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Optimizing the Performance of DC Electric Smart Gate Motor using Ziegler Nichols Tuning Methods

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ABSTRACT

One of the primary functions of the DC motor is exemplified in its utilization for the automated operation of irrigation gates, which involves a variety of DC motor models. The DC motor chosen was influenced by the particular operational requirements of the irrigation gate. The ability to support the massive weight of the gate as well as the extreme pressure produced by river water currents are among these requirements. The gate motor utilized functions at a sluggish pace of 20 revolutions per minute. The approach employed involves tuning utilizing the Ziegler-Nichols (ZN) method. The (Proportional-Integral-Derivative) PID controller is designed to precisely manage a DC motor's position, improving the motor's overall performance. The parameters were designed to be Kp = 17, Ti = 1, and Td = 0.1. The Simulation derived from the analysis of MATLAB step response data are side by side with algorithm utilized to certain the dynamic response of the closed-loop configuration. Essential Specifications such as rise time and settling time, both measured in seconds, will be integrated into the simulation outcomes. The utilization of the (ZN) based algorithm for adjusting the gain constants of the PID control system tends to yield superior outcomes in comparison to that under a unity feedback control system .The rising time was 12.6, but when performance improved, it dropped to 0.713. This improvement is also applicable to the settling time, which decreased from 22.4 to 1.13. The holistic evaluation demonstrates that the (ZN) method yields superior performance in contrast to a system employing unity feedback control.

Keywords: Irrigation gates, DC motor, Proportional-Integral-Derivative (PID), Ziegler-Nichols (ZN) algorithm.

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1. INTRODUCTION

Modern manufacturing systems consist of automated machinery designed to carry out necessary operations. Electric motors are commonly utilized as energy converters in contemporary machine tools and robots **(Jasim et al., 2022; Aribowo et al., 2023)**. After Faraday's law was discovered in 1831, the history of the development of electric machine construction began and continued until the middle of the eighth decade of the previous century. DC motors are devices that rotate by converting electrical energy into mechanical energy **(Hammoodi et al., 2020)**. The accuracy of controlling the angular position of a DC geared motor through the utilization of a PID controller. The primary objective of a motor position controller is to receive a signal that denotes the desired angle and subsequently actuate a motor to reach that specific position **(Maung et al., 2018)**. The limitations of classical controllers lie in their lack of adaptability to parametric variations **(Pillai et al., 2017)**.
Controlled systems often exhibit characteristics like nonlinearity, time-variability, and time delay, all of which contribute to the increased complexity of controller parameter tuning **(Adhikari et al., 2012; Zhang et al., 2023)**. The proportional gain of the controller (KP) aims to diminish the rise time without impacting the steady-state error. The integral gain (Ki) contributes to the reduction of the steady-state error upon increase. An increase in the derivative gain (Kd) affects the stability of the system, yet it mitigates the overshoot **(Maung et al., 2018; Al-khazarji et al., 2020; Abdulwahhab and Abbas, 2020; Rahayu et al., 2022)**. DC Motors have the potential to be utilized in a multitude of applications, across a wide range of sizes and operating speeds. One such practical implementation is in the context of Wheeled Mobile Robots, defense, industries , the sectors of automotive, Aerospace, Consumer, Medical, Industrial automation equipment, and Instrumentation encompass a wide range of industries , electric vehicles, drones **(Aung, 2007; Tibor et al., 2011; Maximo et al., 2017; Al Mashhadany et al., 2022 Ariyansyah et al., 2023; Yıldırım et al., 2024)**. The Simulation Model of DC servo motors (DCSM) is characterized by high specifications, including high torque and low inertia torque, making them suitable for applications in computers and drives **(Abdullah et al., 2023)**. In the realm of DC Motor Modeling, an examination can be conducted through the employment of control methodologies such as Step response, Impulse response, and Bode plot within the framework of MATLAB Simulink **(Aung, 2007; Hummadi, 2012; Al-Araji, 2014)**. Simulink stands out as a viable simulation tool within the MATLAB environment for the purpose of creating electronic controller systems and assessing their performance **(Megalingam, 2019)**. There exist four primary approaches to adaptive control: Gain scheduling, Model Reference Adaptive Controller, Dual control, and Self-Tuning regulators. The present study focuses on the design of a Fuzzy-based Model Reference Adaptive Controller, which exhibits a high level of intelligence and superior disturbance rejection capabilities compared to alternative controller types **(Saud and Mohammed, 2017; Abdullah et al., 2022; Ali and Ali, 2022; Mary et al., 2024)**. PWM, known as pulse width modulation, is a methodology enabling the manipulation of the mean voltage supplied to an electronic apparatus through rapid switching of power. The mean voltage is contingent upon the duty cycle, which represents the duration the signal is activated compared to the duration it is deactivated within a designated time frame **(Maung et al., 2018; Ariyansyah and Ma'arif, 2023)**.
The challenge associated with utilizing the controller pertains to parameter tuning, as the adjustment parameters continue to rely on the trial and error approach for identifying the PID parameter constants, specifically Proportional Gain (KP), Integral Gain (KI), and

Derivative Gain (KD). In this scenario, the genetic algorithm technique is implemented, which has the potential to yield superior outcomes with each successive iteration **(Suseno and Ma'arif, 2021; Ortatepe, 2023; Yıldırımet et al., 2024)**. One approach to adjusting PID parameters for a DC motor involves the utilization of a specific method known as Particle Swarm Optimization (PSO). The process of optimizing parameters through the application of the PSO method demonstrates consistent outcomes in comparison to alternative techniques **(Abdul-Jaleel, 2016; Rahayu et al., 2022; Rasheed et al., 2023)**. The optimized PID coefficients are determined for the DC motor model through the utilization of the firefly algorithm (FA), with the objective of aligning the actual angle with the desired value while avoiding overshooting and oscillations **(Jallad and Badran, 2024)**. A novel approach is proposed for the adjustment of PID parameters in order to enhance the tracking performance of DC motors. Furthermore, it offers an optimal level of stability by developing a hybrid PID-CSA predictive model for parameter tuning of the PID controller in DC motors utilizing the Crow search algorithm **(Alkrwy et al., 2021)**. Finally ,To regulate the angular orientation of the rotor in a direct current motor, the Ziegler and Nichols second technique (Z-N 2nd method) is utilized for the adjustment of the parameters of the proportional-integral-derivative (PID) controller **(Adhikari et al., 2012)**.

This paper examines the operation of an automatic irrigation gate utilizing a direct current motor, where the gate motor's movement speed is identified as slow, operating at 20 revolutions per minute . Consequently, enhancing the motor's performance was deemed essential through the implementation of a significant methodology. By using Ziegler and Nichols tuning methods . The selection of this particular DC motor was based on the specific operational requirements of the irrigation gate. These requirements include the ability to endure the extreme pressure exerted by river water currents and support the substantial weight of the gate, which can reach up to 100 kilograms. The following Sections show the angular position reaction of the DC Motor's rotor using a unity feedback control system. In addition, represent the design and Performance of Ziegler Nichols method to tune PID for bison DC motor.

2. MATHEMATICAL MODEL OF DC MOTOR

A conventional direct current motor comprises a fixed array of magnets located in the stator, alongside an armature featuring one or more windings of insulated wire wound around a pliable iron core that focuses the magnetic field. Typically, these windings consist of numerous loops encircling the core, with larger motors potentially containing multiple concurrent pathways for electrical current **(Kadpan et al., 2024; Mhawesh, 2021; Santana et al., 2021; Onawola et al., 2017)**.

The essential parameters of the Bison DC motor as shown in **Fig. 1** and **Table 1**, are obtained by equations below **(Onawola et al., 2017; Mhawesh, 2021; Santana et al., 2021)**:

$$Kt = \frac{Tm}{Ia} \tag{1}$$

$$Tm = \frac{E \times Ia}{2pi \times n} \tag{2}$$

Where n is revolution per second, the variable was isolated and subsequently inserted into Equation 3 in order to isolate the Armature current.

$$Tm = E \times Ia - R \times Ia^2 \tag{3}$$

Where R is the normal resistance, Substitute derived from Eq. 3 to find the Armature resistance Ra.

$$Ra = \frac{(V - E)}{Ia} \quad (4)$$

$$E = V - R \times Ia \quad (5)$$

Where E is the Electromotive force

$$Kb = \frac{V}{W} \quad (6)$$

Where W=n=revolution per second

$$J = \frac{1}{8}(m \times D^2) \quad (7)$$

Where D = 0.01905 meter is shaft diameter and m is motor mass

$$B = \frac{[V - (Kb \times n)]}{[(R \times Kt) \div n} \quad (8)$$

Lastly, obtained and inserted all these parameters in Eq. 8 to give Viscous-Friction Coefficient *B*.

Table 1. Parameters of DC Bison Motor.

Parameters	Values	Units
Tm : Motor torque	16.947	(N.m)
Kt : Torque constant	4.505	(N.m/A)
Kb: Back-emf constant	5.729	(v/rad/s)
J: Moment of inertia of rotor	6.24×10^{-6}	(Kg.㎡)
B: Viscous-Friction Coefficient	4.97×10^{-6}	(N.m.s/rad)
La: Armature inductance	4×10^{-6}	(H)
Ra: Armature resistance	1.25	Ohm

Figure 1. Bison DC motor type.

The transfer function Tr of DC motor position with respect to the input voltage can be written as follows **(Mhawesh, 2021)**.

$$Tr = \frac{\theta}{V} = \frac{Kt}{La\, J\, S^3 + (RaJ + B\, La)S^2 + (Ra\, B + Kt\, Kb)S} \quad (9)$$

The block diagram for the DC motor model is shown in **Fig. 2**:

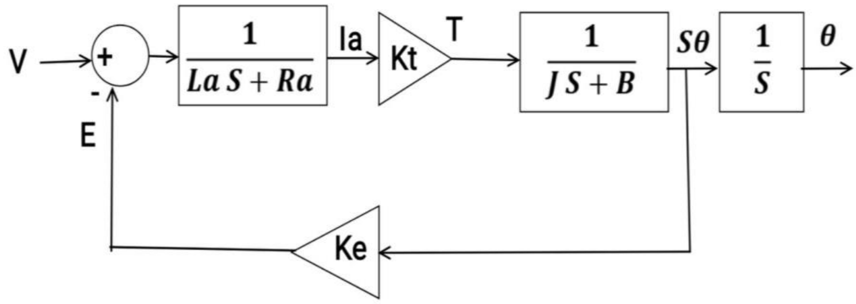

Figure 2. Block diagram of the DC motor model **(Mhawesh, 2021)**.

3. OPEN LOOP AND CLOSE LOOP PERFORMANCE

The design and calibration of a PID controller may seem conceptually straightforward; however, it can prove to be challenging in practical applications when attempting to satisfy multiple, often contradictory objectives such as minimizing transient response while maximizing stability. PID controllers typically yield adequate control performance when utilizing default tuning parameters, yet they can be enhanced through meticulous calibration, and their effectiveness may be deemed unsatisfactory when tuning is suboptimal. Typically, initial design iterations necessitate repeated modifications via computer simulations until the closed-loop system achieves the desired performance or an acceptable compromise is reached **(Abdullah et al., 2023)**.

3.1 Open Loop Response

The transfer function can be expressed in MATLAB by defining the numerator (num) and denominator (den) matrices as shown in **Fig. 3**.
num = kt, den = $La\,J\,S^3 + (Ra\,J + B\,La)S^2 + (Ra\,B + Kt\,Kb)S$ .The parameters of the motor were determined based on its step response around a steady-state working point, which is input voltage V= 12 volts.

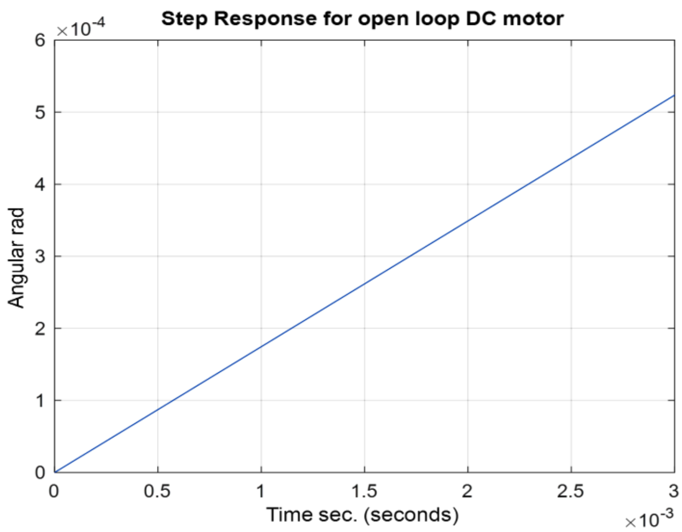

Figure 3. Open Loop Response of Bison DC motor.

3.2 Close Loop Response

A unity feedback control system is employed with the DC motor to analyze its response. The input signal utilized is a unit step function. Through the utilization of a Matlab program, one can acquire the time domain specifications of the transient response along with the response figure. The Response of the system is depicted in **Fig. 4**. The system has been simulated to analyze the unit step response for different parameter models of the Bison DC motor, as illustrated in **Table 1**. The Transfer function can be expressed through the subsequent equation.

$$Tr=\frac{\theta}{V}=\frac{4.505}{(2.496\times10^{-11})S^3+(7.8\times10^{-6})S^2+(25.81)S} \quad (10)$$

The results and performance analysis for the Bison DC motor are presented in **Table 2** using unity feedback control .

Table 2. Close Loop performance of Bison DC motor.

Time Domain Specifications	Values
Rise time (seconds)	12.6 s
Settling time (seconds)	22.4 s
Overshoot (%)	0%
Peak (Amplitude unit)	1s
Peak time (seconds)	>60s

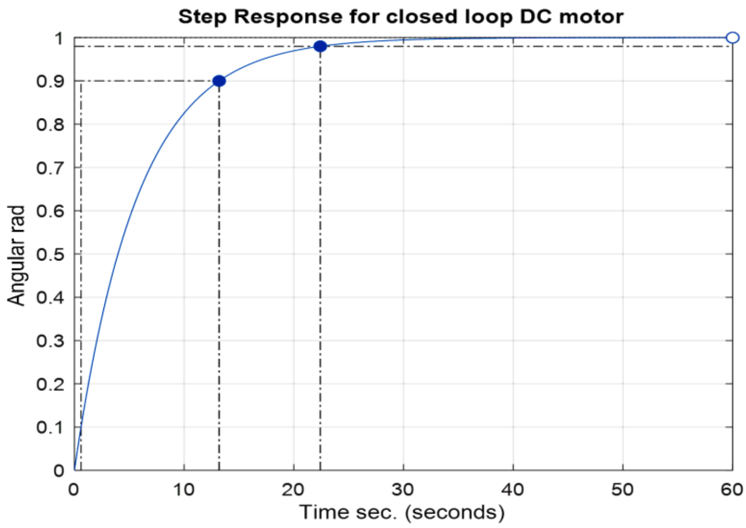

Figure 4. Close Loop Response of Bison DC motor.

4. DESIRED OPERATIONAL REQUIREMENTS OF IRRIGATION GATE

The irrigation gate's specific operating requirements had an impact on the DC motor selection. Among these requirements are the capacity to withstand the enormous weight of the gate and the intense pressure generated by the currents of river water. In addition to some requirements related to the motor's performance, as shown in **Table 3**. Obviously, the operating parameters of the smart gate motor do not match the performance specifications of the motor in the unity feedback control system especially, the rise time and settling time . The significance of the matter pertaining to the reduction of rise time and settling time while concurrently enhancing the accuracy of the smart gate motor's functionality lies in the fact that the gate is integrated with a solar energy system, rendering the aspect of power consumption particularly critical to the operational efficacy of this gate. Furthermore, the enhancement of the continuous electric motor's performance, as delineated by the input voltage (V) specified in Eqns. 9, 10, and 14, will substantially contribute to the preservation of the solar energy system's integrity and mitigate operational expenditures over the long term. The discipline of process control encompasses the endeavor to identify the most favorable compromise among cost, rise time, and overshoot. Thus, the Ziegler-Nichols algorithm was applied, which is considered one of the most important techniques to improve the motor performance of a DC motor, and the design of the controller will depend on these factors.

Table 3. Maximum values for Operational Requirements of irrigation Gate.

Time Domain Specifications	Values
Rise time (seconds)	1 s
Settling time (seconds)	2 s
Overshoot (%)	5%
Peak time (seconds)	>2s

The methodological framework employed in this work is delineated as follows and is illustrated in **Fig. 5.**

- The mathematical model of the direct current motor employed in this study was utilized to control the intelligent irrigation gate.
- The parameters of the mathematical model were delineated and computed through the respective equations corresponding to each parameter, grounded in the specifications pertaining to the type of motor utilized as delineated in the datasheet. All parameters were computed and subsequently integrated into the MATLAB code pertinent to this study.
- The mathematical model was executed within the MATLAB environment to facilitate the analysis of the motor's functionality, and the operational parameters of the engine under both closed-loop and open-loop conditions were thoroughly examined.
- The Proportional-Integral-Derivative (PID) controller has been meticulously engineered utilizing the Ziegler-Nichols tuning technique to meet the desired operational requirements for the irrigation gate as described in the following section.
- Verifying the overall response readings of the DC motor that were analyzed using the step response represented by the rise time and the settling time, which is the goal of this work to reach the lowest value for these specifications.
- Here two possibilities will occur:
- either the desired values of the operational requirements will be reached and the work will end.
- The results of the step response analysis will not be close to the operational requirements and therefore the controller will be redesigned until it reaches the required specification values.

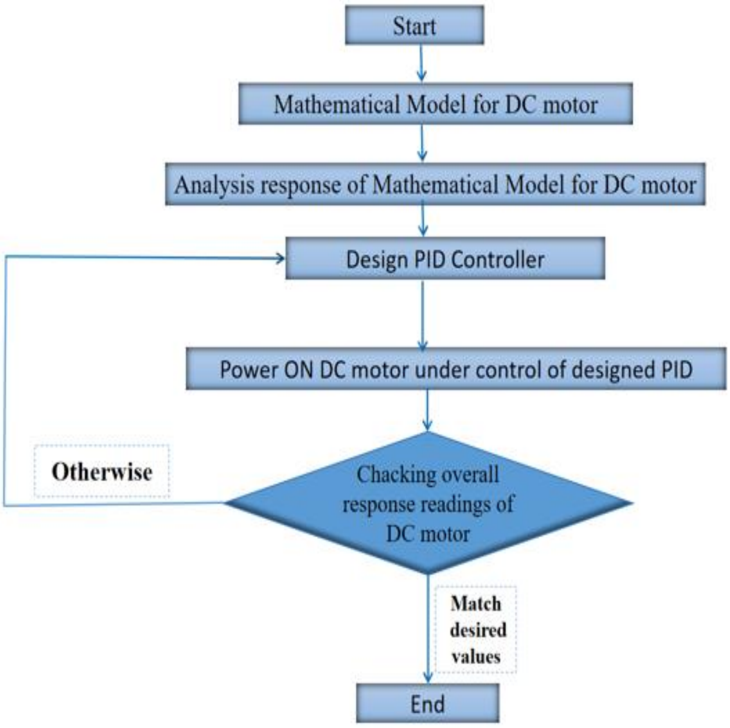

Figure 5. Methodology flow chart

5. ZIEGLER-NICHOLS ALGORITHM

Ziegler and Nichols introduced the most optimal tuning approach for the PID controller, a method that has become widely acknowledged as the standard technique in the field of control systems. Both methodologies involve making initial assumptions about the system model, yet they do not necessitate precise knowledge of these models. The Ziegler-Nichols formulae, utilized for determining the parameters of the controllers, rely on the analysis of plant step responses **(Joseph et al., 2022).** As explained in **Table 4**, it was the first technique to express the PID controller parameters using two sets of rules depending on critical gain Kcr and critical period Pcr.

Table 4. Turning rules of Ziegler-Nichols method **(Adhikari et al., 2012).**

Type of Controller	Kp	Ti	Td
P	0.5Kcr	Infinity	0
PI	0.45Kcr	1/1.2 Pcr	0
PID	0.6Kcr	0.5Pcr	0.125Pcr

Kp, Ti, and Td can be obtained from Ziegler-Nichols second method table, **Table 4**.

$$Kp = 0.6 \times Kcr = 17 \quad (11)$$

$$Ti = 0.5 \times Pcr = lsec \quad (12)$$

$$Kp = 0.125 \times Pcr = 0.l \quad (13)$$

Every design criterion will be met. A step response is obtained by running the Matlab program with the controller parameters adjusted, as seen in **Fig. 6**, and the performance analysis for the Bison DC motor is presented in **Table 5** using Ziegler Nichols Second Method.

Table 5. Ziegler Nichols Second Method performance of Bison DC motor.

Time Domain Specifications	Values
Rise time (seconds)	0.713 s
Settling time (seconds)	1.13 s
Overshoot (%)	1.75%
Peak (Amplitude unit)	1.02 s
Peak time (seconds)	>2s

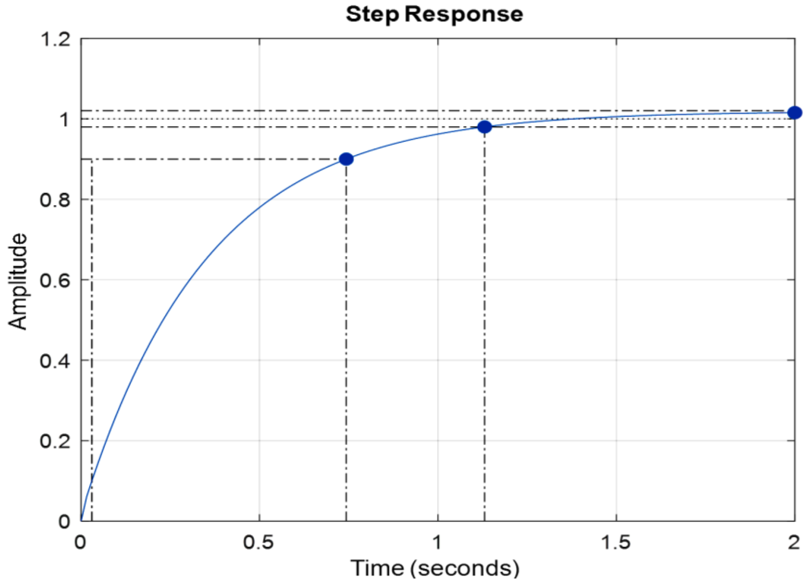

Figure 6. Ziegler-Nichols Response of Bison DC motor

The Transfer function can be expressed through the subsequent equation.

$$Tr = \frac{\theta}{V} = \frac{4.605}{(2496\times10^{-11})S^4 + (7.8\times10^{-6})S^3 + (26.26)S^2 + 76.58\, S} \quad (14)$$

6. ANALYSIS OF RESULTS

The investigation involves comparing the angular position of the DC motor used to operate the smart irrigation gate shown in **Fig. 7** under unity feedback compared to that under conventional PID controller (Ziegler Nichols Second Method), as documented in **Table 6 and Fig. 8** . Different colors are utilized to represent each case of the DC motor response curves. Specifically, the color red depicts the response under the unity feedback control system, while the color blue signifies the response under the conventional PID controller. The presence of a unity feedback control system often results in prolonged settling time and extended rise time within the controlled system. Consequently, the integration of Soft computing techniques into the control loop has been proposed. Ziegler Nichols Second Method (ZN) based tuning approaches have demonstrated remarkable effectiveness in enhancing the steady state properties and performance metrics of the system. The results show that the performance of the DC motor has been optimized .

Figure 7. Automatic irrigation gate.

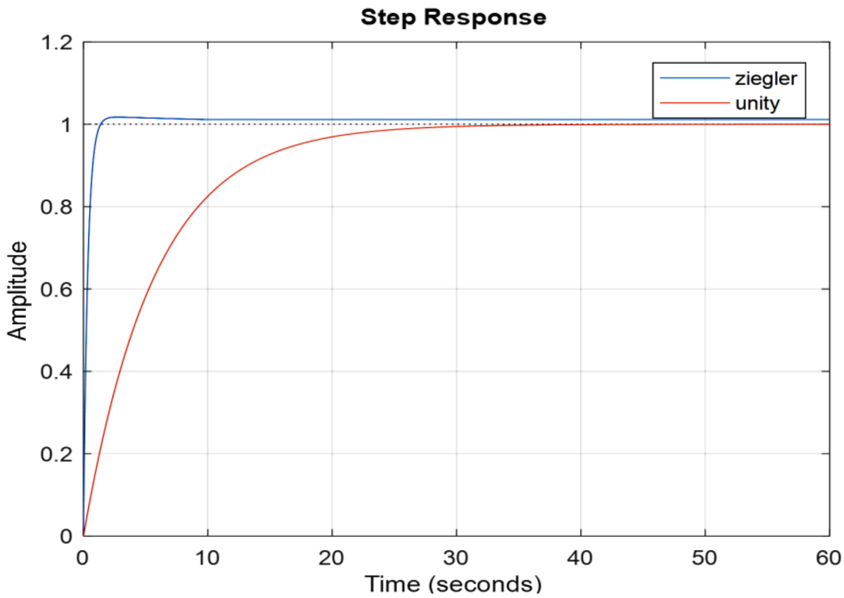

Figure 8. Comparing unity feedback and Ziegler-Nichols Response of Bison DC motor.

Table 6. Bison DC motor performance for two cases.

Time Domain Specifications	Unity feedback control system	Ziegler-Nichols Controller
Rise time (seconds)	12.6 s	0.713 s
Settling time (seconds)	22.4 s	1.13 s
Overshoot (%)	0%	1.75%
Peak (Amplitude unit)	1 s	1.02 s
Peak time (seconds)	>60s	>2s

7. CONCLUSIONS

In this paper, a Proportional-Integral-Derivative (PID) controller is formulated through the utilization of a conventional Ziegler-Nichols tuning technique and unity feedback control system. The efficacy of both approaches is verified through the implementation of MATLAB programming and simulation procedures. Based on the readings and curves from Matlab, a performance comparison for the two cases was conducted. Based on the comparison, the optimal controller was identified. It is best to use a controller that has good specifications. The computer simulation's findings show that the Ziegler-Nichols tuned PID controller performs more effectively than the unity feedback control system. It is closest to the maximum valuesof the irrigation gate's operational requirements and provides the possibility of operating the gate with the best performance. The optimal controller that shows acceptable performances for the goals (minimum rise time and minimum settling time) is the Ziegler-Nichols.

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Credit Authorship Contribution Statement

Wpreen Rashed Kadpan: Writing – review & editing, Writing – original draft, Validation, Software, Methodology. Faiz F. Mustafa: review & editing, Software. Hussein Tbena Kadhim: review & editing, Software. Egorov Igor Nikolaevich: review & editing, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تحسين أداء محرك التيار المستمر للبوابة الكهربائية الذكية بأستخدام طريقة ضبط زيغلر– نيكولز

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الخلاصة

تتجلى إحدى الوظائف الأساسية لمحرك التيار المستمر في استخدامه للتشغيل الآلي لبوابات الري، والتي تتضمن مجموعة متنوعة من نماذج محركات التيار المستمر. وقد تأثر أختيار محرك التيار المستمر بالمتطلبات التشغيلية الخاصة لبوابة الري. ومن بين هذه المتطلبات القدرة على تحمل وزن البوابة العالي بالإضافة إلى الضغط الشديد الناتج عن تيارات مياه النهر. يعمل محرك البوابة المستخدم بمعدل 20 دورة بطيئة في الدقيقة. النهج المستخدم هو ضبط التحكم بأستخدام طريقة زيغلر–نيكولز(ZN). تم تصميم وحدة التحكم (المشتقة المتناسبة والتكاملية) PID لإدارة موضع محرك التيار المستمر بدقة، مما يحسن الأداء العام للمحرك وقد تم تصميم المتغيرات لتكون Kp=17 و Ti=1و Td=0.1 . المحاكاة مستمدة من تحليل البيانات في برنامج MATLAB جنبًا إلى جنب مع الخوارزمية المستخدمة للتأكد من الاستجابة الديناميكية لتكوين الحلقة المغلقة. سيتم دمج المواصفات الأساسية مثل وقت الصعود ووقت الاستقرار، وكلاهما يقاس بالثواني، في نتائج المحاكاة. إن استخدام الخوارزمية القائمة على (ZN) لضبط ثوابت نظام التحكم PID يميل إلى تحقيق نتائج متفوقة مقارنة بنظام التحكم في وحدة التغذية المرتدة . كان وقت الارتفاع 12.6ولكن عندما تحسن الأداء، انخفض إلى 0.713 وينطبق هذا التحسن أيضًا على وقت التسوية، الذي انخفض من 22.4 إلى 1.13 . يوضح التقييم الشامل أن طريقة(ZN) تعطي أداءً فائقًا على عكس النظام الذي يستخدم التحكم في وحدة التغذية المرتدة.

الكلمات المفتاحية: بوابات الري، محرك التيار المستمر، المشتقة المتناسبة والتكاملية، طريقة زيغلر–نيكولز.