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DETERMINATION OF PI COEFFICIENTS IN SPEED CONTROL OF BRUSHLESS DC MOTOR WITH GRAY WOLF OPTIMIZATION AND FPGA APPLICATION

FIRÇASIZ DC MOTORUNUN HIZ KONTROLÜNDE PI KATSAYILARININ GRİ KURT OPTİMİZASYONU İLE BELİRLENMESİ VE FPGA UYGULAMASI

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ABSTRACT

DC motors are widely utilized in various industries due to their efficiency, longevity, and adjustable speed settings. Effective control of these motors is crucial, given their broad application range. As applications vary, so do the controlled motor parameters, necessitating control systems that are suitable for industrial use. However, standard controllers often face challenges due to the non-linear and uncertain nature of the mathematical models involved. This study aims to introduce a novel approach by employing Grey Wolf Optimization (GWO) to determine the PI coefficients for brushless DC motor speed control, which is then implemented on an FPGA. During the study, a control strategy model for the BLDC motor was developed using MATLAB/Simulink. The motor's speed was gradually increased from 300 to 600 and 900 rpm at specific intervals to calculate the controller coefficients. The GWO technique optimized the PI parameters, Kp and Ki, using the ITAE cost function. The results showed an improvement in speed control when comparing the conventional PI and GWO-PI controllers to the reference speed, with GWO-PI achieving closer adherence. As opposed to most studies that focus on simulations, this research tested the model using hardware, specifically the BASYS3 FPGA training card, demonstrating that the BLDC motor can operate at higher speeds in industrial settings with the optimized GWO-PI approach.

Keywords: Brushless DC motor, FPGA, GWO-PI, Speed Control

ÖZET

Doğru akım (DC) motorları, verimlilikleri, uzun ömürleri ve ayarlanabilir hız özellikleri nedeniyle birçok endüstride yaygın olarak kullanılmaktadır. Bu motorların etkin bir şekilde kontrolü, geniş kullanım alanları göz önüne alındığında son derece önemli oldukları görülmektedir. Uygulama alanları değiştikçe, kontrol edilen motor parametreleri de farklılık göstermekte ve bu nedenle sanayi kullanımına uygun kontrol sistemlerinin geliştirilmesi gerekmektedir. Bununla birlikte, standart kontrolörler, genellikle matematiksel modellerin doğrusal olmayan ve belirsiz yapısı nedeniyle zorluklarla karşılaşmaktadır. Bu çalışma, fırçasız DC motor hız kontrolünde PI katsayılarının belirlenmesi amacıyla Gri Kurt Optimizasyonu (GKO) yöntemini kullanarak yeni bir yaklaşım sunmayı hedeflemektedir ve bu yöntem, bir FPGA üzerinde uygulanmıştır. Çalışma sürecinde, BLDC motor için bir kontrol stratejisi modeli MATLAB/Simulink kullanılarak geliştirilmiştir. Motorun hızı, kontrolör katsayılarını hesaplamak amacıyla belirli aralıklarla 300 rpm'den 600 ve 900 rpm'ye kademeli olarak artırılmıştır. GKO tekniği, ITAE maliyet fonksiyonunu kullanarak PI parametreleri olan Kp ve Ki'yi optimize etmiştir. Sonuçlar, geleneksel PI ve GKO-PI kontrolörlerinin referans hız ile karşılaştırılmasında, GKO-PI'nin daha yakın bir uyum sağladığını göstermiştir. Çoğu çalışmanın simülasyonlara odaklanmasının aksine, bu araştırma modeli donanım üzerinde test etmiştir ve özellikle BASYS3 FPGA eğitim kartı kullanılarak BLDC motorun sanayi ortamında daha yüksek hızlarda çalışabileceği optimize edilmiş GKO-PI yöntemi ile gösterilmiştir.

Anahtar Kelimeler: Fırçasız DC motor, FPGA, GWO-PI, Hız Kontrolü

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INTRODUCTION

Brushless DC (BLDC) motors are used in every market sector, including household appliances, industrial control, automation, aerospace, and others. BLDC motors have several key benefits, including high efficiency, extended longevity, lower noise levels, and high-speed range adjustment (Krishnan, 2017; Miller, 1989). The three main categories of BLDC motor operation control are positioning applications, variable loads, and fixed loads. The engine mileage directly affects the load in blower, fan, and pump applications. These are low-cost applications that need open-source controllers (Bharatkar et al., 2011). The engine's load varies according to the applications' fluctuating speed needs. Compressors, dryers, and washing machines are examples of tools that may need precise high-speed control and robust dynamic reactions. Positioning applications comprise the majority of industrial and automation applications. All applications in this category use some kind of power transmission, such as basic belt-driven systems, mechanical straps, time-adjustable straps, or trigger straps. As a result, several controller types can be created to satisfy various application requirements.

Rotor angular speed control is very crucial as the applications for BLDC are often delicate. This is the reason that several control strategies for BLDC speed control have been developed and published in the literature. Jin et al. proposed adaptive control having high performance for BLDC motor with real-time estimation of uncertainties (Jin et al., 2006). In response to the BLDC's system performance, (Gökbulut et al., 2006; Premkumar et al., 2014) proposed the hybrid neuro-fuzzy controller. The utilization of an RBF neural network to implement adaptive speed control for BLDC motors was suggested by (Wang et al., 2007). An adaptive speed controller with speed-sensorless was studied by (Wang et al., 2006) for a BLDC motor. Model reference adaptive control with low-resolution Hall-effect sensors was presented by (Liu et al., 2014). Masoudi et al. proposed a novel control strategy that combines direct power regulation with a weakening zone to minimize torque fluctuation in the non-sinusoidal BLDC motors utilized in the application (Masoudi et al., 2023). A performance comparison of commutation modes based on impact width modulation (DGM) employing sinusoidal DGM and 120°, 180°, and 150° modes was carried out in a different study (Yorat et al., 2023). Using a mathematical technique known as the chaos control and chaotic features of BLDC engines was introduced by Abro and his friends (Abro et al., 2022). In his work, Hooshmand and colleagues suggested a method that would include phase currents and line voltages in estimating speed and rotor position for position-free operation of BLDC motors based on an efficient state prediction algorithm (Hooshmand et al., 2023). Electrical engine technology has been controlled to enable wireless power transmission, allowing the engine to operate without physical touch and allowing the load engine to be employed in remote locations. With a 20 mm wireless power transmission range of 400 rpm to 4000 rpm, the study enhanced transmission efficiency to 80.2% (Wang et al., 2023).

For speed control of electro-mechanical systems, current loop and speed loop are generally considered separately, and in practice Proportional - Integral - Derivative (PID) control structures are used for these loops. PID control; It is still the most preferred and used control method in the industry due to reasons such as its stability, uncomplicated structure, applicability to a wide area, and ease of application on digital/analog platforms (Anwar et al., 2013). There are drawbacks to using these conventional controllers, particularly because of the non-linear mathematical model with uncertainties. Therefore, there are many studies in the literature on determining or improving the coefficients of the PID controller (Ramakrishnan et al., 2023). It also seems that efforts are being made to develop alternative methods. Some of the main studies from these studies are explained below.

Although the most commonly used method for determining controller parameters in PID controls is the Ziegler-Nichols method, artificial intelligence optimization algorithms have also been used widely in recent years. Particle swarm optimization (Ibrahim et al., 2014), artificial bee colony algorithm (Tarczewski & Grzesiak, 2018), genetic algorithm (Ansari et. Al., 2011), and whale optimization algorithm (Banerjee et al., 2022) methods were used to determine the PID controller coefficients used for speed control in BLDC motors and successful results were obtained.

The PID controller is used to regulate the BLDC motor that is fueled by a photovoltaic (PV) battery. The hybrid horse particle approach is used to determine the controller parameters. Traditional controllers containing PI controllers were not observed to meet expectations due to non-linear characteristics of the BLDC motor driver, and therefore it was suggested that efficiency could be improved with a hybrid gray wolf optimization (Younus et al., 2023). On the other hand, a study by Intidam and colleagues compared the performance of the control techniques applied to the high-performance brush-free DC (BLDC) engine (PI-ANFIS, PSO-PI- ANFIS) (Intidam et al., 2023).

The industrial sectors are experiencing a growing need for engine control systems that are accurate and effective. BLDC motors are widely used because of their extensive variety of applications, high efficiency, and dependability. The integration of the FPGA (Field Programmable Gate Array) control system, a versatile platform, with a BLDC motor, is clear to increase the efficiency of the system. However, the integration requires sensors to provide position feedback, a PID control algorithm written in hardware identification language (HDL) to regulate speed, and the necessary signals to power the engine. For instance, research (Muniraj et al., 2023) offered a workable and flexible FPGA-based solution for BLDC engine speed management. In their research, Udayakumar and associates transformed power from the solar panel during the day using a three-phase DC-AC converter, stored it in a battery, and then replicated the process using a three-phase FPGA converter (Udayakumar et al., 2023). In another study, the fuzzy rules of the Fuzzy logic membership function were optimized with the GWO and modeled with FPGA (Ahmed & Yahia, 2024). FPGA was used in a study by Antic and colleagues to create the parity ratio of DC motor failures (Antic et al., 2023).

When traditional controllers are used, disadvantages arise, especially due to the non-linear mathematical model with uncertainties. With this motivation, this study aims to develop an alternative solution to existing studies to solve the problem in question. That is, the purpose is to determine the PI coefficients for speed control of the BLDC motor using Gray Wolf Optimization (GWO) and then apply it using FPGA. In the order that the applications were put into place within the parameters of this goal; i) The traditional PI control is used to implement the control mechanism, ii) To improve the system, PI ratios are determined using the Grey Wolf Optimization method, iii) By using the Systems Generator, the BLDC motor's PI, sensor, and position data are gathered for simulation on the FPGA and then sent to the Matlab/Simulink platform, iv) The engine simulated with FPGA was experimentally tested with the BASYS3 training card.

MATERIAL AND METHOD

The BLDC motor cannot operate at its best when combined with a non-linear system, despite the PI controller's straightforward design and cost-effectiveness as a result of its non-linear feature (Younus et al., 2023). High-performance BLDC motor dynamic speed tracking and load control sensitivity drivers are crucial for industrial applications. To improve the performance of the BLDC motor, this article is adjusted with the GWO-PI-based optimization method for the speed control of the BLDC motor.

Speed control in brushless DC motor

BLDC motors have a permanent magnetic rotor and three stator brackets. The mathematical representation of these motors is similar in many ways to the conventional DC motors. (Shary et al., 2023). The addition of motor phases differs in mathematical representation from the DC motor. The resistant and inductive layout of the BLDC motor is affected by these phases (Nasri et al., 2007). The three-phase star-connected BLDC motor can be described using the following equations.

$$v_{ab} = R(i_a - i_b) + L\frac{d}{d_t}(i_a - i_b) + e_a - e_b \quad (1)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{d_t}(i_b - i_c) + e_b - e_c \quad (2)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{d_t}(i_c - i_a) + e_c - e_a \quad (3)$$

$$T_e = k_f w_m + J\frac{d_{w_m}}{d_t} + T_L \quad (4)$$

$$w_r = \frac{d\theta_r}{dt} \quad (5)$$

Here v_{ab} represents the phase-phase voltages of v_{bc} and v_{ca}, i_a, i_b and i_c amper stator currents. L represents the motor's self-induction, the electromagnetic force e_a, e_b and e_c, the magnetic moment of the motor T_e, the $T_L$load moment. J defines the attribute of the rotor, the friction constant is given by k_f, the motor's rotor speed is given in r (rad/s), and r (rad) gives the position of the rotor. The parameters for the BLDC engine used in the MATLAB/Simulink Simscape Block library used in this paper are given in Table 1.

Table 1. Motor Features Utilized in This Research

Brushless DC motor type	**BLY171D_24_1400**
Terminal voltage	24 V
Output power (P)	9800 W
Phase Number (Connection)	3 (Star)
No load Speed (w)	1400 rpm
Nominal current (I_n)	0.90 A
Number of poles (p)	8

The motor's momentum or current is regulated by the internal control circuit in BLDC motor. To achieve this, the reference current is continuously monitored by monitoring the current, which also monitors the motor phase currents. In the external control circuit, the motor speed is controlled. As feedback, actual engine speed information from position sensors is applied to the speed controller. In this study, an open circuit control was carried out to ensure that the BLDC motor works under nominal conditions without current refueling. So, in the system, the necessary electronic commutation operation has been performed to turn the motor, based on the rotor position information obtained from the sensors of the engine without the current being returned. A block scheme of the driver system is shown in Figure 1. The BLDC motor receives rotor rotation information and signaling to the position sensor. With the incoming signal, the keys receive the transmission information. At the same time, the speed information received from the rotor mill is passed through the speed control of the reference speed and the amount of error, and the inverter is applied V_{dc} voltage. Figure 1 (a) shows the inverter system of a typical BLDC motor, and Figure 1 (b) shows the speed control structure.

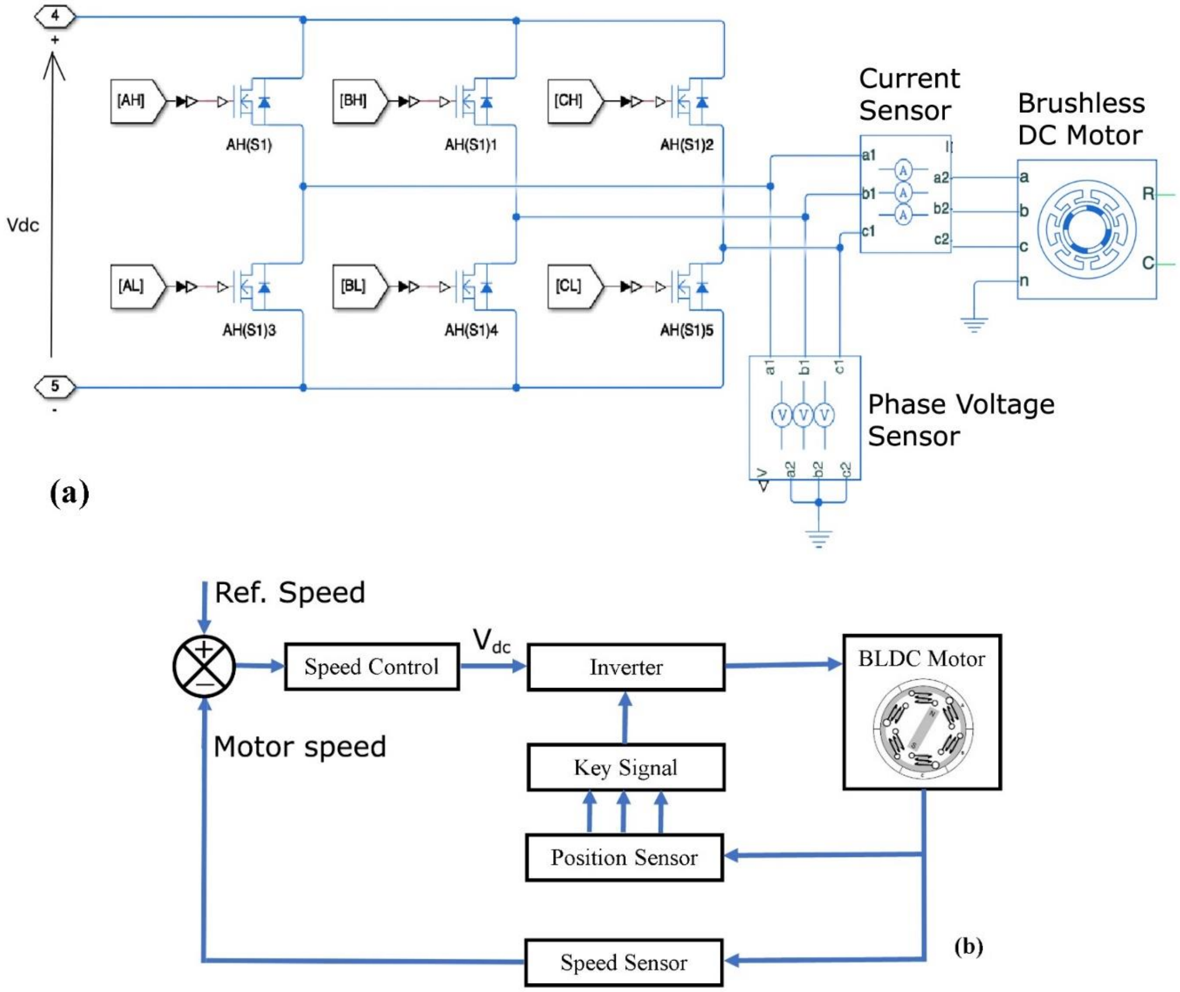


Figure 1. a) Typical Inverter System for a Brushless DC Motor, b) Speed Control System of Brushless DC Motor

Determination of PI parameters in the speed control of a brushless DC motor

This article controls the speed of BLDC motors using traditional PI and GWO-PI controllers. The speed information obtained through both controls was studied together with the reference speed. The details of the methods are briefly described in this section.

i) A Classical approach to determining PI parameters

The system can be properly controlled by the PID (Proportional-Integral-Derivative) controller with the classical degree of integrity, with the correct determination of the parameters of the controller. The PI control method is used to reduce the permanent state error of the system, and the overall structure is shown in Figure 2. PI control is a method that produces a control signal in proportion to the width of the error signal between the input and output signals. (Padula & Visioli, 2011). The mathematical definition of PI coefficients is given in equation 6.

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{6}$$

Artificial intelligence approaches are commonly employed in parameter determination, in addition to the Ziegler-Nichols method, which was designed to obtain PID ratios experimentally (Zhou, 2022). This is a result of the non-linear characteristic of the variables that are asked to be examined. Due to these disadvantages, optimization methods are used to improve PI ratios. In this study, the Kp and Ki parameters of the PI controller were determined using the GWO Method.

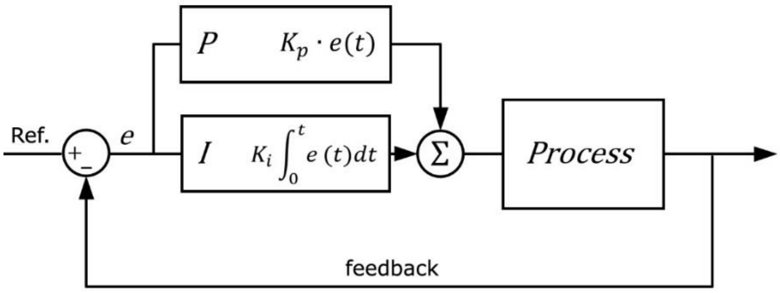


Figure 2. General Structure of the PI Controller

ii) Grey Wolf Optimization algorithm

GWO is inspired by the hierarchy and hunting behavior of gray wolf populations. Wolves are alpha, beta, delta, and omega gray wolves. Exploration, encirclement, and attack are the three phases of the hunting process. All stages are performed simultaneously with the optimization process. Mirjalili introduced a brand-new, potent meta-intuitive optimization called GWO (Mirjalili & Lewis, 2014). It is comprehensible and useful to use because it is based on animals and the natural world. The primary advantage of GWO is its adaptability, simplicity, and clarity. In power system and machinery control applications, in HVDC (High voltage direct current) applications for optimum power flow, and in high voltage transmission lines, the GWO method is used in the account of transmission line parameters (Shaikh et al., 2021). In order to optimize engineering design challenges, a GWO method was proposed by the reference study (Mirjalili, 2015). Because it abides by the laws of the wolf pack, the alpha is a dominating species among the four groups of wolves. Beta class refers to the secondary wolves that help alpha decide. Omega represents the gray wolves in the lowest order. The wolf community is a delta if it does not belong to any of these three groups.

Mathematically, any optimization problem that considers alpha (α) as the optimal answer can be addressed while accounting for the wolf's social order. Beta (β) and Delta (δ) represent the second and third best solutions, respectively. The GWO approach consists of three main steps: tracking, searching, hunting, and approaching potential catches.

Wrapping around the hunt; Gray wolves surround the hunt during hunting; equations (7-11) are used to mathematically model surrounding behavior (Mirjalili & Lewis, 2014; Shaikh et al., 2021; Mirjalili, 2015):

$$D = \left| C X_p(t) - X(t) \right| \tag{7}$$

$$X(t+1) = X_p(t) - A.\left|C.X_p(t) - X(t)\right| \tag{8}$$

$$A = 2a.r_1 - a \tag{9}$$

$$C = 2.r_2 \tag{10}$$

$$a = 2 - 2\frac{t}{Max\_iter} \tag{11}$$

Where X represents the gray wolf's position vector, X_p represents hunting position vectors. t displays the existing repetition, *A* and *C* are vectors of the coefficient, representing the random number between r_1 and r_2, [0,1], and a represents the linear decrease in the coefficient and *Max_iter* maximum repetition as iteration progresses from 2 to 0.

Hunting Strategy (Search): Gray wolves have the ability to identify potential hunting locations, and the search process is mainly conducted under the guidance of α, β, δ wolves. Every iteration maintains the top three wolves (α, β, δ) in the existing population, after which the locations of the remaining search agents are adjusted based on the location data. The equations (12–14) are applied in this stage.

$$D_\alpha = |C_1 * X_\alpha - X(t)|$$

$$D_\beta = \left|C_2 * X_\beta - X(t)\right| \tag{12}$$

$$D_\delta = |C_3 * X_\delta - X(t)|$$

$$X_1 = |X_\alpha - a_1 D_\alpha|$$

$$X_2 = \left|X_\beta - a_2 D_\beta\right| \tag{13}$$

$$X_3 = |X_\delta - a_1 D_\delta|$$

$$X(t+1)\ \frac{X_1 + X_2 + X_3}{3} \tag{14}$$

where, X(t+1) represents the new location of the catch.

Attacking Hunt: By reducing the value of a, the range of change of A is reduced. The calling agent's next position will be in between the hunting and the catching locations when A reaches any value in the range [-1, 1].

iii) Performance Index

The GWO method is used to determine the optimal values and the performance index is used for the optimal solution under the GWO. In this study, the performance index is Integral Time Absolute Error (ITAE), as defined in equation 15.

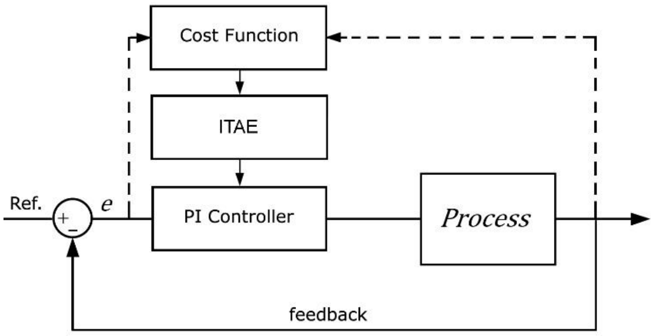
$$ITAE = \int_0^\infty t|e(t)|dt \tag{15}$$

The frequency of the error occurring in each iteration is determined by ITAE and the minimum ITAE-error value is sought for optimal parameters.

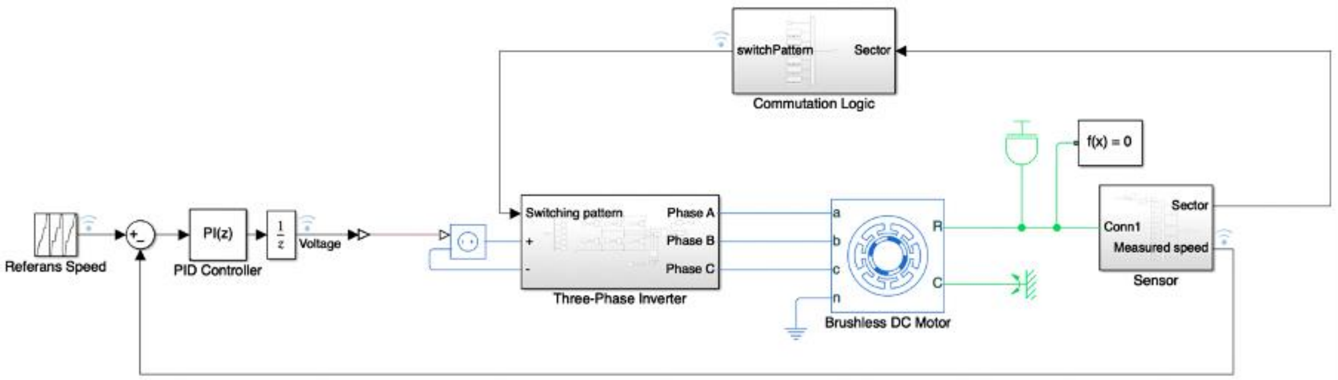
Determination of GWO parameters in the speed control of a brushless DC motor

In this study, the aim is to determine PI ratings for the speed control of a BLDC motor with GWO and to apply FPGA. The block diagram of the proposed design is shown in Figure 3(a). The optimization method minimizes errors, and instant error types that occur throughout time are achieved using these functions, as you can see. The ITAE cost function, which performs well in the literature, was utilized in this paper.

MATLAB/Simulink was used to model the BLDC motor's speed regulation based on the previously described study. The BLDC motor provided information about rotor speed, which was then sent to the position sensors. The error was obtained by comparing the speed information received from the rotor shaft with the reference speed. The error is routed through traditional PI control, and the inverter receives a V_{dc} voltage. A PI control comparison is shown in Figure 3(b).



(a)



(b)

Figure 3. (a) General Structure of the PI Controller,
(b) Speed Control Simulation of BLDC Motor in MATLAB/Simulink

FPGA Application

FPGA can be defined as a matrix of configurable logic ports combined with configurable paths (Arserim et al., 2019). The study's applicability can be tested on the flexible and potent FPGA integrated circuit, which has a distinctive approach to digital hardware design (Muniraj et al., 2023). The availability of numerous scientific works in industry is a topic of dispute when it comes to literature. In order to overcome this problem, field programmable gate sequences (FPGA) have been introduced. The FPGA-based PI speed control device is designed to effectively withstand changes in speed during dynamic motor conditions (Usman & Rajpurohit, 2020). Therefore, the recommended FPGA controller is used in the industry to maintain the constant speed response of a motor in operation in the event of any failure. To validate the findings of the MATLAB/Simulink comparison study, this paper looks at an experimental examination of a BLDC engine driver using an FPGA-based algorithm created on the Xilinx ISE tool.

The Basys3 FPGA card is a start-up card with an affordable clock speed of 100 MHz with an AMD-Xilinx Artix-7 FPGA (Figure 4). The Basys3 card has LEDs and other input-output cards to design without the need for any other hardware (digilent, 2022).

Figure 4. BASYS3 FPGA Training Card Utilized in this Research

RESULTS

Defining PI Parameters with Classical and GWO

The goal is to employ GWO to determine the PI coefficients for the BLDC motor's speed control and to implement it using FPGA. For this reason, an empirical method has been mostly used to determine the PI parameters. Then, GWO is used to optimize the PI values. In this optimization process, different numbers of agents have been tested and the best performance has been achieved with 30 gray wolf agents. 50 iterations were used in the optimization work. Thus, the PI parameters obtained with both classical and GWO are shown in Table 2.

Table 2. PI Coefficients and Associated Cost Value

	Kp	Ki	Cost
PI	0.001	2	---
GWO- PI	10	10	6.0710

The GWO and ITAE cost functions were used to improve the speed result of the simulation, and the Kp and Ki parameters for the new PI were determined. The performance change of the classic PI parameters with the new parameters obtained is shown in Figure 5. The BLDC motor began to turn at 300 rpm in 0.5 seconds, then 600 and 900 rpm in 1 second intervals. As seen in the figure, the speed change obtained with GWO-PI has the same change as the ref. speed. However, the classical PI speed exhibits a change close to the ref. speed.

Considering the purpose of this study and the suggested method, no study with the exact same scenario has been found. However, similar studies using different aims and methods can be seen in the literature. One of these researches was suggested by Gökçe et al. and in this study, a sinusoidal disturbance was employed as a load to brushed DC motor for speed control. PSO and classical methods were compared for various frequencies of disturbance and it was seen that PSO clearly has more performance than that of classical method especially in higher frequencies. In another research, Ibrahim et al. compared the PSO method with the Bacterial Foraging (BF) approach for determining the ideal PID controller settings for BLDC motor speed regulation. It is demonstrated by the suggested way that the PSO method performs better than BF, particularly in terms of the system's dynamic performance. In another study, it was aimed to determine PID parameters by hybrid method including PSO and GWO. The suggested method gives better results than the PSO and GWO algorithms.

It is seen that successful studies have been carried out in PID parameter determination related to BLDC, but most of these studies have been completed on simulations, not on hardware implementation. The difference in this study is that the simulation study was tested on hardware.

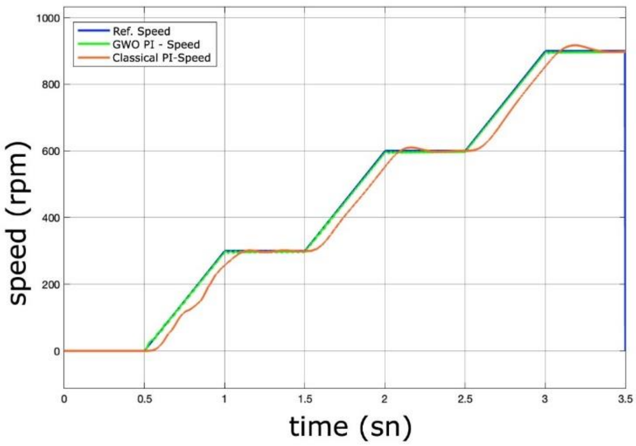


Figure 5. Speed-time Chart of the BLDC Motor with PI, GWO-PI

Color Space Modeling and Co-Simulation of Speed Control of BLDC Motor with FPGA

Similarity in MATLAB/Simulator modeled in FPGA via System Generator. In the modeling work, the PI, the Key Signals, and the Sensor block were re-modelled with FPGA.

The modeling used improved Kp and Ki parameters obtained by the GWO-PI optimization method in the second phase. Figure 6 shows a model with FPGA of the BLDC motor speed control PI, key signal, and position sensor blocks, modeled through the System Generator.

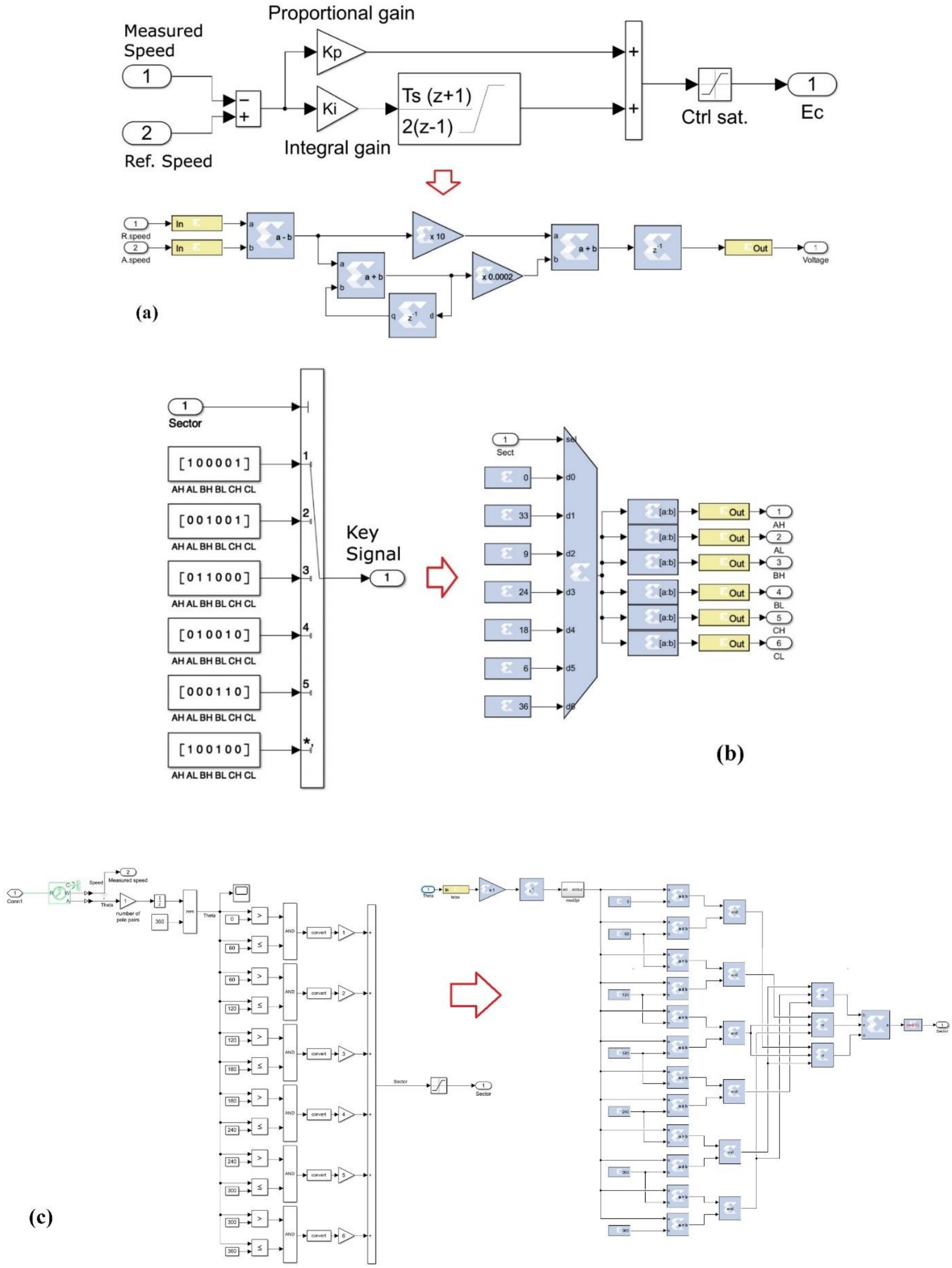


Figure 6. (a) PI, (b) Key Signal, (c) Models of Position Sensors Blocks with FPGA

A co-simulation of the parallel study in the next phase was carried out. The applicability of the study through co-simulation has been tested in industry. Figure 7 shows a co-simulation of the BLDC motor speed control.

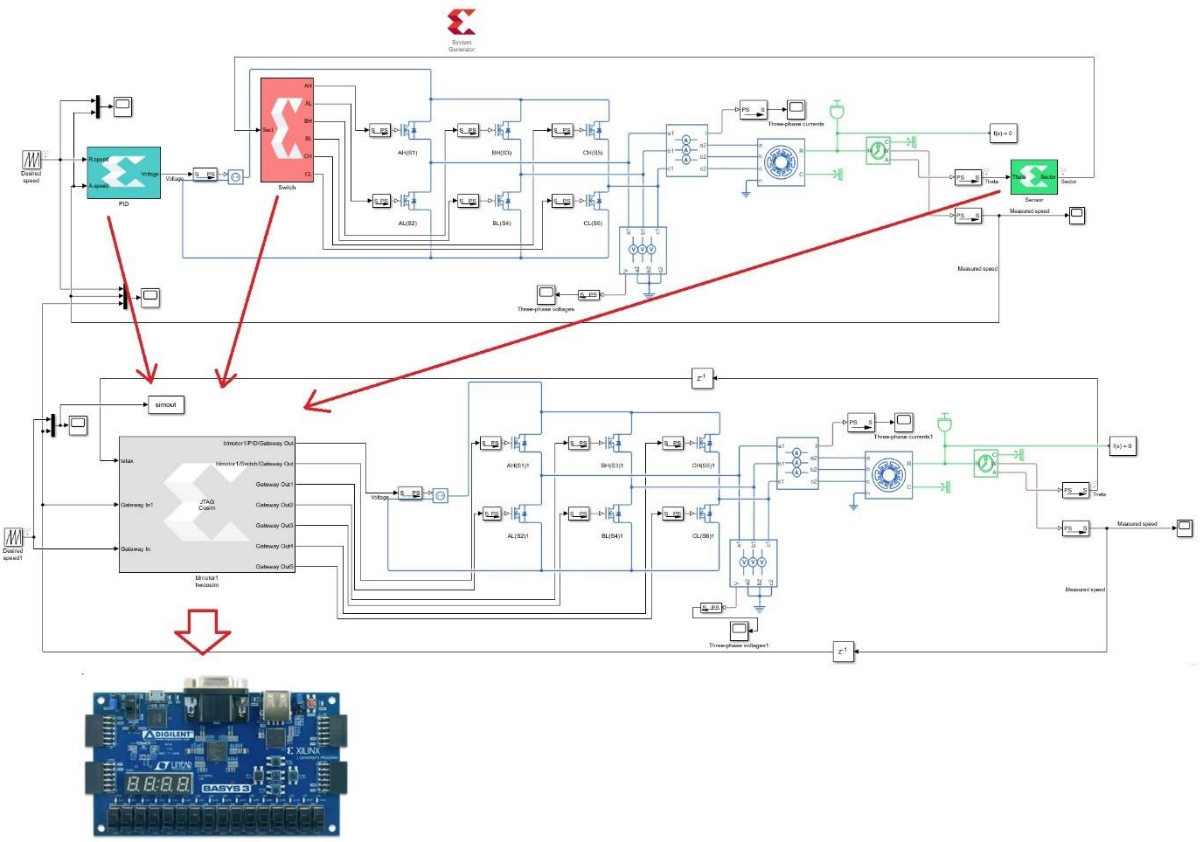


Figure 7. (a) PI, (b) Key signal, (c) Models of Position Sensors Blocks with FPGA

Figure 8 displays a picture of the experimental investigation that is displayed beneath the text. The speed control of a BLDC motor was made using the FPGA block optimization of the Gray Wolf PI provided by the AMD-Xilinx System Generator in the Matlab/Simulink program.

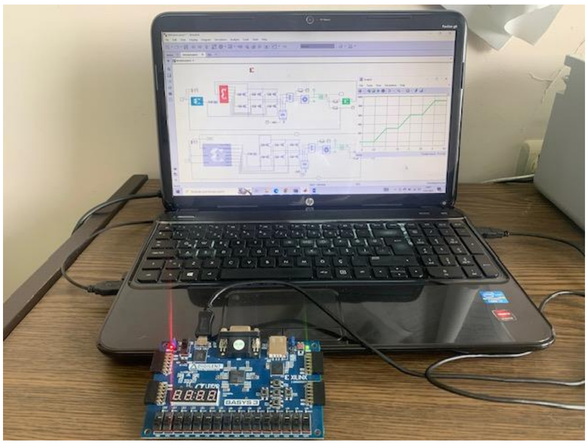


Figure 8. Experimental Application of BLDC Motor Speed Control with Basys3 FPGA Card

CONCLUSION

When traditional controllers are used, disadvantages arise, especially due to the non-linear mathematical model with uncertainties. With this motivation, this study aims to develop an alternative solution to existing studies to solve the problem in question. That is, the purpose is to determine the PI coefficients for speed control of the brushless DC motor using GWO and then implement it with FPGA. Using MATLAB / Simulink, the control strategy model for the BLDC motor was first constructed during the investigation stages. In determining the coefficient of controllers, the speed of BLCD was gradually increased, that is the BLDC motor began to turn at 300 rpm in 0.5 seconds, then 600 and 900 rpm in 1 second intervals. Speed control results were obtained with the classical PI controller and the

GWO method was optimized using the ITAE cost function to improve the Kp and Ki values of the PI parameters. Kp and Ki values obtained with classical PI and GWO-PI were compared with the reference speed and the improvement of speed control in optimization was observed. That is, the speed change obtained with GWO-PI has the same change as the reference speed. However, the classical PI speed exhibits a change close to the reference speed. It is seen also that successful studies have been carried out in PID parameter determination related to BLDC, but most of these studies have been completed on simulations, not on hardware implementation. The difference in this study is that the simulation study was tested on hardware. The performance obtained from the GWO-PI method was simulated on FPGA via the model's Systems Generator program with increased values. The results of the simulation were co-simulated with the BASYS3 FPGA training card. Improved GWO-PI results show that the BLDC motor can be used in industry at increasing speeds.

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