AN OPTIMAL ELECTRIC MACHINE CONTROL SYSTEM DESIGN USED IN PLUG-IN HYBRID ELECTRIC BOAT

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ABSTRACT

The hybrid system is increasingly important in waterborne transportation due to an increase in fuel prices and people's awareness of climate change. Hybrid system is basically a combination of an internal combustion engine and an electric machine (EM). In this paper, an optimal design of EM, that is, the brushless direct current motor for plug-in hybrid electric boat is introduced. The EM model is developed in Matlab/Simulink SimPowerSystem environment together with the closed-loop feedback PI controller. By using a power demand curve as a reference for the model, the optimal performance of the machine is obtained by using the particle swarm optimization. The results of optimal control parameters of the system are compared with those of the trial and error method. It has been found that the proposed optimal system design can improve the machine performance significantly.

Keywords: brushless DC motor, plug-in hybrid electric boat, PSO optimization.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), the global temperature rises about 0.85 °C from 1880 to 2012 [1]. The main factor that contributes to the global warming is the increasing of the greenhouse gases which includes water vapor, carbon dioxide, methane, nitrous oxide and ozone. It has been reported that the concentration of carbon dioxide in the atmosphere nowadays has increased about 40% since the pre-industrial era (1750) due to the burning of fossil fuel [1]. As the world population increases, the demand of the fuel for transportation also increases with more vehicles powered by petrol or diesel. The global oil demand is continuously rising and it is estimated that the energy consumption of the world will be increasing up to 44% by 2030 [2]. This non optimistic prediction has gathered the researcher to come out with the solution in order to overcome the problem. One of the solutions is the invention of hybrid electric vehicle (HEV). HEV is a vehicle that combines a conventional internal combustion engine (ICE) and an electric propulsion systems.

In order to improve the climate situation, the number of HEV such as hybrid car should be increased and the government policy on the green transportation should be reviewed from time to time [3]. Consequently, instead of having hybrid system in land transport, there is also in need for research to be carried out for water transportation. Small or medium boat is the most common marine transportation and they are used for many purposes such as recreation, fishing, passengers and goods transportation. Most of the boats is powered by internal combustion engine which is using diesel as the primary source of energy. In this regards, the researchers have come out with the idea of converting the ICE into a hybrid propulsion system that coupled with an electric machine (EM) powered by batteries [4]. Such technology is known as Plug-in Hybrid Electric Boat (PHEB) [5]. A typical block diagram of PHEB is as shown in Figure-1.

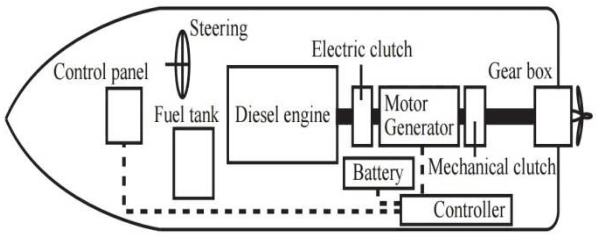

Figure-1. A typical construction of PHEB.

In PHEB, the operation mode of the boat is designed to safe fuels by selecting either running by using the fuel of batteries. In addition, PHEB can contribute to the quietness and energy saving while providing reliability. When running mode is switched in battery only mode, it is desirable to improve the control performance to save the battery energy especially when travelling long distance. This paper presents an optimization method using the heuristic optimization approach of particle swarm optimization (PSO) algorithm in order to improve the EM performance of the PHEB when running in battery only mode. The EM model developed was based on the brushless DC (BLDC) motor while the control of the machine has been constructed based on the conventional PI control method. With the help of the optimization algorithm of PSO, optimal tuning of the control parameters has been carried out in Matlab/Simulink environment. The results of the model development and verification as well as the performance of the proposed system has been compared with the conventional trial and error method.

MATERIALS AND METHODS

There are 3 stages in conducting the study which are modeling, optimization, and analysis. For modelling of the EM, the BLDC motor was chosen since it offers more advantages compared to other EM types. It has higher

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efficiency and easier to achieve high performance torque due to the elimination of magnetizing current and copper loss in the rotor [6]. The BLDC motor used is a three phase motor with two stators and a rotor in the center. The parameter and specifications of the EM are presented in Table-1.

Table-1. Parameters and specification of EM model.

Parameters and specification	
Max. recommended speed	5000 RPM
Input voltage	0 – 96 V
Peak current	600 A
Torque constant	0.15 Nm/Ampere
Phase to phase winding resistance	0.013 ohm
Efficiency	92%
Weight	15.8 kg
Cooling	Fan

Once the parameters and specifications of the machine is determined, the model of the system component is developed in SimPowerSystem. The BLDC model was built based on the mathematical formula where the physical system of the machine is as shown in Figure-2.

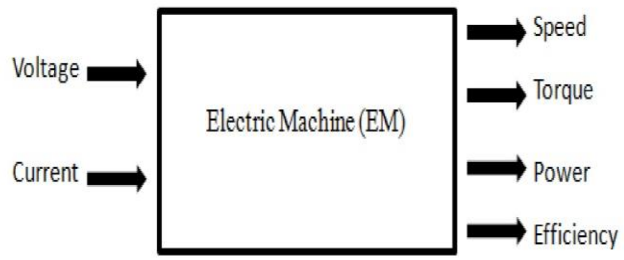

Figure-2. Basic block diagram of EM.

As illustrated in Figure-2, the desired input and output variables are calculated. Keeping in mind that although there are different types of DC motors, however their basic operation is the same. Firsly, as stated in Table-1, the phase to phase winding resistance of the motor is 0.013 ohm. Since the EM used is a three phase motor with two stators, the internal resistance of the motor must be doubled up as follows:

$$R_m = (3 \times 0.013) \times 2 = 0.078\,\Omega \quad (1)$$

The internal back-EMF voltage, V_m, of the motor is the difference between the input voltage, V, and the product of the input current, I, and the internal resistance, R_m, of the motor, therefore,

$$V_m = V - IR_m \quad (2)$$

Other important parameters of the motor are speed constant, K_v, and torque constant, K_t, and they are inverse with each other [7]

$$K_v = \frac{1}{K_t} \quad (3)$$

From equation (2) and (3), the shaft rotational speed, ω, can be calculated by multiplying the internal back-EMF voltage, V_m to the speed constant, K_v as follows:

$$\omega = V_m \times K_v = \frac{V - IR_m}{K_t}\,. \quad (4)$$

The equation of torque, τ, is the product of torque constant, K_t and the input current, I as follows:

$$\tau = K_t \times I \quad (5)$$

By relating the rotational speed and torque, the output power can be calculated by using the following equation,

$$P_{out} = \omega \times \tau = VI - I^2 R_m \quad (6)$$

The efficiency, Eff of the motor is equal to the output power, P_{out} divided by the input power, P_{in}

$$Eff = \frac{VI - I^2 R_m}{VI} \times 100\% \quad (7)$$

From the mathematical equations presented in equation (1) to (7) the model has been implemented in the Matlab/Simulink Sim Power System. Figure-3 shows the EM model with the corresponding input and output variables representing the BLDC motor.

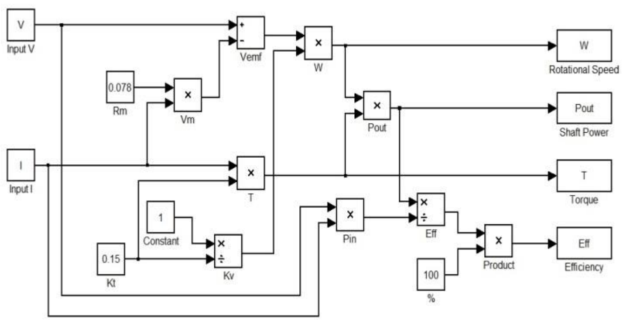

Figure-3. Simulink model of EM.

Once the model is developed, a feedback closed-loop system with PI controller has been constructed as shown in Figure-4. The PI controller will be used in such a way so that the input current of the EM 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 EM. The power output of the EM will be based on the power demand curve that represents typical motion of a PHEB such as constant speed, accelerating, decelerating and et cetera.

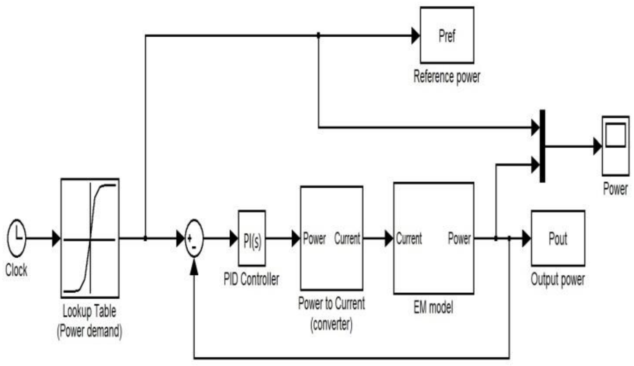

Figure-4. Feedback closed-loop system with PI controller for EM model

For the purpose of optimization of the system, PSO has been used to train the system control parameters [8]. Figure-5 illustrates the block diagram of the PI controller with the corresponding PSO tuning algorithm implemented in Matlab/Simulink. In this case, there are two members for each particle in PSO algorithms that are k_p and k_i. In other words, the search space has two space and the particles are moving according to the two dimensional space. In searching for the best set of parameters, Figure-6 provides the flowchart which describes how the PSO-PI control system works.

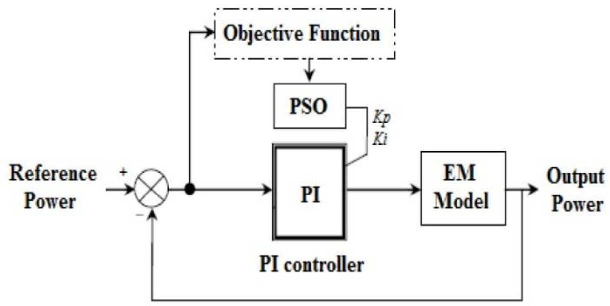

Figure-5. Block diagram of PI controller with PSO algorithms.

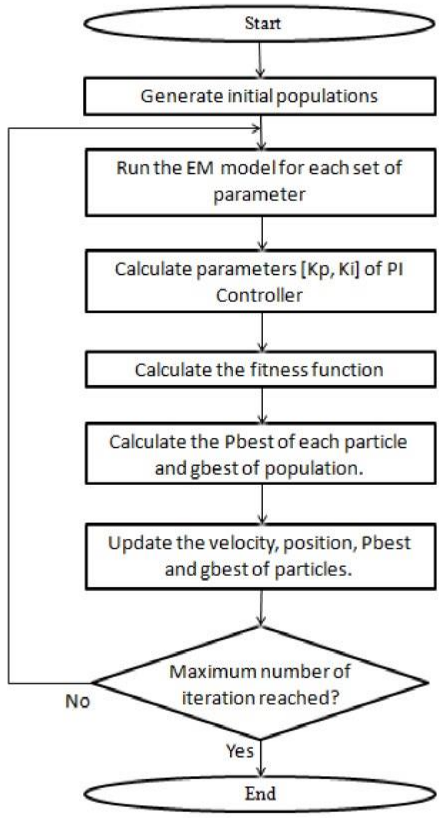

Figure-6. The flowchart of PSO-PI control system.

RESULTS AND DISCUSSION

Before running the optimization of the model, EM model validation has been carried out. The input voltage of the EM model was fixed at 72 volt which results in optimum output power of around 16 kW. This output power is sufficient to power a typical 6 meter PHEB with the displacement of 1.5 tons [4].

Figure-7 shows the relationship between the speed and torque under a range of current at constant 72 V supply. As shown in the graph, the torque produced by the EM is directly proportional to the current supply. This is because the magnetized stator produces a stronger magnetic field as the current increases. Therefore, the force acting on the permanent magnet in the rotor is getting higher as the magnetic field getting stronger. On the other hand, the speed of the EM is inversely proportional to the current. When a torque, is acts on a rotational body with an angular velocity, the product of both torque and angular velocity will produce power. Therefore, the speed of a rotating body is inversely proportional to its torque.

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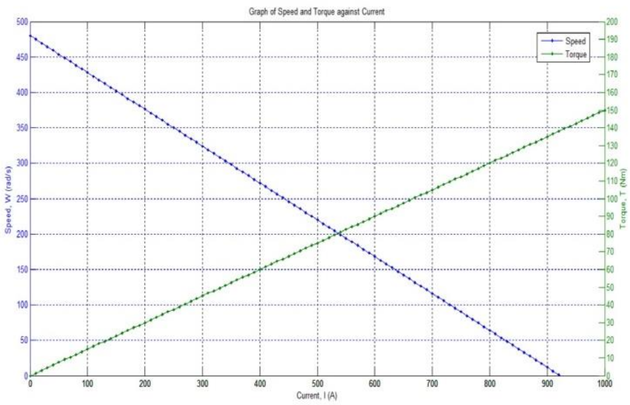

Figure-7. Graph of speed and torque against current at constant 72V.

Figure-8 shows the shaft power and efficiency curve under the same current and voltage supply. The maximum power can be achieved by the EM is about 16.5 kW at the current about 450 A. Efficiency is the relationship between the mechanical power output and the electrical power input. As the current increases, the efficiency decreases due electrical power input increased more rapidly compared to the mechanical power output. The internal resistance of the mechanical components in the EM is one of the factors of the inefficiency where it converts the electrical input energy to heat energy.

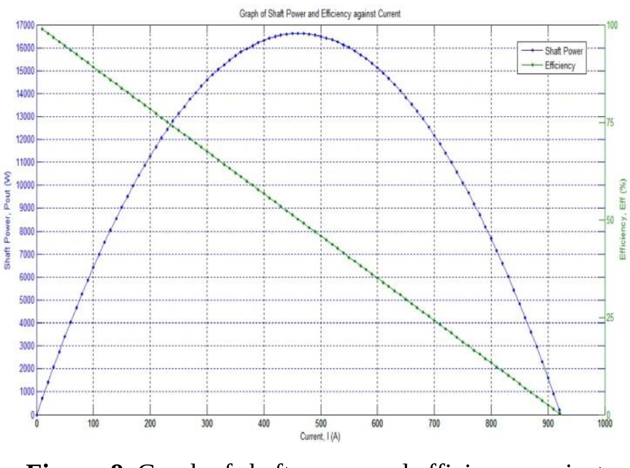

Figure-8. Graph of shaft power and efficiency against current at constant speed 72 V.

Figure-9 shows the graph of speed against torque of the EM at different voltage level of 36 V and 72 V. It shows that the speed versus torque curve reacts parallel to the input voltage. Furthermore, the no-load speed and stall torque also can be obtained in speed versus torque curve. No-load speed is the speed where the EM is operating under zero torque condition whereas the stall torque is the torque when the rotational speed of EM goes to zero. The current under the stalled condition which also known as the stall current, is the current needed to start the EM [7].

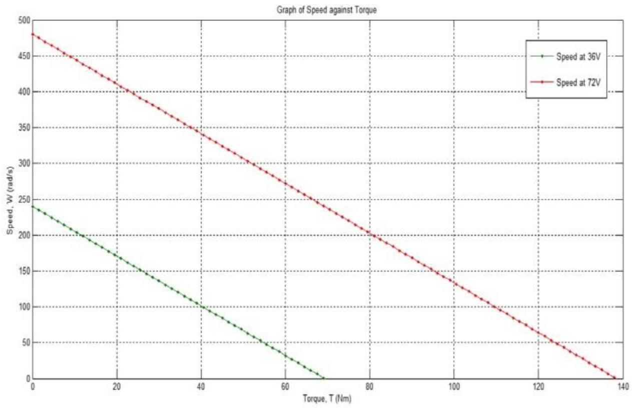

Figure-9. Graph of speed against torque at constant 36 V and 72 V.

From Figure-9, the no-load speed obtained from the EM is 240 rad/s (2292 RPM) at 36 V and 480 rad/s (4584 RPM) at 72 V, respectively. The stall torque obtained from the EM is 69 Nm at 36 V and 138 Nm at 72 V, respectively. Whereas, the corresponding stall current, of the EM at 36 V and 72 V is 461.54 A and 923.08 A, respectively.

The power generated by the EM under different input voltage is as shown in Figure-10. The maximum power generated by the EM at 36 V is about 4 kW whereas 72 V of input voltage produces the power of around 16.5 kW.

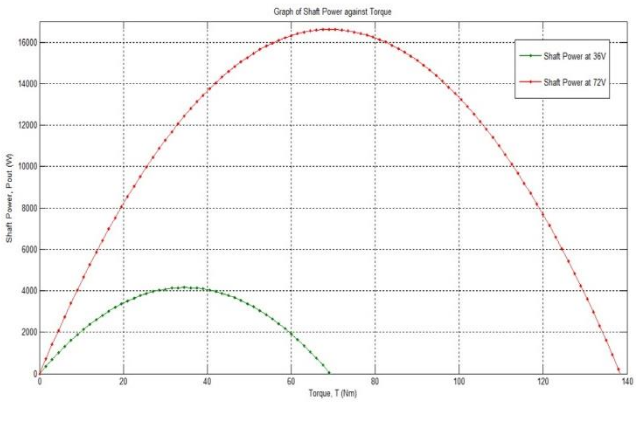

Figure-10. Graph of shaft power against torque at constant 36 V and 72 V.

For the efficiency, there is no significant difference for the maximum efficiency of the EM between 36 V and 72 V. Both 36 V and 72 V EM have the maximum efficiency around 98% as shown in Figure-11.

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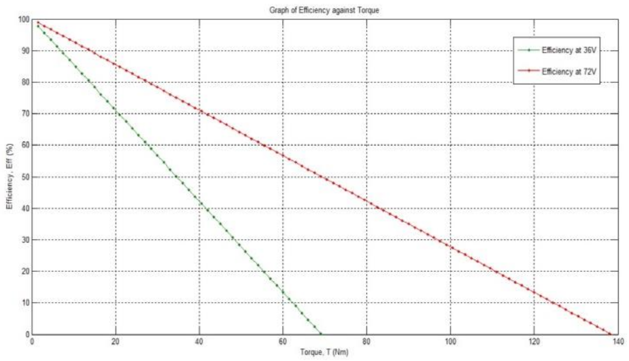

Figure-11. Graph of efficiency against torque at constant 36 V and 72 V.

As Figure-9, 10, and 11 combined, an EM map is produced. Figure-12 presents the EM map of a BLDC motor with different specification at constant 12 V and 24 V supply [7]. By comparing the results obtained in Figure-9, 10, and 11, the curve pattern is exactly the same as shown in Figure-12. This means the behaviors of a BLDC motor was verified.

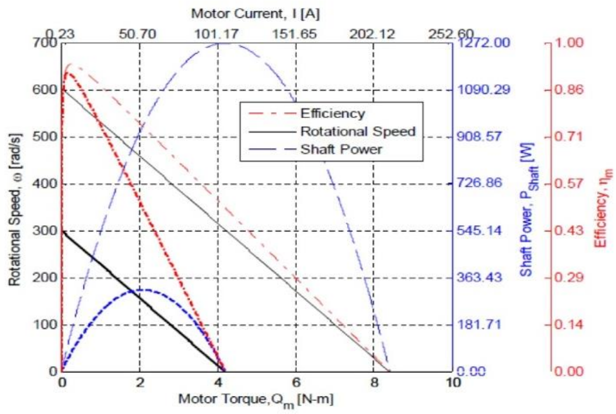

Figure-12. Electric motor map at constant 12 V and 24 V [7].

Using PSO, the parameters of the PI controller have been optimized. The initial kp and ki parameters were set using trial and error value of 1, respectively. The parameter of the PSO algorithm used are as shown in Table-2.

Table-2. Parameter of PSO algorithm.

Parameter	Value
Population size	20
Number of iteration	300
c_1	1.5
c_2	1.5
w_{min}	0.1
w_{max}	0.6

The EM performance that is the capability of the machine to response to the desired power curve with and without PSO tuning of the PI controller is given in Figure-13 and 14, respectively. Whereas, Figure-15 shows the performance trajectory index of the PSO optimization where the objective function represents the error occurs in the system. By comparing the results of both Figure-13 and 14, the performance of the EM has improved significantly with the help of PSO algorithms. The improvement of the performance is highly related to the rise time, overshoot, settling time, and steady-state error of the system.

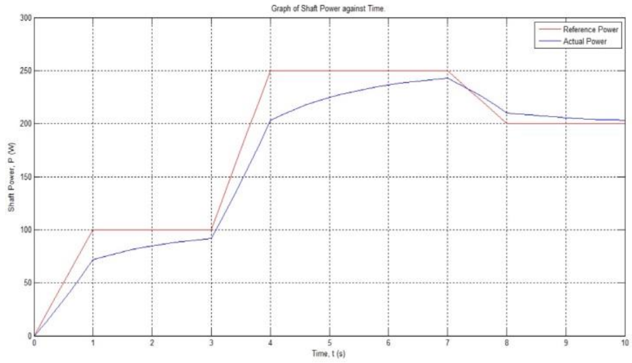

Figure-13. Power response curve of EM without using PSO algorithms.

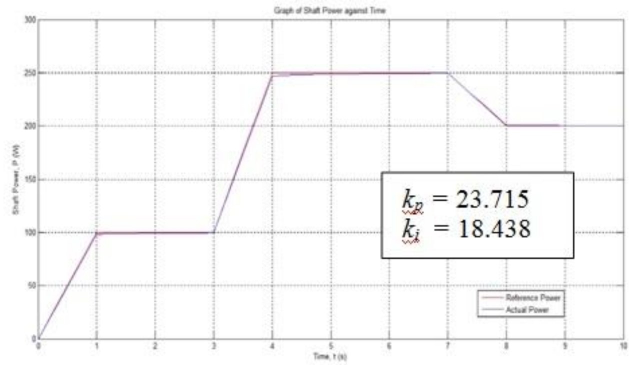

Figure-14. Power response curve of EM with optimized parameters obtained using PSO.

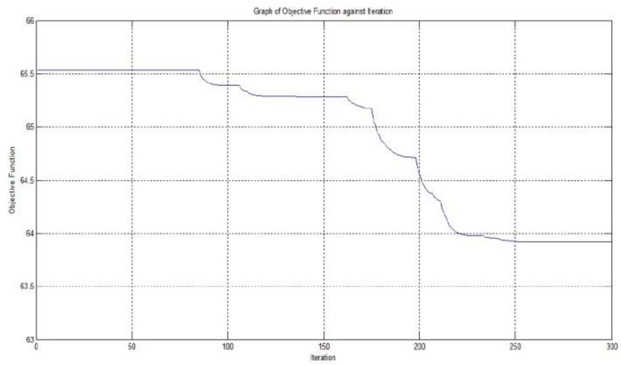

Figure-15. Objective function convergence graph of the PSO-PI controller.

Table-3 presented how the PI controller parameter affects the four characteristics of a typical system. The proportional gain, will decrease the rise time and the steady-state error of the system. The integral gain, can eliminate the steady-state error but it will bring negative effects on the transient response which means it will cause the system to perform badly.

Table-3. Characteristics effects of PI controller parameters on a typical system [9].

Parameter	Rise time	Overshoot	Settling time	Steady-state error
k_p	Decrease	Increase	Small change	decrease
k_i	Decrease	Increase	Increase	Eliminate

CONCLUSIONS

The paper has presented the development of BLDC based PHEB during battery only operation. The model was built based on a 30 kW BLDC motor parameters, specification and requirement. The validity of the developed model has been verified and the optimal performance of the model has been studied by using PSO-based tuning algorithm of the conventional PI controller. The results show the accuracy of the model developed and proven that the PSO based optimization can significantly improve the control system performance of the BLDC.

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