Tuning PID Control using GEO Algorithm for Dual Axis Sun Tracker System

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Abstrak

Energi surya menggunakan energi matahari untuk menghasilkan listrik menggunakan photovoltaic (PV) sebagai media untuk menangkap energi surya. Panel PV populer digunakan karena efektivitasnya, keterjangkauan dan skalabilitasnya. Permasalahan umum pada penangkapan energi surya adalah letak geografis suatu wilayah, cuaca dan pergeseran arah datangnya sinar matahari sehingga suatu sistem penjajak matahari perlu dilakukan suatu kendali sistem. Di negara yang memiliki sinar matahari yang cukup, panel surya akan didesain agar memiliki kendali atau sistem kontrol yang mengikuti arah pergerakan matahari. Metode kontrol yang digunakan umumnya adalah Proportional-Integral-Derivative (PID) control menggunakan auto-tuning. Untuk meningkatkan performa dari PID maka perlu dilakukan optimalisasi pada tuning PID. Pada penelitian ini, algoritma GEO akan digunakan untuk mengoptimasi kendali PID pada sistem pelacak matahari dua sumbu yang disimulasi menggunakan simulink MATLAB. GEO adalah salah satu metode optimalisasi berbasis metaheuristic. GEO bekerja dengan cara menyesuaikan pada kecenderungan menyerang atau meluncur pergi saat mencari mangsa dan berburu. Pada penelitian ini menggunakan perbandingan tiga desain model yaitu s istem tanpa kontrol, sistem dengan kontrol PID menggunakan auto-tuning, dan sistem dengan kontrol PID menggunakan tuning GEO (PID-GEO). Hasil dari simulasi menunjukkan bahwa performa dari ketiga desain model yang terbaik adalah PID-GEO model. PID-GEO memiliki settling time tercepat, overshoot dan undershoot terkecil baik untuk sumbu horizontal maupun sumbu vertikal. Dimana overshoot sumbu horizontal sebesar 11.372% dan undershoot sebesar 0%. Sedangkan untuk sumbu vertikal, overshoot sebesar 11.559% dan undershoot sebesar 0%. Sehingga dapat disimpulkan bahwa PID-GEO memiliki performa terbaik dibanding dengan tiga desain model yang lain dan algoritma GEO dapat mengoptimalisasi kendali PID.

Kata Kunci: Sistem Pelacak Matahari, PID, PID-GEO

Abstract

Solar energy utilizes sunlight to produce electricity via photovoltaic (PV) panels, which act as a medium for capturing solar energy. PV panels are widely used for efficiency, cost-effectiveness, and scalability. Common challenges in solar energy capture include geographical location, weather conditions, and fluctuations in the direction of incoming sunlight. So, a control system is important. In countries with adequate sunlight, photovoltaic (PV) panels are designed with control systems that track the movement of the sunlight. Given the continuous motion and changing position of the sun, the development of advanced dual-axis solar *trackers* with intelligent control systems remains an ongoing area of research. Control methods used by sun tracker system is Proportional-Integral-Derivative (PID) with auto-tuning. For increase performance PID control is important to optimize PID at sun tracker sytem dual axis, simulated by MATLAB Simulink. GEO algorithm is optimization method using metaheuristic. GEO is founded on the intelligent adjustments on attack propensity and cruise propensity that golden eagles perform while searching for prey and hunting. In this study, the GEO algorithm will be used to optimize PID with a dual-axis solar tracker simulated by MATLAB Simulink. This research compares three model designs: uncontrolled, PID control using auto-tuning, and PID using GEO tuning (PID-GEO). The result of the simulation, we get comparison performance from three model designs is PID-GEO has the fastest settling time, smallest overshoot and undershoot of all model designs. Where the overshoot horizontal axis is 11. 372% and the undershoot is 0%, that also at the vertical axis, the overshoot is 11. 559% and undershoot is 0%. It can be concluded that PID-GEO has the best performance compared to PID auto-tuning and uncontrolled. So, this research concludes that GEO can be used to optimize PID control.

Keywords: Sun Tracker *System*, PID, PID-GEO

1. Introduction

Electrical energy is a fundamental requirement of modern society. According to data the Ministry of Energy and Mineral Resources (ESDM) in 2024, the electricity consumtion in Indonesia reached 1048 kWh per capita and this increase will occur at every year (ESDM, 2024). Electricity consumtion used in all sectors, such as places of worship, residential areas, and industries, including factories and large-scale households. The inscrease of electricity consumtion is in a line increase electrical energy. In the course of its evolution, the modern era is characterized by a shift toward clean energy, specifically electrical energy derived from renewable sources. Since 2008, Indonesia has had potential in the field renewable energy (EBT). This is shown by Perpres No. 5 Tahun 2006 concerning energy policy states that the contribution of primary energy in 2025 is 17 % with composition of 5% vegetative fuel, 5% geothermal, 5% biomass, nuclear, water, solar, wind and 2% liquefied coal.

One of renewable energy resources is solar or sunlight. Solar energy utilizes sunlight to produce electricity through photovoltaic (PV) panels, which act as a medium for capturing solar energy. According data of ESDM, potential solar energy in Indonesia reached 112.000 GWp. So, this phenomena support development at photovoltaic system. PV panels are widely used for efficiency, cost-effectiveness, and scalability. However, several factors impact the effectiveness of solar energy capture, including geographical location, weather conditions, and variations in the sun's trajectory.

Geographical location has different characteristics, if PV placed at highland and cities with tall building will impact PV to solar capture, so placement of PV panels must be considered. Geographical location also impacts seasonal variations in insencity and duration sunlight. For example, areas near the north pole have more frequent winter. That is influence number of hours of sunlight. Then variation sunlight trajectory factor, every location on earth has inclination to the sun throughout the year. It is impact for solar capture by PV panels. For example, areas near equator have sun position will perpendicular year-around. It is PV can more solar capture. Because some of this factors, optimazition PV panels is important. In countries with adequate sunlight, photovoltaic (PV) panels are designed with control systems that track the movement of the sunlight (Buana et al., 2024).

Control method used by sun tracker system is Proportional-Integral-Derivative (PID) control. This purpose of this sun tracking sytem is to place cross sections so that it is always in a position facing the sun, so that if solar cell panels are placed on top, electrical energy is produced by the cell panels the sun is at its maximum. For increase performance of sun tracker system use optimation at tuning PID. Generally, PID use auto tuning for running the control system. In this paper, PID will use Golden Eagle Optimization (GEO) algorithm. GEO algorithm is optimization method using metaheuristic. GEO is founded on the intelligent adjustments on attack propensity and cruise propensity that golden eagles perform while searching for prey and hunting (Mohammadi-Balani, 2021). In this study, GEO algorithm as tuning at PID control for optimize sun tracker system with a dual-axis solar tracker simulated by MATLAB Simulink.

2. Research Methods

2.1 GEO (Golden Eagle Optimizer)

The Golden Eagle Optimizer (GEO) is a bio-inspired, swarm intelligence-based metaheuristic algorithm developed for solving global optimization challenges. The GEO is primarily inspired by the hunting behavior of golden eagles, particularly their ability to adjust their speed at different phases of a spiral trajectory during prey capture. In the initial stages of hunting, golden eagles tend to explore and search for prey, while in the later stages, they focus on attacking. The eagle's ability to dynamically modify both the speed and trajectory to optimize prey capture is mathematically modeled in GEO, emphasizing the balance between exploration and exploitation in global optimization tasks (Mohammadi-Balani et al., 2021). In this context, GEO is applied to tune a Proportional-integral-derived (PID) controller, resulting in a PID-GEO approach. A robust PID-GEO controller is developed with the Integral Time Absolute Error (ITAE) as the objective function, aimed at enhancing the stability of power systems.

2.2 Transfer Function

In control theory, transfer functions are extensively utilized to represent the relationship between a system's input and output variables, particularly for systems governed by time-invariant linear differential equations. It is defined as the quotient of the Laplace transform of the system's output (also known as the response function) and the Laplace transform of the input, assuming zero initial conditions (Putri & Muhafzan, 2019).

2.3 PID Controller

A PID controller is composed of three primary components: proportional control, derivative control, and integral control. k_p represents the proportional control, is effective in minimizing the error, and improving response time. Integral control, denoted as k_i, is employed to eliminate steady-state errors. Derivative control, denoted as k_d, is used to reduce overshoot and decrease the settling time of the system (Wibawa et al., 2019). An ideal PID controller is described by the control law shown in equation 1.

$$c(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{d}{dt} e(t) \qquad (1)$$

$C(t)$ is the controlling signal, k_p is the proportional gain, $e(t)$ represents the error signal as a function of time, k_i represents the integral gain (k_p/τi) and k_d represents the derivative gain (k_p*τd). Tuning a PID controller involves adjusting these proportional, integral, and derivative constants to achieve optimal control for a specific process. Fine-tuning the controller gains to meet performance criteria such as stability margin, transient response, and bandwidth enhances the robustness of the system. The performance of a tuned controller is typically assessed through error-based quantitative analysis. Commonly used performance metrics include Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Integral Squared Error (ISE), and Integral Time Squared Error (ITSE) (Girirajkumar, S. M., Hemavathy, G., Madhubala, V., Gayathri, 2022). For PID controller tuning, methods based on minimizing error integrals are commonly employed. The closed-loop system's dynamic performance can be analyzed using the shape of the complete response, from the initial time $t = 0$ to when the system reaches a steady state. Among the most frequently applied criteria are the Integral of Time-Weighted Absolute Error (ITAE), Integral of Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time-Weighted Squared Error (ITSE), or the Mean Squared Error (MSE). The research, ITAE, is used as the basis for PID tuning. The basic formula of ITAE is shown in equation 2 (Gül & Tan, 2017).

$$ITAE = \int_0^\infty t.|e(t)|\ dt \qquad (2)$$

2.4 DC Motor Model

Motors play an important role in everyday life. Motors are used both on a household scale and in the industrial world. To manage these motors, a good control system is required. Direct current motors are widely used in the industrial field in various applications (Arifin & Budisusila, 2020). A direct current (DC) motor is a commonly employed actuator in control systems, providing rotary motion that can be transformed into linear motion when paired with components such as wheels, drums, or cables. In order to simulate the system's behavior, it is essential to develop an appropriate model. Thus, a model based on the motor's specifications must be derived. Figure 1 illustrates the DC motor circuit, taking into account factors such as torque and rotor angle.

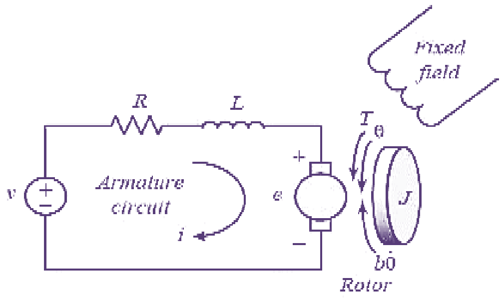

Figure 1. Schematic diagram of a DC motor

The motor torque T is directly proportional to the armature current i, with the relationship governed by the torque constant k, as described by equation 3.

$$T = ki \quad (3)$$

The resulting voltage, e_a, relative angular angle, which is shown in equation 4.

$$e_a = K\omega_m = k\frac{d\theta}{dt} \quad (4)$$

Based on Figure 1, the following equations can be derived by applying Newton's law in conjunction with Kirchhoff's law, as presented in equation 5 and equation 6 (Sao et al., 2015).

$$J\frac{d^2\theta}{d^2t} + b\frac{d\theta}{dt} = Ki \quad (5)$$

$$L\frac{di}{dt} + Ri = V - K\frac{d\theta}{dt} \quad (6)$$

By applying the Laplace transform, equations 5 and 6 can be expressed as equations 7 and 8.

$$Js^2\theta(s) + b\theta(s) = KI(s) \quad (7)$$

$$Ls.I(s) + RI(s) = V(s) - K.s.\theta(s) \quad (8)$$

Where s denotes the Laplace operator. From equation 8, $I(s)$ can be derived, as represented in Equation 9 (Adhim & Musyafa, 2016).

$$I(s) = \frac{V(s) - Ks\theta(s)}{R + Ls} \quad (9)$$

Substitute equation 9 into equation 7 to get equation 10.

$$Js^2\theta(s) + b\theta(s) = \frac{K(V(s) - Ks\theta(s)}{R + Ls} \quad (10)$$

The transfer function relating to the input voltage $V(s)$ to the output angle θ is presented in equation 11 (Sao et al., 2015).

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{K}{[s\{(R+sL)(Js+b)+K^2\}]} \quad (11)$$

2.5 Axis Torsion Moment of Inertia

The torque generated by the photovoltaic load is determined by the product of the moment of inertia of the photovoltaic panel and its angular acceleration. The moment of inertia for a photovoltaic panel with a horizontal rotating axis can be expressed in Equations 12 and 13. Similarly, for a vertical rotating axis, the corresponding formulation is provided in Equations 14 and 15.

$$J_1 = \frac{1}{12} m_{pv} L^2 (\frac{N_2}{N_1})^2 \ [kg.m^2] \quad (12)$$

$$J_{T1} = J_{st} + J_1 \ [kg.m^2] \quad (13)$$

$$J_2 = \frac{1}{2} m_{pv} (L^2 + W^2)(\frac{N_2}{N_1})^2 \ [kg.m^2] \quad (14)$$

$$J_{T2} = J_{st} + J_2 \ [kg.m^2] \quad (15)$$

J represents the moment of inertia, L is the length of the photovoltaic (PV) panel, and m_{pv} denotes the mass of the PV panel. J_{st} refers to the moment of inertia of the solar tracker without any load, while W represents the width of the PV panel. (Buana et al., 2024).

2.6 Dual-axis Rotation Transfer Function

The moment of inertia for dual-axis rotation in PV solar tracking has been transformed into a transfer function considering the load. Consequently, Equations 11 are modified to form Equations 16 and 17.

$$\frac{\theta(s)}{v(s)} = \frac{K}{s((JT1s+b)(Ls+R)+K^2)} \quad (16)$$

$$\frac{\theta(s)}{v(s)} = \frac{K}{s((JT2s+b)(Ls+R)+K^2)} \quad (17)$$

J represents the moment of inertia for gear 1 or 2, R denotes the electrical resistance, L is the electrical inductance, and b is the friction viscosity constant of the motor. K refers to the electromotive force constant (back EMF), while V symbolizes the voltage. The variable s is a function of time in Laplace notation format (Ali et al., 2021).

3. Results and Discussion

The transfer function for the dual-axis sun tracker system is presented in Figure 2, while the design of the PID controller with GEO tuning (PID-GEO) is illustrated in Figure 3.

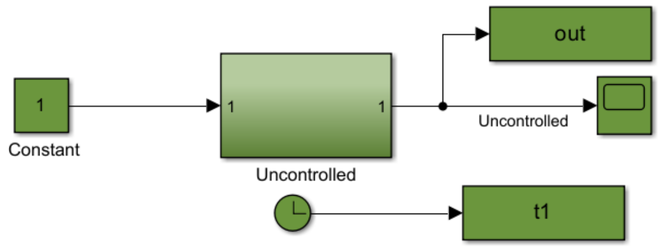

Figure 2. Design transfer function dual axis traker system for simulation

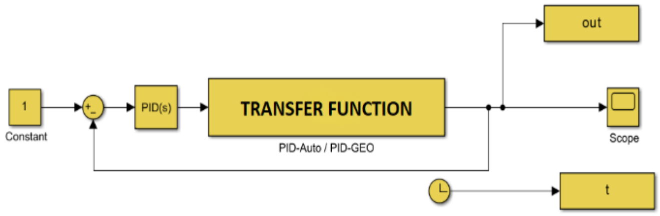

Figure 3. Design PID-GEO control for dual axis simulation

3.1. Data Dual Axis Sun Tracker

The photovoltaic panel serves as the load for the tracking system, positioned to ensure that the panel remains perpendicular to the sun at all times. This study employs a spur gear simulation or gear unit, consisting of two types of spur gears: M1B12 and M1A20, as detailed in Table 1. The photovoltaic model used in this research is the STM 40-50, as described in Table 2. The technical specifications and system parameters utilized in the study are provided in Table 3. Parameter data for the GEO algorithm script code is shown in Table 4.

Table 1. Type of gear

No.	Spurs Gear Models	Number of teeth	Mass (g)
1	Model M1A20	120	1320
2	Model M1B12	12	10

Table 2. Specification M1A20 gear

No.	PV Parameter	Value
1	Dimension (mm)	637X545X35
2	Mass (Kg)	4.5
3	J_1 ($Kg.m^2$)	0.0015216
4	J_{T1}($Kg.m^2$)	0.0015488
5	J_2 ($Kg.m^2$)	0.0158129
6	J_{T2} ($Kg.m^2$)	0.01584
7	L (m)	0.637
8	W (m)	0.545

Table 3. Specification M1B12 gear

No.	Parameter	Value
1	J ($Kg.m^2$)	$3{,}2284x10^{-6}$
2	b (N.m.s)	$3{,}5077\ x10^{-6}$
3	Kb ($Vsec.rad^{-1}$)	0,0274
4	Kt ($Nm.Amp^{-1}$)	0,0274
5	R (Ω)	4
6	L (H)	$2{,}75\ x10^{-6}$

Table 4. Set and design parameters for GEO algorithm

No	Set Parameter GEO Definition	Parameter value of the GEO script code
1	options.PopulationSize	20;
2	options.MaxIterations	20;
3	options.AttackPropensity	0.5+1.5 * rand(options.PopulationSize, 3);
4	options.CruisePropensity	0.5+0.5 * rand(options.PopulationSize, 3);
No	**Design Parameters**	**Design Parameter value of the GEO script code**
1	nvars	3;
2	lb	[0.1, 0.1, 0.1];
3	ub	[50, 50, 50];

3.2. Results of Simulation

This section shows the result of the simulation from the design transfer function with no control (uncontrolled), design PID using auto-tuning, and design PID-GEO for the dual-axis sun tracker system. Because at dual axis sun tracker system there are two axes. These are horizontal and vertical axes. First, we simulate the horizontal axis uncontrolled, and the result is shown in Figure 4. Then, the simulation for the vertical axis uncontrolled can be seen in Figure 5.

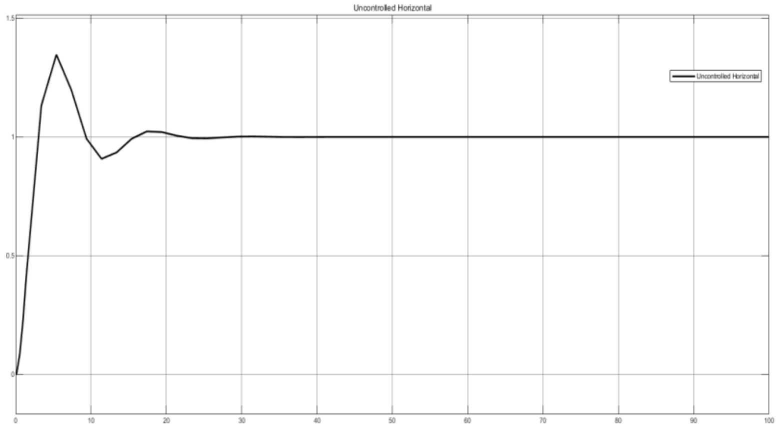

Figure 4. Horizontal axis uncontrolled

From Figure 4 and Figure 5, we get some information about rise time, overshoot, undershoot, and settling time. The information for the horizontal axis and vertical axis is shown in Table 5 and Table 6.

Table 5. Result horizontal axis uncontrolled

Description	**Uncontrolled**
Risetime	2.1688 s
Transient Time	19.4683 s
Settling Time	19.4683 s
Settling Min	0.9077 rad
Settling Max	1.3464 rad
Overshoot	34.6426 %
Undershoot	9.23 %
Peak	1.3464 rad
Peaktime	5.4092 s
Kp	-
Ki	-
Kd	-
N	-

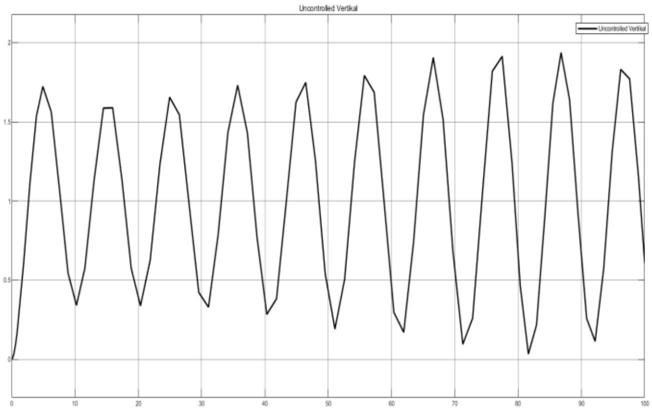

Figure 5. Vertical axis uncontrolled

Table 6. Result vertical axis uncontrolled

Description	**Uncontrolled**
Risetime	1.2822 s
Transient Time	99.9520 s
Settling Time	99.9781 s
Settling Min	0.0335 rad
Settling Max	1.9373 rad
Overshoot	219.6194 %
Undershoot	96.65 %
Peak	1.9373 rad
Peaktime	86.7795 s
Kp	-
Ki	-
Kd	-
N	-

From Table 5 can be see that for horizontal axis uncontrolled overshoot sebesar 34.6426 dan settling time 19.4683 s. Then for vertikal axis uncontrolled show at Table 6 that overshoot is 219.6194 and settling time 99.9781 s.

3.3. PID Auto-Tuning

This section simulation design PID control using auto-tuning for dual axis sun tracker system. Divide to the horizontal axis and vertical axis. The result simulation can be seen in Figure 6 and Table 7 for the horizontal axis and Figure 7 and Table 8 for the vertical axis.

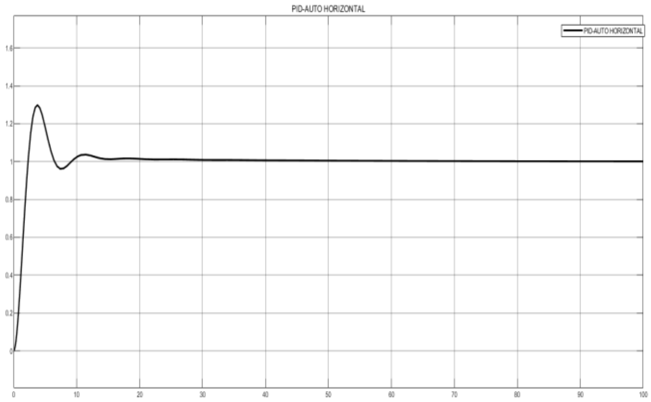

Figure 6. PID auto-tuning for horizontal axis

Table 7. Result PID auto-tuning horizontal axis

Description	**Auto**
Risetime	1.5526 s
Transient Time	13.3302 s
Settling Time	13.3302 s
Settling Min	0.9052 rad
Settling Max	1.2986 rad
Overshoot	29.7206 %
Undershoot	9.48 %
Peak	1.9373 rad
Peaktime	86.7795 s
Kp	0.417132980886252
Ki	0.0106530668689785
Kd	1.95332987302911
N	0.781653683569699

From Table 7 can be seen that is overshoot for the vertical axis is 19.4683 using PID control auto-tuning and then settling time at 13.3302 s.

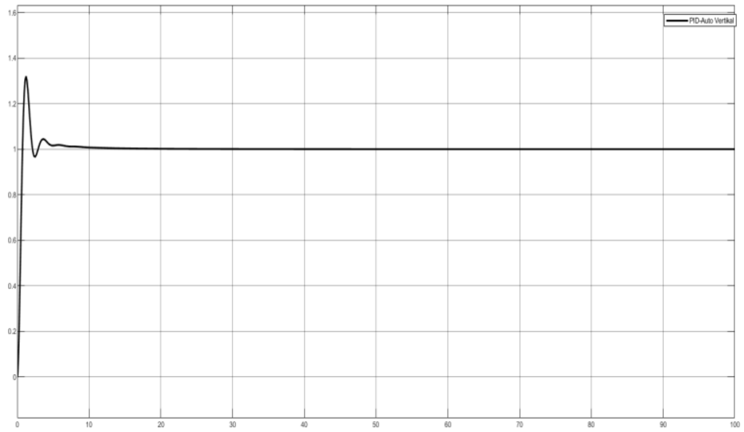

Figure 7. PID auto-tuning for vertical axis

From the Table 8 can be seen is overshoot for vertical axis is 31.9909 using PID control auto-tuning and then settling time at 4.5103 s.

Table 8. Result PID auto-tuning vertical axis

Description	**Auto**
Risetime	0.4941 s
Transient Time	4.5103 s
Settling Time	4.5103 s
Settling Min	0.9657 rad
Settling Max	1.3199 rad
Overshoot	31.9909 %
Undershoot	3.43%
Peak	1.3199 rad
Peaktime	1.2247 s
Kp	2.40936779676302
Ki	0.147833463450262
Kd	6.9195379349691
N	2.42859295278801

3.4. PID-GEO

This section simulation design PID control using tuning GEO for a dual-axis sun tracker system. Divide to the horizontal axis and vertical axis. The result simulation is shown in Figure 8 and Table 9 for the horizontal axis and Figure 9 and Table 10 for the vertical axis. A robust GEO-optimized Proportional-Integral-Derivative (GEO-PID) controller is developed, utilizing the Integral Time Absolute Error (ITAE) as the objective function to improve the stability of the power system. At the simulation, we get the ITAE number. This makes a difference with PID auto-tuning. The convergence of the ITAE number for the dual-axis sun tracker system can be seen in Figure 10. From Figure 10, we get ITAE from 3173 to 2437.

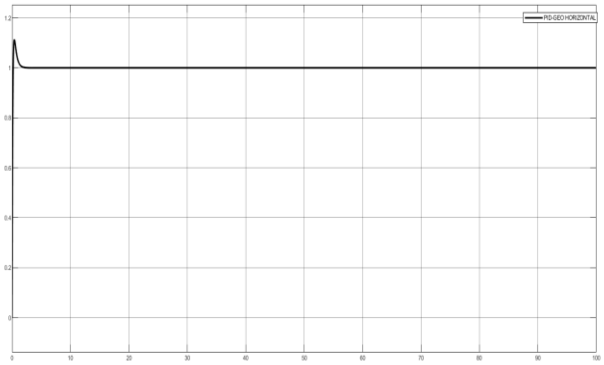

Figure 8. PID-GEO for horizontal axis

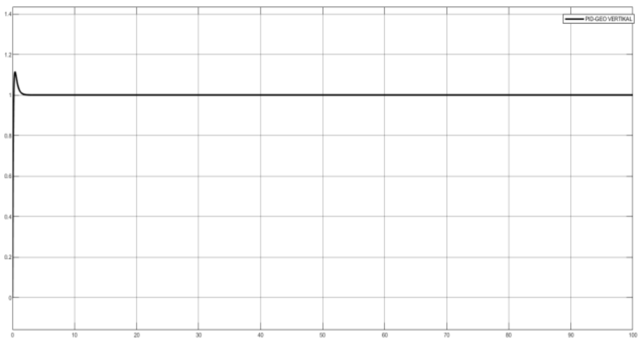

Figure 9. PID-GEO for vertical axis

Table 9. Result PID-GEO horizontal axis

Description	**Auto**
Risetime	0.1348 s
Transient Time	1.1628 s
Settling Time	1.1628 s
Settling Min	0.9000 rad
Settling Max	1.1137 rad
Overshoot	11.3718 %
Undershoot	0 %
Peak	1.1137 rad
Peaktime	0.3882 s
Kp	48.746021
Ki	0.100038

Description	Auto
Kd	23.222916
N	100
ITAE	23772.044163

From the Table 9 can be seen is overshoot for horizontal axis is 11.3718 using PID-GEO and then settling time at 1.1628 s.

Table 10. Result PID-GEO vertical axis

Description	Auto
Risetime	0.1374 s
Transient Time	1.1744 s
Settling Time	1.1744 s
Settling Min	0.9001 rad
Settling Max	1.1156 rad
Overshoot	11.5593 %
Undershoot	0 %
Peak	1.1156 rad
Peaktime	0.3949 s
Kp	48.746021
Ki	0.100038
Kd	23.222916
N	100
ITAE	2437.318139

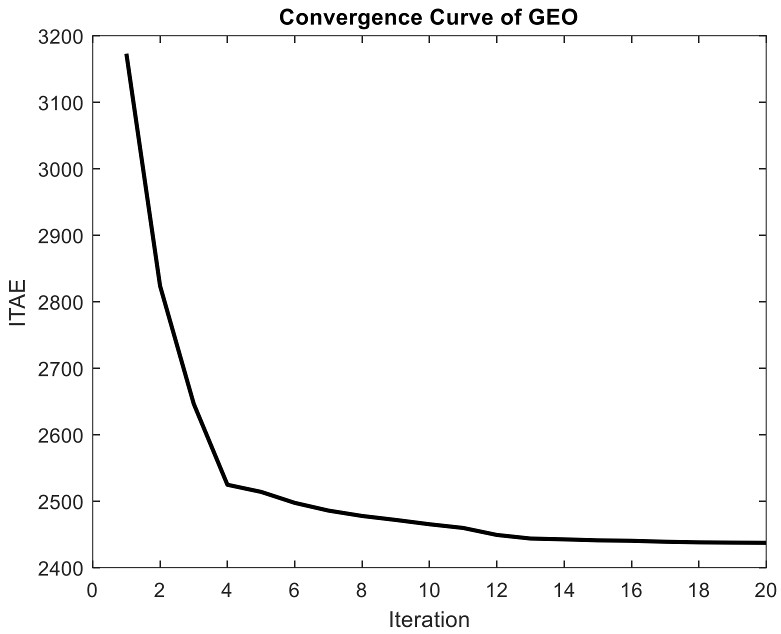

Figure 10. Convergence GEO ITAE

From the Table 10 can be seen is overshoot for vertical axis is 11.5593 using PID-GEO and then settling time at 1.1156 s.

3.5. The Results of Three Methods were Compared

Comparing three methods for dual-axis sun tracker systems are uncontrolled, PID auto-tuning, and PID-GEO. This section will show the results of comparing three methods on horizontal axis and vertical axis. For horizontal axis can be seen in Figure 11 and the vertical axis in Figure 12.

Figure 11. Comparison simulation horizontal axis

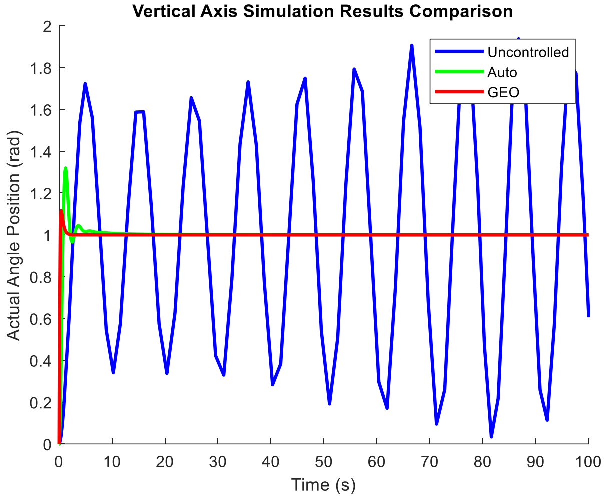

Figure 12. Comparison simulation vertical axis

Table 11. Result horizontal axis

	Uncontrolled	PID	PID-GEO
Settling Time	19.4683 s	13.33 s	1.1628 s
Overshoot	34.6426 %	29.72 %	11.372 %
Undershoot	9.23 %	9.48 %	0 %
Kp	-	0.41713	48.746021
Ki	-	0.01065	0.100038
Kd	-	1.9533	23.22292
ITAE	-	-	23772.04

Table 12. Result vertical axis

	Uncontrolled	PID	PID-GEO
Settling Time	99.9781 s	4.5103 s	1.1744 s
Overshoot	219.619 %	31.991 %	11.559 %
Undershoot	96.65 %	3.43%	0 %
Kp	-	2.4094	48.746
Ki	-	0.1478	0.100038
Kd	-	6.9195	23.223
ITAE	-	-	2437.318

From Table 11, PID-GEO has the fastest settling time is 1.1628, and the smallest overshoot dan undershoot for horizontal axis sun tracker systems are 11.372% and 0%. Likewise, the vertical axis sun tracker system has the fastest settling time at 1.1744 s, the smallest overshoot and undershoot are 11.559% dan 0 %.

4. Conclusion

This section explain result of tuning GEO algorithm at PID control (PID-GEO). For knowing about performance various tuning PID, we do comparison of the performance of each model design, namely the uncontrolled model, PID auto-tuning model, and PID-GEO model. At simulation each model design, we have overshoot and undershoot for conclude the best result. Overshoot and undershoot are important points in the control system. Overshoot and undershoot show that respons system to reach the target (setpoint). Systems that have controlled overshoot and undershoot can work more stably and efficiently, because they are able to reach setpoint in a more controlled manner without too much fluctuation. So, we can see comparison overshoot and undershoot at each model design for concluse the best result. This running simulation model using MATLAB Simulink. The simulation results show that the best model design using PID-GEO with the fastest settling time, smallest overshoot, and undershoot of all model designs. Where the overshoot horizontal axis is 11. 372% and the undershoot is 0%, that also at the vertical axis, the overshoot is 11. 559% and undershoot is 0%. This shows that GEO (Golden Eagle Optimization) has the performance to optimize PID control.

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