Energy Consumption Optimization with PSO Scheme for Electric Power Steering System

R. A. Hanifah, S. F. Toha, and S. Ahmad

***Abstract*—Energy management in Electric Vehicle (EV) technology is very important as the energy source of all its system operations are solely relying on the battery. The unique characteristic of Electric Power Assist Steering (EPAS) system provides a way in realizing minimum energy consumption in EV subsystem. The controller in the EPAS system need to be tuned with the optimal performance setting so that less current is needed for its optimum operation. In this paper, Particle Swarm Optimization (PSO) algorithm is implemented as tuning mechanism for PID controller. The aim of this hybrid controller is to minimize energy consumption of the EPAS system in EV by minimizing the assist current supplied to the assist motor. The PSO searching method will search for the best gain parameters of the PID controller and providing the fast tuning feature that distinguish it from the conventional trial and error method. Simulation results shows the performance and effectiveness of using PSO algorithm for PID tuning.**

***Index Terms*—Electric power assist steering (EPAS), C-type EPAS, PID, particle swarm optimization (PSO), electric vehicle (EV).**

I. Introduction

Electric vehicle (EV) is not a new technology because the history of EV had started since 1834 after the discovery of electricity and the knowledge of electromechanical energy conversion. During that time, a non-rechargeable battery-powered electric car was used and it only for a short distance travel. EV then becomes outnumbered by the Internal Combustion Engine (ICE) vehicle as it can overcome the distance travel issues faces by the EV. Then in 20th century, the scenario turned in favor to EV due to energy crisis faces by all around the world. In EV, an electric motor or a few electric motors are used to drive wheels of a vehicle.

Battery in EV system served as energy source and provides electric power to electric motor drives and other electrical equipment in the system. The whole system of electric vehicle can be divided into three major subsystem which are electric propulsion subsystem, energy source subsystem and auxiliary subsystem. The electric propulsion subsystem is dealing with the drive train and vehicle's propulsion. As for auxiliary subsystem, it comprises of the power steering unit, temperature control unit and auxiliary supply. And since all operations in EV is supported by the energy source subsystem, it has been a major concern in EV technology in terms of battery energy capacity to support the long-range operation [1].

Energy consumption is very vital in electric vehicle technology as the energy source of all its system operations are solely relying on the battery. Efforts are being made to reduce the energy consumed as much as possible in EV system. As one of the auxiliary elements of the system, EPAS system can be controlled or manipulated in such a way that minimum energy from the battery source is being draws during its operation. The controller in the EPAS system needs to be tuned with the optimal performance setting so that less current is needed for its optimum operation. With the dynamic changes of vehicle speed and external disturbance resulted from road condition, the controller need to be able to deliver a sufficient and best possible assist torque to the driver with minimum power consumed. For that reason, significant improvement should be made to the controller of EPAS system to ensure optimum performance with lowest possible current draws from the battery.

Mechanical steering system or hydraulic power assist steering (HPAS) draws a constant energy supply from battery to maintain the pressure in hydraulic pump [2]. Whereas the EPAS system improves the energy efficiency due to its on-demand system feature which is only operating when the steering wheel is turned [3]. It offers an additional advantages than hydraulic power steering as it can reduce the steering torque, provide various steering feel and improve return-to-center performance of a steering wheel when it is steered [4]. The EPAS system becomes an alternative to the automotive manufacturer in providing the convenience of steering assist without adding value to the engine cost and fuel consumption. Only approximately one-twentieth of energy is consumed by the EPAS system compared to the conventional HPAS system and this feature make EPAS a very suitable candidate in EV steering system [5].

Fig. 1 shows a model arrangement of column-type EPAS. Electric motor is attached to the steering rack or column via gear mechanism and sensors are located on the input shaft in EPAS system. It uses electromechanical actuation where the sensors determine the driver's torque, steering angle and speed and direction of the steering wheel. The sensors together with the vehicle velocity are fed into the ECU. The resulting demand from the ECU process is used to excite the circuitry of the motor and finally giving an output to the rack [6].

In the research on EPAS system, some of the goals are to reduce the steering torque exerted by the driver and also to improve the steering performance. In line with these goals, many control strategies have been applied and implemented in the EPAS system such as a reference model, fuzzy logic, PID, H2 and H∞ [7]-[10]. Parmar and Hung in [11] discussed a simplified model and optimal controller structure of an EPAS by employing LQR and Kalman filter technique. In Marouf [12] a simplified model of the sensorless control of EPAS system with the permanent magnet synchronous motor (PMSM) using sliding mode techniques was introduced.

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While Hassan in [2] integrated the genetic algorithm (GA) with the PID controller to provide optimized controller parameters. Many studies on EPAS system has been done however only limited number of study on EPAS concerning on the energy consumption of the EPAS system and involving evolutionary algorithm such as Particle Swarm Optimization (PSO). Therefore, this paper aims to study the potential of hybrid PSO to the PID controller in the EPAS system to reduce the energy consumption.

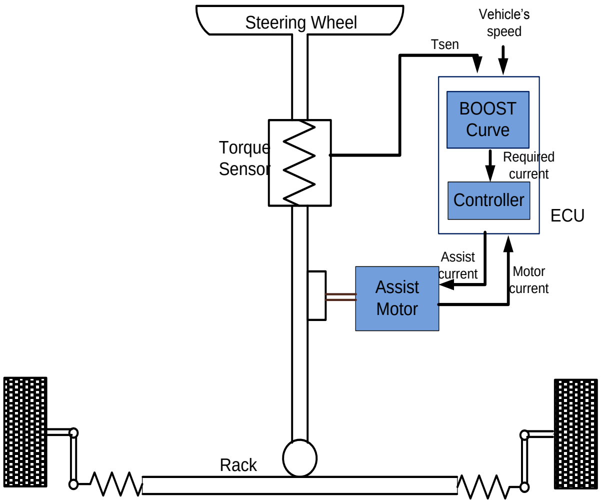

Fig. 1. Model diagram of the EPAS system.

II. PID Controller

Proportional-Integral-Derivative (PID) control technique continues to provide the simplest and effective solutions in industrial control system application since its introduction in 1936. The PID controller has been widely used in the industry because of its simple structure and robust performance as well as low cost and cheap maintenance [13], [14]. Three individual values of proportional, integral and derivative parameters involved in the PID controller calculation. The proportional value determines the reaction of the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing the weighted sum of these three actions is used to adjust the process via the final control element [15].

The PID controller tuning aim to determine its proportional, integral and derivative parameters that fit into the system to assure the closed loop system performance specification and robust performance of control loop over a wide range of operation are met [15]. In practice, it is difficult to ensure the system meets all the desirable qualities simply because the behavior of the parameters. For example, in achieving a better transient response of the system, its response under disturbance condition will be slow.

In the industrial plants, it has been difficult to tune the PID controller gains properly because of the uncertainties encountered in control system both in the environment and within the system [16]. Resulting from this, the conventional PID controller cannot provide solutions to all control problems because of the complexity, inadequate dynamic definition and time-variant with delays and non-linearity [14]. To improve the conventional PID, many optimization methods have been developed such as auto tuning and intelligent PID controller.

III. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a population based evolutionary algorithm which originally developed by J. Kennedy and R. C. Eberhart on 1995 [17]. It was developed through simulation of a simplified social system, and has been found to be robust in solving continuous nonlinear optimization problems [13]. Using this algorithm, the solution obtained is a high-quality solution which is generated within the shorter calculation time and can achieve stable convergence characteristic.

This method is developed from research on swarm such as bird flocking and fish schooling. It has features of easy implemented technique, stable characteristic convergence and good computational efficiency [18]. Instead of using evolutionary operators such as mutation and crossover to manipulate the particle, a flock of particles is put into the d-dimensional search space for a d-variable optimization problem. Each particle flies within the search space with velocities and positions which is dynamically adjusted according to its own flying experience and its neighbors' flying experience [13], [15].

The PSO technique combines the artificial-life methodology to bird flocking, fish schooling and swarming theory in its algorithm [19] . Stimulate by the animal social behavior such as fish schooling and bird flocking, PSO algorithm emulates the physical movement of individual member in the school or flock and also their cognitive and social behavior in its searching technique. This algorithm uses very straightforward mathematical concept and paradigm which can be realize within a few lines of computer code. Less codes needed couple together with small computer memory and speed requirement gives salient feature to PSO in terms of computational cost [20]. As one of the discipline in the CI, PSO shares similarities with other disciplines in terms of stochastic optimization method which based on population, random initial population generation, fitness concept application on the objective function and population update and search for optimum solution using random technique.

However, PSO does not apply the concept of survival of the fittest instead all individuals do not die, retain their memory and share their information with others [20]. A fitness function is used in determining the optimal solution. At each iteration, the fitness of each particle is evaluated. Each particle keeps track of its own best position and its best fitness in the problem space it has achieved so far. This is called particle best or pbest. The algorithm used for updating the particle velocity and position at each iteration is in equation (1) and (2) below:

$$v_{id_{new}} = (w \times v_{id}) + C_1\big(rand_1(p_{id} - x_{id})\big) + C_2\left(rand_2(p_{gd} - x_{id})\right) \quad (1)$$

$$x_{id_{new}} = x_{id} + v_{id_{new}} \quad (2)$$

PSO also tracked another best value associated with the location of the best fitness particle which is called as global best or gbest. These two best values influence how the solution change or particle movement in the search space. PSO is faster in finding solutions than evolutionary computation methods because it produces random initial population and generates new population based on current cost [21]. It is important to note that each coefficient in the algorithm contributes to the changes in behavior of the particle in the swarm. In 1999, Clerc introduces a constriction factor in velocity update equation to increase the rate of convergence [22].

The model was only valid for certain problem because when it is applied on benchmark problem, the model failed to converge within the specified range. This is due to wide spread of particle from the desired range of search space. To improve the performance of this model, clamping is used by setting Vmax = Xmax as proven by Eberhart [23]. In this study, the parameters of inertia weight and acceleration coefficients are varied according to the method proposed by Ratnaweera in [24] as described by equation (3) –(5) below, C_1 will decreases linearly over time while C_2 will increases linearly. This method is known as Linear Decreasing Inertia Weight (LDIW) and Time-Variant acceleration coefficients (TVAC).

$$w = (w_1 - w_2) \times \frac{(maxiter\ - iter)}{maxiter} + w_2 \quad (3)$$

$$C_1 = \left(C_{1f} - C_{1i}\right)\frac{iter}{maxiter} + C_{1i} \quad (4)$$

$$C_2 = \left(C_{2f} - C_{2i}\right)\frac{iter}{maxiter} + C_{2i} \quad (5)$$

IV. System Modeling

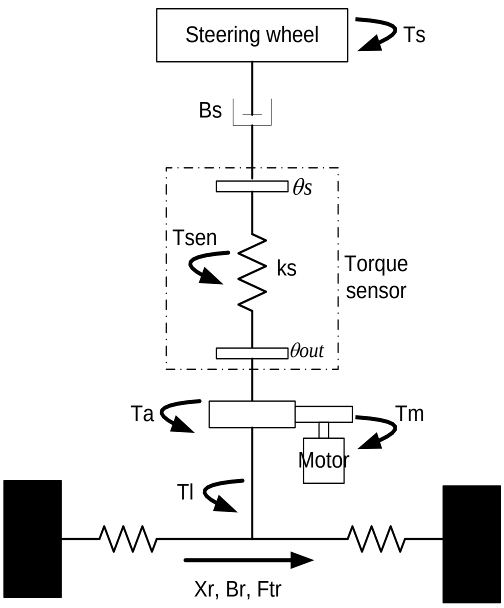

Fig. 2. Schematic model of the EPAS system.

In this study, Column-type (C-type) EPAS system is used and Fig. 2 shows the schematic model of the EPAS system. The mathematical model of the EPAS system can be described as equations shown below,

$$J_s\ddot{\theta}_s + B_s\dot{\theta}_s + K_s\theta_s = T_s + K_s\left(\frac{x_r}{r_s}\right) \quad (6)$$

$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m + K_m\theta_m = T_m + GK_m\left(\frac{x_r}{r_s}\right) \quad (7)$$

$$M_r\ddot{x}_r + B_r\dot{x}_r + K_r x_r = \frac{K_s\theta_s}{r_s} + \frac{GK_m\theta_m}{r_s} - F_d \quad (8)$$

where *Js* is the steering column moment of inertia; *Bs* is the steering column viscous damping; *Ks* is the steering column stiffness; *Jm* is the motor moment of inertia; *Bm* is the motor viscous damping; Km is the motor stiffness; G is the motor gear ratio; *Mr* is the mass of the rack; *Br* is the rack viscous damping; *Kr* is the tire spring rate; *Fd* is the road random force; *xr* is the rack position; *rs* is the pinion radius; *Ts* is the steering wheel torque from the driver and Tm is the electromagnetic torque provided by electric motor.

According to the mathematical model, a Simulink diagram is designed. PID controller is used in the system to help minimizing the current and hence reducing its power consumption. The PID is known for its satisfying impact to the system performance, however it needs some tuning optimization to ensure maximum performance. Hence, PSO is applied in the system to improve the tuning of the PID controller. The mechanism is illustrated in the Fig. 3.

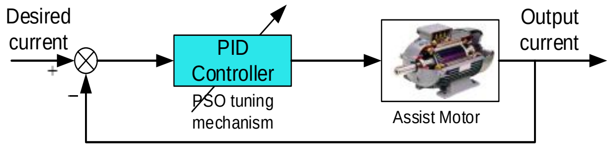

Fig. 3. PID controller with ACO tuning of the EPAS subsystem.

V. Simulation and Result

A Simulink model was built according to the mathematical model obtained for simulation. The simulation was performed using Matlab/Simulink on a Core i7-4770 CPU at 3.40GHz computer with 16.00GB RAM. Simulink model of EPAS system was given sinusoidal input to represent the steering wheel input torque with the range of 0 to 6.4N.m and the vehicle speed was set to 60km/h. Table I shows the initialization value for PSO parameters with maximum number of 100 iterations and population of swarm is set to 60.

TABLE I: PSO Parameters

Parameters	***Value***
Number of iterations	100
Number of variables	3 (*Kp, Ki, Kd*)
Swarm	60
Inertia weight, w	Wmax = 0.9, Wmin = 0.4
Acceleration coefficient, C1 & C2	C1max = 2.0, C2max = 2.0, C1min = 0.05, C2min = 0.05
Objective Function	MSE

Fig. 4 shows the convergence of the objective function with final MSE value is 0.00040005. The parameters value of k_p, k_i, k_d obtained are $k_p = 125.4541, k_i = 2.0909$ and $k_d = 4.1818$ and the convergence profile of each parameters are presented as in Fig. 5, Fig. 6 and Fig. 7. From Fig. 4, it illustrates that the fitness function reach stable MSE value at 55 iterations. Before 55 iterations, as demonstrated in Fig. 5, Fig. 6 and Fig. 7, values of k_p, k_i, k_d changing before each finally reach their final stable value. The changes of these parameters which make the changes in of the MSE value.

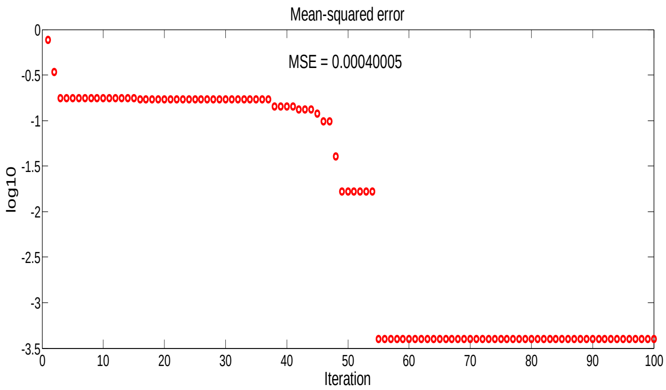

Fig. 4. MSE convergence profile.

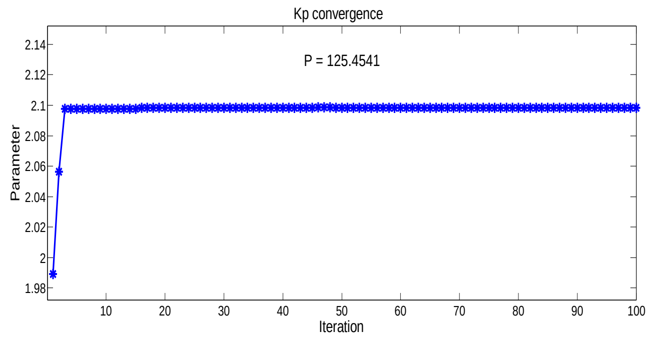

Fig. 5. Convergence profile of k_p.

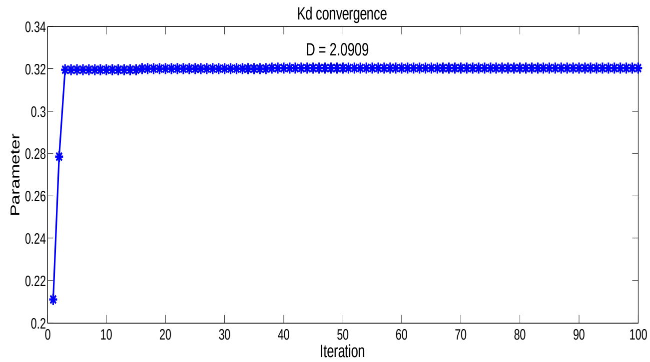

Fig. 6. Convergence profile of k_i.

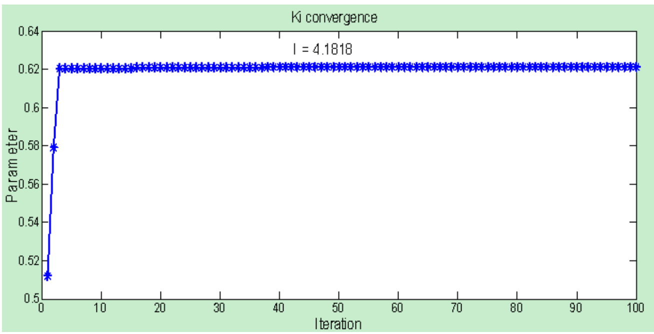

Fig. 7. Convergence profile of k_d.

To show the reduction in power consumption, the assist current of the assist motor is first being compared between manual tuned PID (labeled as PID) and PSO tuned PID (labeled as PSO-PID) as illustrated in Fig. 8. From Fig. 8, it shows that less current consumed by the PSO-PID as compared to PID. Power consumption analysis of the assist motor is then shown in Fig. 9. It is observed form Fig. 9 that PSO-PID consumed less power than PID with reduction of 33.1W. Maximum power of PID is 490.4W and maximum power achieved using PSO-PID is 457.2. These shows that significant power reduction obtained using PSO-PID because the tuning has been optimized for better performance using PSO algorithm. Table II summarized the parameters value of PID using manual tune and ACO algorithm.

From the results obtained, the PSO algorithm is able to tune properly the PID and effective to use as PID optimization technique. However, the solution of obtained is not the universal solution and this is an offline tuning technique.

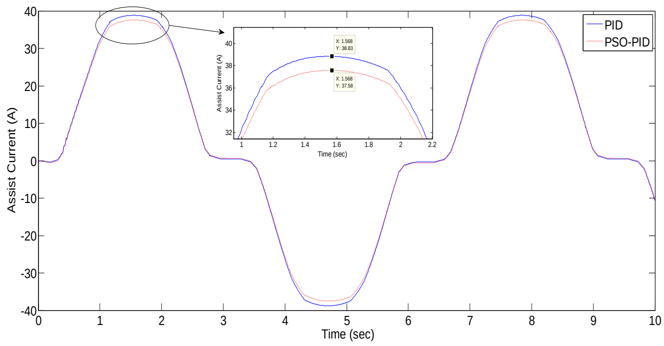

Fig. 8. Assist current to motor.

TABLE II: PARAMETERS VALUE FOR K_P, K_I AND K_D

PID tune using:	k_p	k_i	k_d
Try and error (manual tune)	200	10	5
PSO tuning mechanism	125.4541	2.0909	4.1818

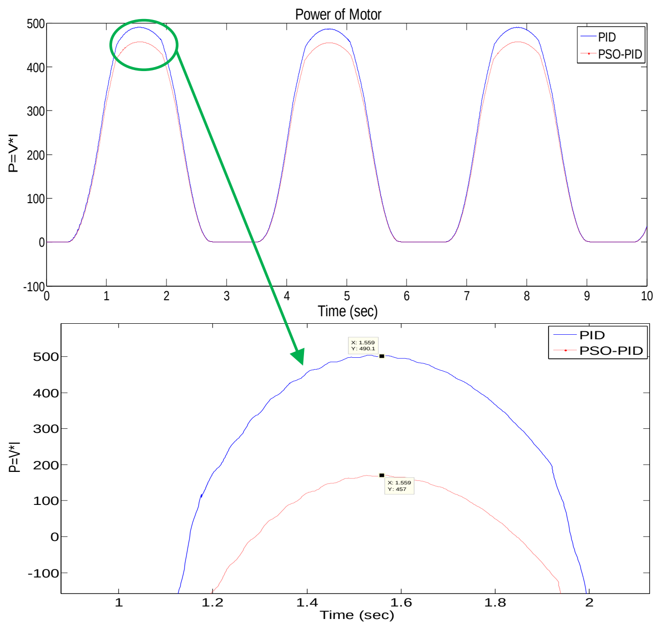

Fig. 9. Assist motor power.

VI. CONCLUSION

An EPAS system Simulink model has been developed using PSO as the tuning mechanism for PID controller. The simulation done shows the feasibility of using PSO for tuning purpose in controlling assist current of the assist motor. The result shows that PSO-PID controller able to reduce the power consumed by the assist motor as an effort to minimize energy consumption for EV application. In future work, further improvement need to be carried out in the case of dynamic vehicle velocity. The PSO-PID based controller shows a potential in optimizing energy efficiency of EPAS system.

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