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OPTIMAL TUNING OF A PID CONTROLLER FOR EMDAP-CVT USING PARTICLE SWARM OPTIMIZATION

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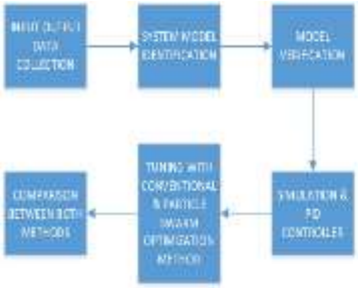
Graphical abstract



Abstract

This paper looked into optimal tuning of a Proportional-Integral-Derivative (PID) controller used in Electro-mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP-CVT) system for controlling the output obtained, and hence, to minimize the integral of absolute errors (IAE). The main objective was to obtain a stable, robust, and controlled system by tuning the PID controller by using Particle Swarm Optimization (PSO) algorithm. The incurred value was compared with the traditional tuning techniques like Ziegler-Nichols and it had been proven better. Hence, the results established that tuning the PID controller using PSO technique offered less overshoot, a less sluggish system, and reduced IAE.

Keywords: Auto tuning; particle swarm optimization; PSO; PID controller; CVT

Abstrak

Kertas kerja ini adalah berkenaan penalaan optimum pengawal berkadar-kamiran-derivatif (PID) yang digunakan dalam system pengerak-dua-takal-elektro-mekanikal penghantar kuasa pembolehubah berterusan (EMDAP-CVT) bagi mengawal keluaran yang diperolehi dan dengan itu mengurangkan kamiran ralat mutlak (IAE). Objektif utama adalah untuk mendapat satu sistem yang stabil, kukuh, dan terkawal dengan menala pengawal PID menggunakan algoritma pengoptimuman gerombolan zarah (PSO). Nilai yang diperolehi dibandingkan dengan teknik-teknik penalaan tradisional seperti Ziegler Nichols dan ia adalah terbukti lebih baik. Oleh itu, keputusan menunjukkan bahawa penalaan pengawal PID menggunakan teknik-teknik PSO memberikan lajakan yang lebih kurang, menjadikan sistem kurang lembap, dan juga mengurangkan nilai IAE.

Kata kunci: Penala automatic; pengoptimuman gerombolan zarah; PSO; PID; CVT

1.0 INTRODUCTION

Over recent years, the PID controller has been the most popular controller of the century because of its effectiveness, simplicity of implementation, and broad applicability. Nevertheless, it has been a challenge to obtain optimal tuning for PID controller in practice. Most PID tunings are done manually, which is difficult and time consuming. In order to use PID controller better, the optimal tuning of its parameter have become an important research field [1]. The basic function of controller is to execute an algorithm based on the input of the control engineer, and hence, to maintain the output at the level so that there is no difference between the proses variable and the set-point [2]. The popularity of PID controllers is due to their functional simplicity and reliability. They provide robust and reliable performance for most systems and the PID parameters are tuned to ensure a satisfactory closed-loop performance [3]. A PID controller improves the transient response of a system by reducing the overshoot, and by shortening the settling time of a system [4]. The PID control algorithm is used to control almost all loops in process industries and it is also the cornerstone for many advanced control algorithms, as well as strategies [2]. For this control loop to function properly, the PID loop must be properly tuned. Standard methods for tuning include Ziegler-Nichols Ultimate-cycle tuning [1], Astrom and Hagglund [5], and many other traditional techniques.

2.0 DYNAMIC MODEL OF EMDAP-CVT SYSTEM

The Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP-CVT) was developed by Universiti Teknologi Malaysia Drive-train Research Group (DRG) [6,7,8] in 2010. EMDAP-CVT used V-belt as its ratio variator, while electro-mechanical actuation system actuated the movement of the dual pulley sheaves simultaneously during the event of changing ratio. The electro-mechanical actuation system in EMDAP-CVT used 2 DC electric motors for shifting ratio and clamping. The first work related to the EMDAP-CVT was conducted by Sugeng Ariyono [8]. In his research, Ariyono controlled the engine speed for the vehicle with EMDAP-CVT system. His work focused on developing an intelligent control system using adaptive artificial neural network (AANN) method that provided an appropriate CVT ratio. The research was then continued by Bambang Supriyo [6,7], who focused on designing and developing EMDAP CVT ratio controllers in time domain analysis based on several algorithms, including the modeling of the overdrive and under-drive of the system. Meanwhile, the current research on EMDAP CVT was continued by Izahari Izmi [9], who designed a new concept pertaining to the changing ratio for primary motor and proposed an independent controller at the secondary motor, as shown in figure 1. In this paper, the overall plant model was obtained by experimental identification using different step-shaped disturbances in the command feed. The actual CVT ratio, $RCVT_{actual}$, was proportional to the input feed. The overall system of the EMDAP-CVT was modelled as a fifth-order system, and the experimental identification procedure yielded the transfer function as:

$$G(s) = \frac{-0.011s^4 + 0.002s^3 - 0.0001s^2 + 1.965e^{-6}s + 1.631e^{-7}}{s^5 + 0.098s^4 + 0.012s^3 + 0.0005s^2 + 1.634e^{-5}s + 1.638e^{-7}}$$

Where *s* is the Laplace operator, *f* is the input feed, and *F* is the CVT ratio. The model did have certain limits in representing the complexity and the uncertainty of overdrive and under-drive of the system. However, it provided a rough description of the process behavior that was essential for designing a network-based PID control system.

3.0 ZIEGLER-NICHOLS TUNING METHOD

The PID controller was the most popular controller in this century because of its effectiveness, simplicity of implementation, and broad applicability. Nevertheless, it is hard to obtain optimal tuning for PID controller in practice. In fact, most PID tunings are done manually, which is difficult and time consuming. Hence, in order to use the PID controller better, the optimal tuning of its parameter has become an important research field [1].

In this paper, the PSO tuning technique was compared with Ziegler Nichols' [5] tuning method. In the 1940s, Ziegler and Nichols devised two empirical methods for obtaining controller parameters. The Ziegler-Nichols' closed-loop tuning method allows one to use the ultimate gain value, K_U, and the ultimate period of oscillation, P_U, to calculate K_C. It is a simple method of tuning PID controllers and it can be refined to give better approximations of the controller. Even though this method was devised in 1940, it is still one of the most widely used methods for tuning a PID controller because of its applicability to almost all the systems irrespective of its order. Although many other methods of tuning have been developed in this field in recent years, not many have proved to be as efficacious as the one abovementioned. Table 1 portrays the important table for the Ziegler-Nichols' tuning method.

Table 1 Ziegler-Nichols' method

Control type	Kp	Ki	Kd
P	0.5Ku	-	-
PI	0.45Ku	1.2Kp/Pu	-
Classic PID	0.6Ku	2Kp/Pu	KpPu/8
No overshoot	0.2Ku	2Kp/Pu	KpPu/3

The ultimate gain value for the above mentioned system was calculated to be K_U=18000 and the ultimate period of oscillation was P_U =159. Based on Ziegler-Nichols' tuning method, the tuning parameters were calculated as:

***Kp*= 10800**, ***Ki* = 135.8491**, and ***Kd*= 214650**

The objective of the paper was to use the PSO algorithm in order to obtain optimal PID controller settings for a high performance drilling process, which is non-linear in nature. Every possible controller setting represents a particle in the search space, which changes its parameters proportionality constant, K_p, and integral constant, K_i, in order to minimize the error function (objective function in this case). The error function used here is Integral Time of Absolute errors (IAE). The tuning results of conventional techniques are discussed in this section. Section 4 deals with the explanation of the PSO algorithm and its implementation. Meanwhile, the comparative studies and results are given in Section 5. The conclusions arrived at, based on the results, are given in Section 6, followed by conclusion and reference in sections 7 and 8 respectively.

The frequency response of the system with PID tuned with Ziegler-Nichols was compared with the method suggested in this study for tuning in the forthcoming paragraphs.

4.0 PSO-BASED PID CONTROLLER

The PID controller has been the most popular controller of this century because of its effectiveness, simplicity of implementation, and broad applicability. It is hard to obtain optimal tuning for PID controller in practice. Most PID tunings are done manually, which is difficult and time consuming. In order to use PID controller better, the optimal tuning of its parameter has become an important research field [1]. The basic function of controller is to execute an algorithm based on the input given by the control engineer, and hence, to maintain the output at the level so that there is no difference between the proses variable and the set-point [2]. The popularity of PID controllers is due to their functional simplicity and reliability. They provide robust and reliable performance for most systems and the PID parameters are tuned to ensure a satisfactory closed-loop performance [3]. A PID controller improves the transient response of a system by reducing the overshoot, and by shortening the settling time of a system [4]. The PID control algorithm is used to control almost all loops in process industries and it is also the cornerstone for many advanced control algorithms and strategies [2]. For this control loop to function properly, the PID loop must be properly tuned. Standard methods for tuning include Ziegler-Nichols' Ultimate-cycle tuning [1], Astrom and Hagglund [5], and many other traditional techniques.

4.1 Particle Swarm Optimization

The optimization algorithms are another area that has been receiving increased attention in the past few years by the research community, as well as the industry [10]. An optimization algorithm is a numerical method or algorithm for finding the maximum or the minimum of a function operating with certain constraints [11].

Particle swarm optimization (PSO) is a computational algorithm technique based on swarm intelligence. This method is motivated by the observation of social interaction and animal behaviors, such as fish schooling and bird flocking. It mimics the way they find food by the cooperation and the competition among the entire population [12]. A swarm consists of individuals, called particles, each of which represents a different possible set of the unknown parameters to be optimized. The 'swarm' is initialized with a population of random solutions [13]. In a PSO system, particles fly around in a multi-dimensional search space, adjusting its position according to its own experience and the experience of its neighboring particle. The goal is to efficiently search the solution space by swarming the particles towards the best fitting solution encountered in previous iterations with the intention of encountering better solutions through the course of the process and eventually converging on a single minimum or maximum solution [14]. The performance of each particle is measured based on a pre-defined fitness function, which is related to the problem being solved. In fact, the use of PSO has been reported in many recent works [15] in this field. Moreover, PSO has been regarded as a promising optimization algorithm due to its simplicity, low computational cost, and good performance [16].

In PSO algorithm, the system is initialized with a population of random solutions, which are called particles, and each potential solution is also assigned a randomized velocity [17]. PSO relies on the exchange of information between particles of the population called swarm. Each particle adjusts its trajectory towards its best solution (fitness) that is achieved so far. This value is called P_{best}. Each particle also modifies its trajectory towards the best previous position attained by any member of its neighborhood. This value is called g_{best}. Each particle moves in the search space with an adaptive velocity.

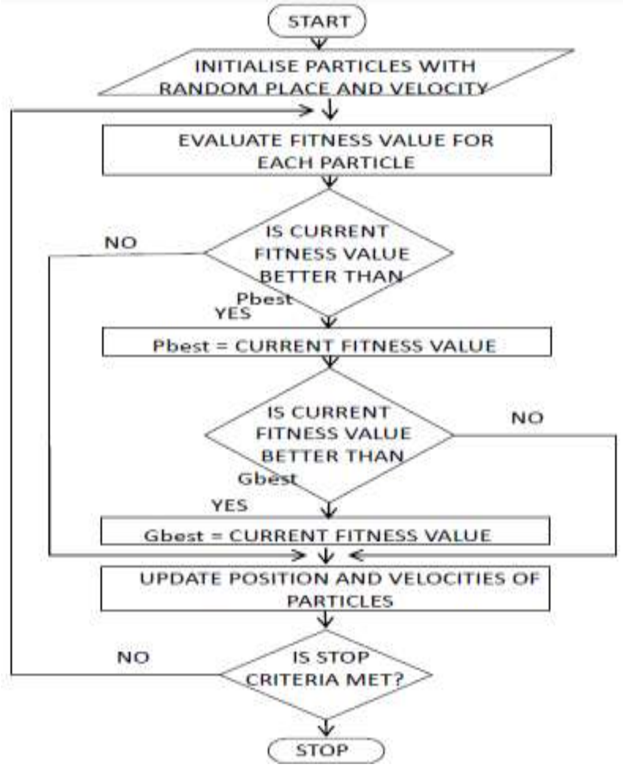


Figure 1 Particle swarm optimization algorithm [18]

The fitness function evaluates the performance of particles to determine if the best fitting solution is achieved. During the run, the fitness of the best individual improves over time and typically tends to stagnate towards the end of the run. Ideally, the stagnation of the process coincides with the successful discovery of the global optimum.

5.0 COMPARATIVE ASSESSMENT

The optimal values of the PID controller parameters K_p, K_i, and K_d, were found to use PSO. All possible sets of controller parameter values are particles whose values are adjusted so as to minimize the objective function, which in case is the error criterion is discussed in detail. For the PID controller design, it is ensured of the controller settings estimated results in a stable closed-loop system.

5.1 Selection of PSO Parameters

A few parameters, such as velocity constant, population size, and number of iterations need to be defined before the process was begun. Selection of these parameters decides to a great extent the ability of global minimization. The maximum velocity affects the ability of escaping from local optimization and refining global optimization. The size of swarm balances the requirement of global optimization and computational cost. Table 2 shows the initialized values for the selected parameters.

Table 2 The initialized value for selected parameters

Population size	50
Number of iterations	50
Velocity constant, c1	2
Velocity constant, c2	2

5.2 Performance Indices for the PSO Algorithm

The objective function considered had been based on the error criterion. The performance of a controller is best evaluated in terms of error criterion. A number of such criteria are available and in the proposed work, controller's performance was evaluated in terms of [16]:

i. Integral of Absolute Error (IAE) criterion, given by

$$I_{IAE} = \int_0^T |e(t)dt|$$

The IAE weighs the error with time, and hence, emphasizes the error values over a range of 0 to T, where T is expected as settling time.

ii. Integral Square of Error (ISE) criterion. The error criterion is given by the equation

$$I_{ISE} = \int_0^T e^2(t)dt$$

iii. Integral of Time multiplied by Absolute Error (ITAE) criterion, given by

$$I_{ITAE} = \int_0^T t|e(t)|dt$$

The time is considered as, t=0 to t=Ts, where Ts is the settling time of the system to reach steady state condition for a unit step input.

iv. Mean Square Error (MSE)

$$MSE(\hat{\theta}) = E\left|(\hat{\theta} - \theta)^2\right|$$

5.3 Performance Indices for the PSO Algorithm

The parameter for optimization algorithm can take place either when the maximum number of iterations gets over or with the attainment of satisfactory fitness value. Fitness value, in this case, is nothing, but reciprocal of the magnitude of the objective function, since minimization of objective function was considered. In this paper, the termination criteria were considered to be the attainment of satisfactory fitness value, which occurred with the maximum number of generations as 50.

For each generation, the best among the 50 particles considered as potential solution had been chosen. Therefore, the best values for 50 generations were sketched with respect to generations, and are shown in Figs. 2, 3, and 4.

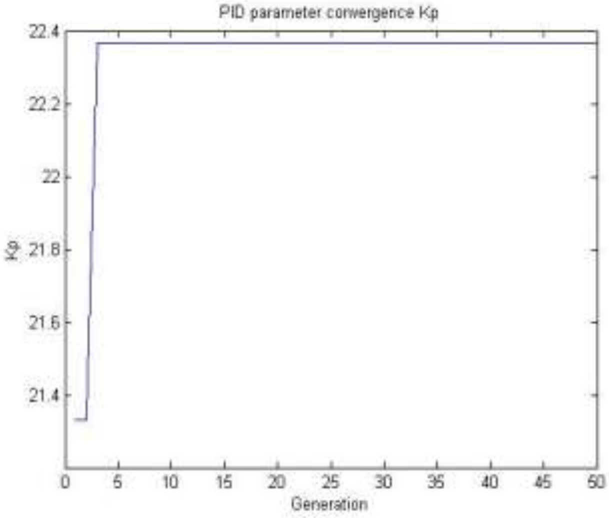


Figure 2 Best solutions for K_p in 50 generations

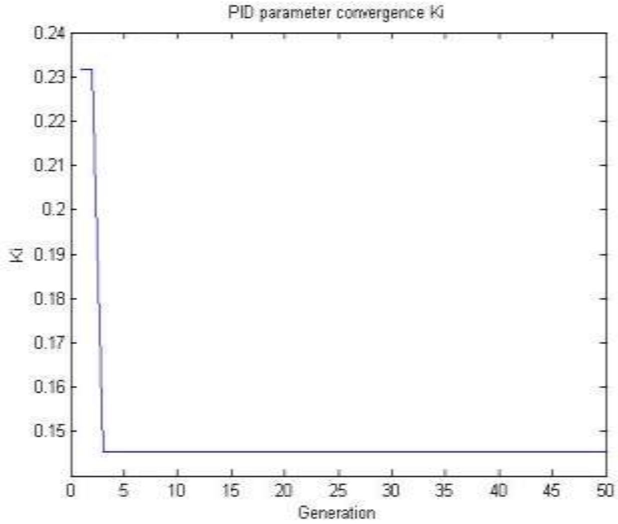


Figure 3 Best solutions for K_i in 50 generations

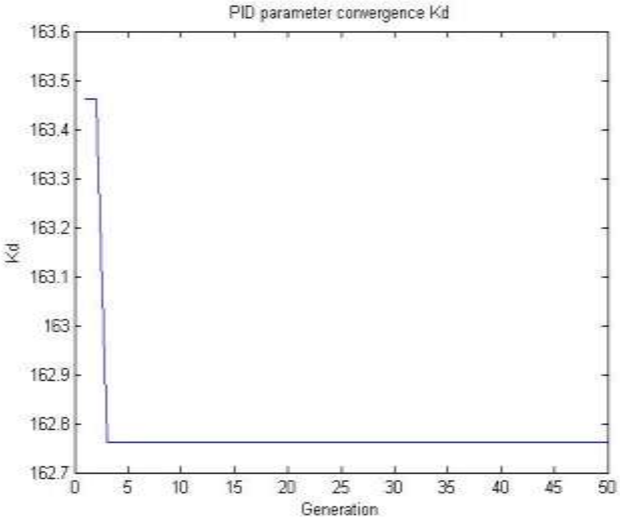


Figure 4 Best solutions for K_d in 50 generations

The PID controller was formed based upon the respective parameters for 50 generations, and the global best solution was selected for the set of parameters, which had minimum error. A sketch of the error based on IAE criterion for 50 generations is given in Figure 5.

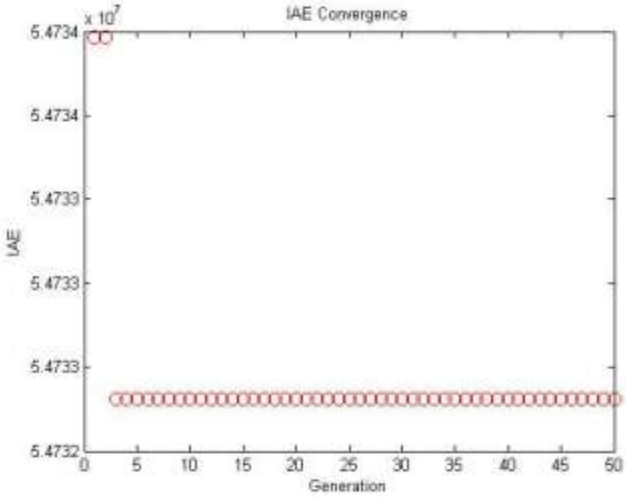


Figure 5 IAE value for 50 generations

It had been noted that the error value tended to decrease for a larger number of generations. As such, the algorithm was restricted to 50 generations and beyond as there was only a negligible improvement. Based on PSO for the application of the PID tuning, the obtained PID tuning parameters for the model had been:

Kp = 22.37, Ki = 0.1455, and **Kd = 162.8**

6.0 RESULTS AND COMPARISON

The analysis showed that the design of the proposed controller offered better robustness, and the performance was satisfactory over a wide range of process operations. Meanwhile, the simulation results showed improvement in performance for time domain specifications for a step response. Using the PSO approach, global and local solutions were simultaneously identified for better tuning of the controller parameters.

The PID value, which was obtained by the PSO algorithm, was compared with that of the one derived from Zeigler-Nichols' method in various perspectives, namely robustness and stability performances. All the simulations were implemented using MATLAB.

6.1 Performance Related to Steady State Conditions

In order to investigate the performance of the controller, a desired input of unit step was given to the closed-loop system. The above procedure was implemented into the controller, as the PID values were tuned by Ziegler-Nichols, as well PSO algorithm. Besides, two types of controllers from the Zeigler-Nichols' table were used, which were the Classic PID controller and the no-overshoot controller. The response curve obtained is shown in Figure 6.

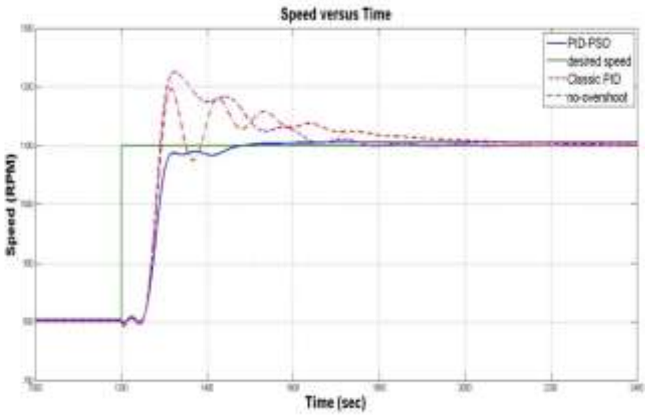


Figure 6 System response using Classic PID, no-overshoot, and PID-PSO

There had been a high overshoot using the Ziegler-Nichols, and even with the integral gain, it still failed to eliminate the off-set. Meanwhile, the no-overshoot controller was used to overcome the problem, and it was found that the response was stable, but it was insufficient to eliminate the big off-set. On the other hand, the PID-PSO controller gave a good response. There was no overshoot and the output response was stable. A comparison of time domain specifications peak overshoot, peak time, rise time, and settling time are tabulated in table 3. It had been very clear that the PSO-based controller drastically reduced the overshoot by a large value. Settling Time, Rise Time, and Peak Time were also improved, henceforth, outperformed the traditionally-tuned controller with Ziegler-Nichols' criterion.

Table 3 Comparison of time domain specification

Type of controller	Ziegler-Nichols	PSO
Peak time(sec)	0.7	0.6
Peak overshoot (%)	40	0
Rise time(sec)	0.223	0.17
Settling time(sec)	3.0	1.6

6.1 Robustness Investigation

The PID controllers tuned by the PSO-based method should not be compared only with their time domain response, but also with its performance index from the four major error criterion techniques of Integral Time of Absolute Error (ITAE), Integral of Absolute Error (IAE), Integral Square of Error (ISE), and Mean Square Error (MSE). Robustness of the controller is defined as its ability to tolerate a certain amount of change in the process parameters without causing the feedback system to go unstable. A comparison of all performance indexes obtained from Ziegler-Nichols and PSO is tabulated in table 4.

Table 4 Comparison of performance index obtained from Zeigler-Nichols and PSO

Performance index	Ziegler-Nichols	PSO
ITAE	3.2684	2.7981
IAE	7.5696	5.4733
ISE	3.7754	2.3287
MSE	0.1452	0.1236

From these values obtained, it is clearly visible that the error magnitude obtained for Zeigler-Nichols is far too high as compared to the proposed tuning method based on PSO algorithm.

7.0 CONCLUSION

As a conclusion, in this paper, a systematic design method aimed at enhancing PID control for complex process using PSO had been proposed. It showed analytically and graphically that there was substantial improvement in the time domain specification in terms of lesser rise time, peak time, settling time, as well as lower overshoot. The performance index for various error criteria for the proposed controller using PSO algorithm had been proven to be less than the controller tuned by the Ziegler-Nichols' method.

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