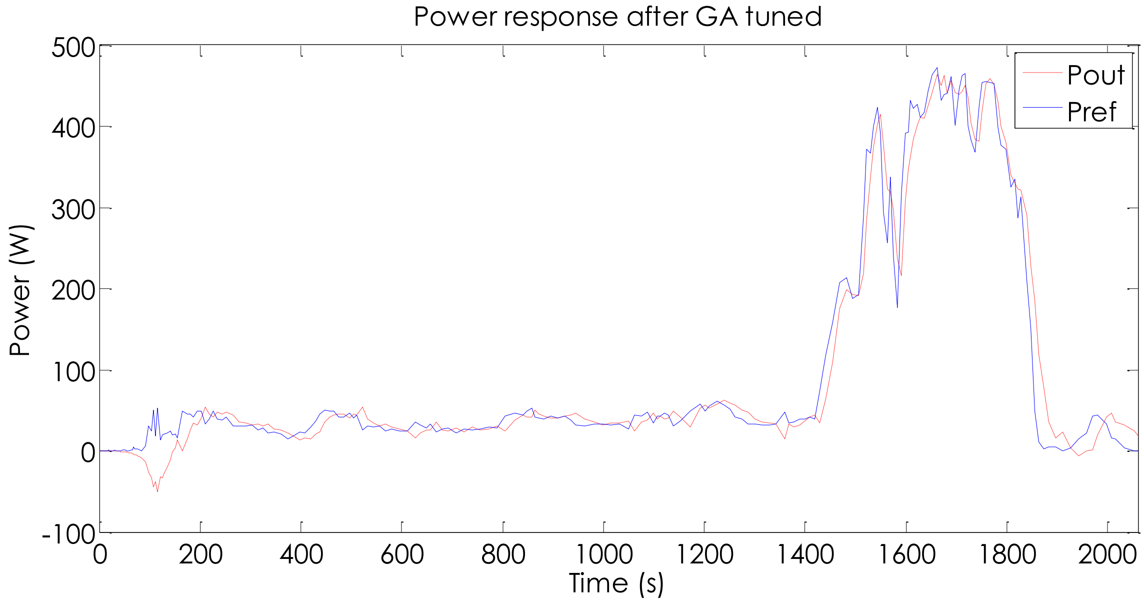

Figure 17 Power response after using GA

4.0 CONCLUSION

This study is about the designing the model of ICE for PHERB using MATLAB/SIMULINK environment is presented. The ICE specifications and parameters were obtained based on the component specification data sheet. The results obtained from simulation in MATLAB/SIMULINK environment shows the ICE model that can provide power to the PHERB. The reference load curve was designed based on acceleration, deceleration and at constant speed at a specific time. Optimization was done by tuning the PI controller via GA in the MATLAB/SIMULINK model corresponds to the reference power to obtain the power response of the system. This is because of GA is one of the optimization method that can tune the PI controller to improve its performance. After the model has been optimized, the size of error and response factors was decreased. This shown that it had improved the performance of the ICE which was more suitable to be implemented to PHERB powertrain.

Acknowledgement

The authors would like to be obliged to Universiti Malaysia Terengganu (UMT) for UMT Scholarship, Ministry of Education Malaysia for providing financial assistance under FRGS (59353) grant and School of Ocean Engineering, UMT for all their technical and research support for this work to be successfully complete.

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