OPTIMAL TILT INTEGRAL DERIVATIVE (TID) CONTROLLER DESIGNFOR AN IRRIGATION VALVE CONTROL MODEL USING ADAPTIVE SPIRAL DYNAMIC ALGORITHM

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ABSTRACT

A solenoid valve which is used in an irrigation farming system where prescribed amount of water needs to be discharge for healthy growth and development of plants to improve food security needs some precision control in other to perform this task. This research tends to exploit the application of adaptive spiral dynamic algorithms (ASDA) and adaptive particle swamp optimization algorithms (APSO) in tuning controller parameters as well as selecting the best controller for the purpose of an irrigation valve control where the Proportional Derivative and Integral (PID) and Tilt Integral and Derivative (TID) controllers have been deployed for this task. At first, a mathematical model of the solenoid valve was developed and implemented in MATLAB SIMULINK; a search space for the controller's parameters (K_p, K_i and K_d) for PID controller were estimated using PID tuner block in MATLAB while those of TID controller (K_t, K_i , K_d and n) were selected based on the obtained PID controller gains except for the tilt parameter „n" whose search space was selected ($0 < n < 10$) base on literature. The optimized parameters were then obtained after successful 200 iterations on a population size of 100 for each algorithms using minimal Integral Time Absolute Error (ITAE) as the performance index. A transient response analysis and disturbance rejection (of magnitude 10000 occurring at 150 second) test was carried out on the tuned controllers and upon successful investigation, the ASDA tuned TID controller (having K_t=30179, K_i =53801,K_d =4430 and n=1.3) performed best with a rise time of T_r =1.53 second, settling time T_s =101.52 and peak overshoot M_p =0.00% making the overall system very stable, robust and fast. Developing an autonomous monitoring system that will adjust the system parameters and enables prompt action thereby eliminating human intervention would be the focus in the near future.

Keywords: Control valve, TID, PID, ASDA and ASPO

1 INTRODUCTION

Food and water security are critical issues for both developed and developing countries. Improving water management is urgent due to increasing food demand and competition. Improving agricultural efficiency and water distribution is necessary. Irrigation consumes more than 80% of the water resources worldwide, with an efficiency of almost 50% [1]. Manual irrigation system is easy to do and inexpensive [2]. However, this kind of irrigation system is waste a lot of water that may be used for other purposes [3]. The manual irrigation method has massive water losses since the amount of water given to the crops is always more than it should which presented almost 80% of all water consumption, compared to 15% of industry and 5% for domestic use [3]. Manual irrigation efficiency is inadequate, with water scarcity due to climate and mismanagement. This leads to crop dryness or flooding, necessitating the use of control valves for effective water management [3]. Valves are devices used to control liquid flow, ranging from simple on-off devices to sophisticated metering instruments, allowing for on-off control, modulation, back flow prevention, pressure relief, and safety [4]. Valves regulate downstream pressure and watering profiles in drip irrigation, sprinkler, and flood irrigation to achieve optimal watering and minimize water waste [5]. Control valves have two major components, the valve body housing and the actuation unit [6]. A control valve is a system that automatically controls flow by combining a valve, a valve actuator, and a sensing device [7]. The Tilt Integral Derivative (TID) controller is a fractional order type of controller, having similar structure to Proportional integral derivative (PID) controller but instead of proportional behaviour (like in PID), TID has a tilted behaviour which can be recognized by the transfer function of TID controller [8]. A PID controller is an instrumentused in industrial control applications to regulate temperature, flow, pressure, speed and otherprocess variables as it used a control feedback loop mechanism to control process variables and it is regarded as one of the simple and stable controller [9]. The PID controller's process input can be unstable if incorrect parameters are chosen, causing output divergence and limited by saturation or mechanical breakage [10]. TID, or Tilted Integral Derivative, is a feedback controller that combines three controllers to produce a control signal. It offers advantages like changing closed-loop system parameters, robustness, and superior disturbance rejection. TID controllers are widely used in industries like paper winding, boiler temperature, and metal working, as well as in modern cars [11]. The Tilted Integral Derivative (TID) controller operates the majority of the control system in the world and according to [12], more than 95% of the controllers in the industrial process control applications are of TID type as no other controller match the simplicity, clear functionality, applicability and ease of use offered by the TID controller. TID controllers also provide robust and reliable performance for most systems if the PID parameters are tuned properly. The Spiral Dynamic Algorithms will be utilized to optimize the parameters of a TID controller, thereby improving its performance in controlling water flow rate into farm land. Watering plants in irrigation systems is crucial for healthy growth, but overwatering can lead to root rotting and irreversible decay. Automation in farming is needed to address this issue, using controllers to manipulate the control irrigation valve, thereby reducing the need for manual watering. [13]. The control irrigation valve manipulates aflowing water to compensate for the load disturbance (dryness and surface evaporation) and keep the regulated process variable (flow rate) as close as possible to the desired set point. Researchers struggle with nonlinear water flow systems, leading to the use of PID controllers. However, parameter variation and external disturbances reduce their performance by 30%, lowering efficiencies for wider set point variation. The TID controller, with its 30% parameter variation, can be optimized using an Adaptive Spiral Dynamic Algorithm (ASDA) to ensure precise irrigation valve manipulation, preventing stunted plant growth.

2 REVIEW OF RELATED LITERATURE

[14] studied remote-control and supervision of irrigation systems: an attempt to better water management. This study focuses on controlling an irrigation system for efficient water management. A fuzzy controller was developed to manage open channels and user demand. A supervision stage was proposed for agricultural irrigation systems. The system, equipment, and control software architecture were presented, and a functional study was conducted using the GTST-1vlPLD method. [12] studied optimal proportional integral derivative (PID) controller design forsmart irrigation mobile robot with soil moisture sensor. The smart irrigation system uses a soil moisture sensor to automatically switch the water pump. The mobile robot uses a tracked vehicle chassis and an ultrasonic sensor to avoid obstacles. A 2-Degree of Freedom Proportional Integral Derivative (2-DOF PID) controller is proposed for optimal control. [15] presented the development of an improved spiral dynamic optimization algorithm with application to fuzzy logic dynamic modeling of a twin rotor system. The spiral dynamic algorithm's exploration and exploitation strategies are unique, but it settles into local optima. A bacterial foraging algorithm is adopted to solve this problem. The fuzzy model optimized by the algorithm is better and adequate for the helicopter model prototype system. [16] reviews the spiral dynamics optimization (SDO) algorithm and investigates its characteristics. The SDO algorithm, a straightforward physics-based optimization technique, has seen recent advances, including adaptive, improved, and hybrid approaches. Its growth, application, theoretical analysis, and comparison with other algorithms are detailed. The review discusses spiral paths and their application in optimization, concluding with shortcomings and future research perspectives.

3 MATERIALS AND METHOD

3.1 Materials

The materials that was used in this research include; Personal computer, MATLABR2018a software and the Internet for research.

3.2 Methodology

The following steps were adopted to achieve the aim and objective of this research work.

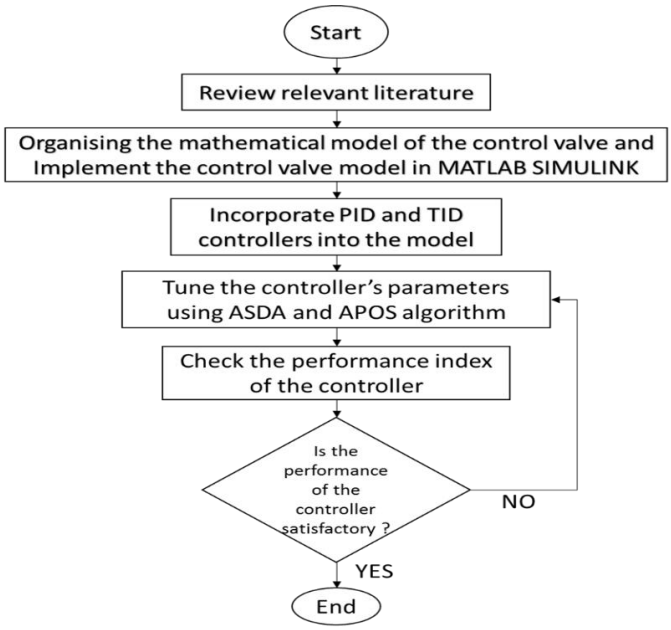

Figure 1. The Work Flow Chart [13]

3.2.1 The Solenoid Control Valve Model

A solenoid can be considered as an electric control valve as it is an electromagnet device as shown in plate 1, and as soon as an electrical current passes through the coil, each section of wire generates a strong and uniform magnetic field inside the hollow of the solenoid [17]. The magnetic field strength is influenced by the electric current in the coil, with the iron core moving within the solenoid casing. When current is cut off, the plunger returns to its original position.

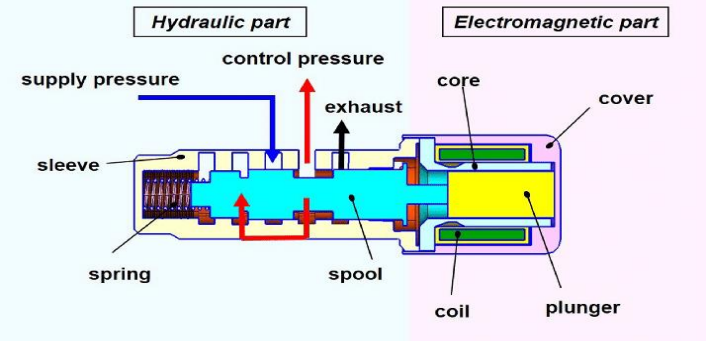

Figure 2. The Solenoid Valve [17]

The control valve, a non-linear, sophisticated mechanical element with hydraulic properties, is crucial for controlling plants in the chemical and petrochemical industry. Control engineers face challenges in modeling and simulating control valves, which include an electronic pneumatic converter, actuator, and seat. The structure is presented in Figure 3.

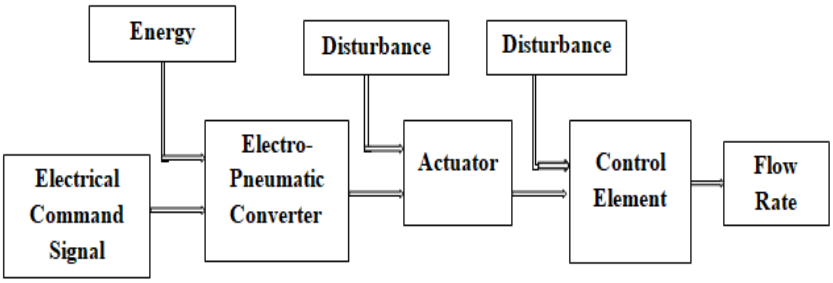

Figure 3. The control Valve Block Diagram Model [9]

3.2.2 Mathematical Model of Solenoid Valve

A mathematical model of the solenoid can be subdivided into its electrical, magnetic, and mechanical parts, as shown in Figure 4. The solenoid's electrical subsystem is triggered by an input signal of voltage, which is then applied by a magnetic block, causing the spool plunger to move.

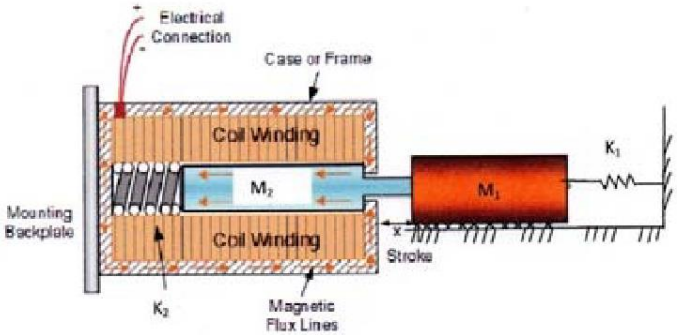

Figure 4. Solenoid Valve [18]

Figure 6a show the Solenoid Valve which consist of the electrical and the mechanical part. The solenoid valve is divided into Electrical Circuit Representation and Mechanical Representation as shown in Figure 5 below.

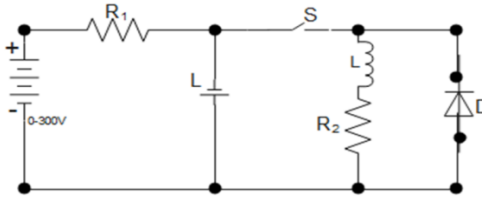

Figure 5. The Electrical Representation of a Solenoid [18]

The electrical part of the solenoid coil is a series combination of inductance and resistance and can be considered as an RL circuit, as shown in Figure 5. According to Kirchhoff's (1845) voltage law (KVL), the voltage across the solenoid coil is the algebraic sum of the voltages across the inductance and the resistance of the coil; it can thus be calculated as in equation 1 [18]. From the Electrical circuit in Figure 6.

$$L\frac{di}{dt} + (R_1 + R_2)i + (2\pi al\beta)\dot{\theta} = e_i(t) \quad (1)$$

$$L\frac{di}{dt} + (R_1 + R_2)i + \alpha\dot{\theta} = e_i(t) \quad (2)$$

State variable: v = $\dot{\theta}$

$$\frac{di}{dt} = \frac{1}{L}[-\alpha v - (R_1 + R_2)i + e_i(t)] \quad (3)$$

Where $2\pi al\beta N$

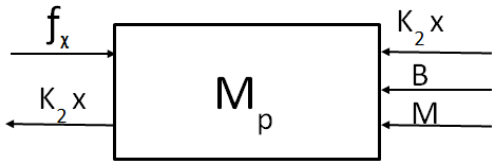

Figure 6. Mechanical Representation of a Solenoid [18]

The solenoid's mechanical component comprises a spool plunger, shaft, spring, and magnetic circuit, which generates magnetic force through electrical current and applies it to the armature as shown in Figure 6. The produced magnetic force (Fx) of the coil depends on the distance travelled by the plunger (x) as well as the electrical current i (t); this can be calculated [18] as below. The spool displacement is influenced by spring force, plunger mass and spool mass [18].

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = f_e \quad (4)$$

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = 2\pi aN\beta_i$$

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = \alpha i$$

State variable: $\dot{X} = v$

$$\dot{v} = \frac{1}{M_1 + M_2}(-(K_1 + K_2)X - bV + \alpha i) \quad (5)$$

The Transfer function of equation 5 and equation 6 will be:

$$(LS + R_1 + R_2)I(S) + \alpha X(S) + E(S)$$

$$[(M_1 + M_2)S^2 + B(S) + (K_1 + K_2)X(S) = \alpha I(S)$$

$$[(M_1 + M_2)S^2 + B(S) + (K_1 + K_2)]X(S) = \alpha\left[\frac{E(S)-\alpha I(S)}{LS+R_1+R_2}\right]$$

$$(LS + R_1 + R_2)[(M_1 + M_2)S^2 + B(S) + (K_1 + K_2)]X(S) = \alpha E(S) - \alpha^2 I(S)$$

The results of the modeling are input output equation, which input is electric voltage (E) and theoutput is spool displacement (X). Input output is given by equation 6.

$$\frac{X(S)}{E(S)} = \frac{\alpha}{(LS+R_1+R_2)[(M_1+M_2)S^2+B(S)+(K_1+K_2)]+\alpha^2} \quad (6)$$

3.2.3 The PID Controller

In the model of Figure 7, The term P is proportional to the current SP-PV error e(t), causing a large control output. Proportional control alone results in an error between set point and process value [19]. The term I integrate past set point and process variable errors over time to produce an item. It eliminates residual errors by adding a control effect. The integral term ceases to grow, diminishing the proportional effect as the error decreases [19]. The term D, also known as "anticipatory control," estimates the future trend of the SP-PV error based on its current rate of change, aiming to reduce its effect [20].

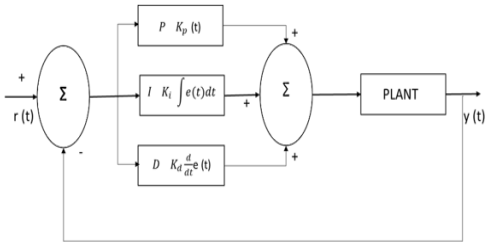

Figure 7. PID control structure

3.2.4 Tilt Integral Derivative (TID)

A TID controller, derived from fractional order calculus, is a tunable feedback control system with advantages such as simple tuning, better disturbance rejection ratio, and less effects of plant parameter variations on closed loop response, originating from fractional order calculus. The structure of TID controller is like the structure of PID controller but the proportional gain is replaced by tilted gain (K_T) that has transfer function $1/S^{\frac{1}{n}}$ and the equation that presents the TID controller is:

$$U(t) = \frac{k_t}{S^{\frac{1}{n}}} + \frac{k_i}{s} + k_d s \quad (7)$$

Where U (t) is a controlled signal, k_t is tilted gain, k_d is derivative gain, k_i is an integral gain and (n) is nonzero real number preferably kept between 2 and 3. According to [21], the TID controller when compared to PID controller, offers the abilities to overcome the plants parameter variations, as disturbances and can be easily tuned. The basic structure of TID controller is shown in Figure 8.

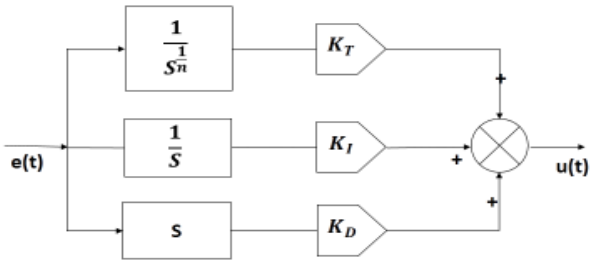

Figure 8. Basic structure of TID controller

The TID controller offers high flexibility in control parameters, simple tuning, improved feedback control, and parameter variation without affecting system response, with its design significantly influencing system performance [22]. The process requires an optimal value of controller parameters which is obtained by computational efforts. The compensator consists of three components connected parallel along a control line, a summer receiving and summarizing plant control signals, and an actuator controlling the plant in response to the compensated signal output. Selecting the values of k_T, k_d and k_i is called tuning and will be done by the spiral adaptive dynamic algorithms and adaptive particle swamp optimization algorithms respectively. Figure 9 shows the block representation and the tuning algorithms of the TID controller.

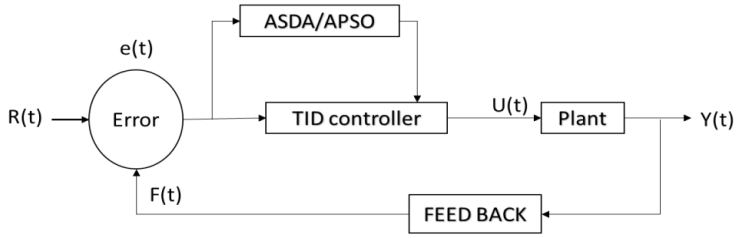

Figure 9. Close Loop ASDA/APSO Tuned Control TID Controller

Figure 9 above show the block representation and the tuning algorithms of TID controller with ASDA/APSO for the solenoid valve. The integral time absolute error (ITAE) is used as the objective function for minimization in order to optimally size the controller parameters as given by the equation 8.

$$ITAE = \int_0^t t|\varepsilon|dt \tag{8}$$

The ITAE is chosen because of its advantages of producing better performance in terms of multiplication of the error term with time augments its effect at high values. This helps in reducing settling time (t_s), and percentage overshoot (% OS) than other indices.

3.2.5 The Adaptive Spiral Dynamic Algorithms (ASDA) and Adaptive Particle Swamp Optimization Algorithms

These algorithms were implemented using the MATLAB/Simulink where a population size of 100 is selected and the stopping criterion is set at 200 iterations based on the work of [19] and [13]. In tuning the PID controller, K_p , K_i and K_d are the decision variables whereas in tuning TID controllers, four decision variables where taking into consideration which are; K_t , K_i , K_d and n are selected for tuning and the objective function is in equation 8. The ASDA and ASPO used in tuning the controllers are shown in the flow charts of Figure 10 and Figure 11 respectively.

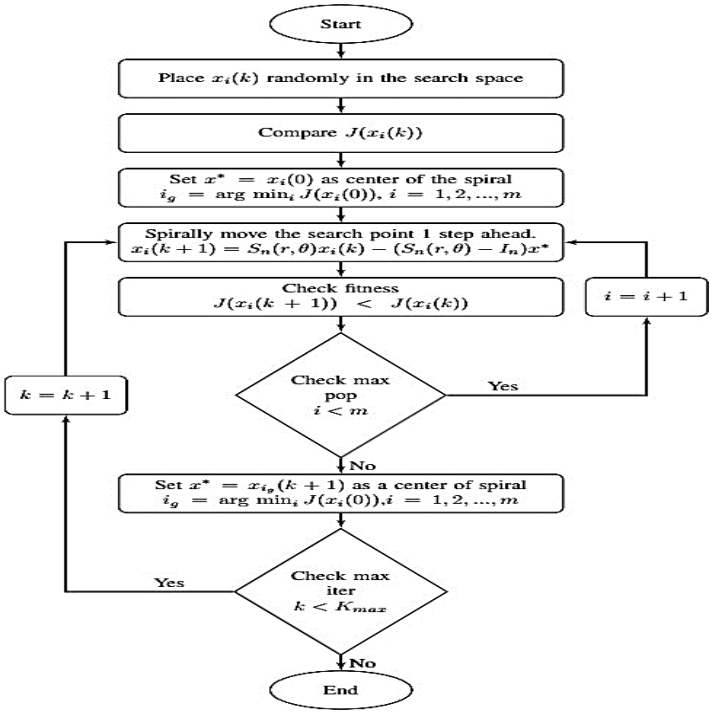

Figure 10. The Adaptive Spiral Dynamic Algorithms (ASDA) [13].

The flowchart of Figure 10 above shows the Adaptive Spiral Dynamic Algorithms (ASDA) use to tune the parameters of the TID controller, and also Figure 11 below the Adaptive Particle Swamp Optimization Algorithms (ASPO) for tuning the parameters of the TID controllers.

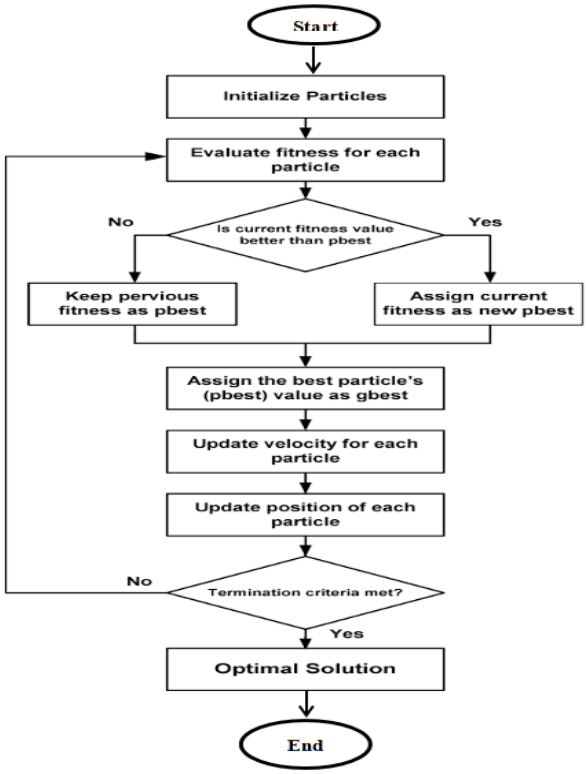

Figure 11. The Adaptive Particle Swamp Optimization Algorithms (ASPO) [13]

3.2.6 Implementation of the Control Valve in Simulink

The Simulink model of a solenoid valve without a controller implemented using equation 6 and equation 8 is shown in Figure 12. The valve parameters used in this model are those used by [18]: L=0.59H, R_1=100 ohms, R_2=50 0hms, B=1.4Nsm^{-1}, M_1=0.15kg, M_2 =03kg, N=40, a=0.05m, 4volts^{-1}

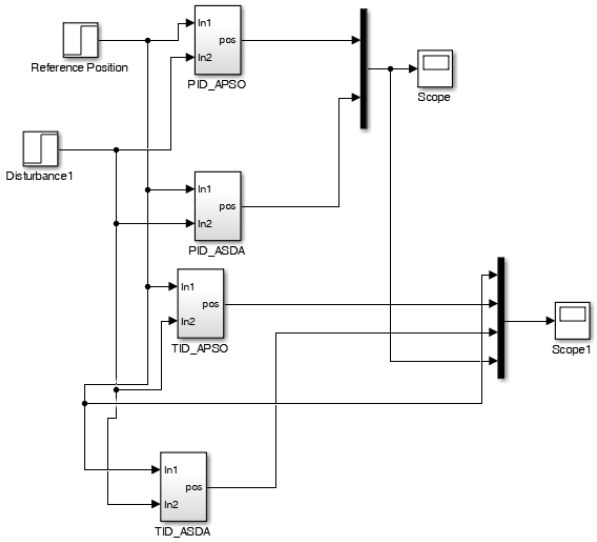

Figure 12. The Simulink Model of a Solenoid Valve

4 RESULTS AND DISCUSSION

4.1 Valve Position Response without a Controller

The result of the response of the control valve without controller is shown in the Figure 13. The system's stable nature is compromised by its oscillatory response during transients, resulting in poor steady state error in command tracking, prompting the need for a controller. This agrees with the works of [13, 19, 23].

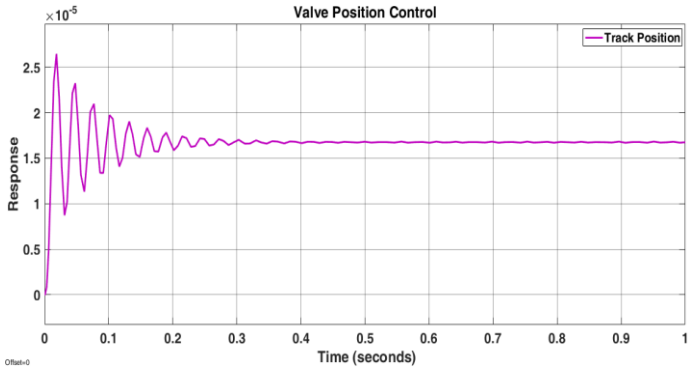

Figure 13. Response of the Valve without a Controller

4.2 Response of the Controlled Valve

Controller (PID and TID) were incorporated into the valve model to form a controlled loop and the parameters were tuned using APSO and ASDA so as to obtain the best control law by

studying the convergence of the algorithms.

4.3 Convergence of ASDA and APSO Algorithms

The convergence of adaptive spiral dynamic algorithms (ASDA) and adaptive particle swampoptimization (APSO) for tuning the PID and TID controllers for a controlled solenoid valve are shown in Figure 14 and Figure 15 respectively. Figure 14 shows how fast the APSO converges as compared to the ASDA in the case of the tuned PID controller, within the first 5 iterations. ASDA achieved steady convergence until after the 26th iteration. But the APSO has a fitness value of 111 which is higher than that of the ASDA with 104.5 [24, 25].

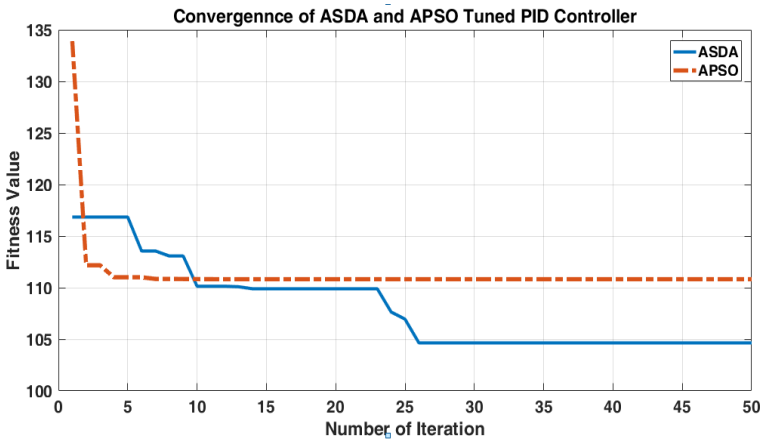

Figure 14. Convergence of ASDA and APSO Tuned PID Controller for Valve Control

For the tuned TID controller in Figure 15, APSO still maintains the speed of convergence when compared to the ASDA within the first 5 iterations. ASDA achieved steady convergence until after the 26th iteration. ASDA has a fitness value of 104.5 and APSO has 107. It can be seen that ASDA has lower fitness value compared to APSO [24, 25]. It is seen that although the APSO converges faster in all scenarios, it does not reach the global optimum as compare with the ASDA which achieved the smallest possible fitness value.

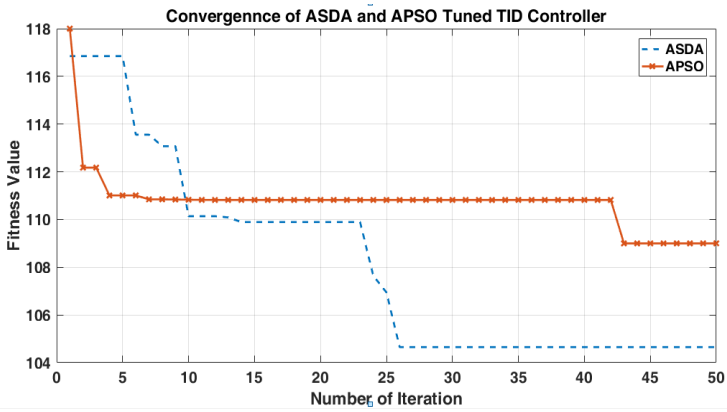

Figure 15. Convergence of ASDA and APSO Tuned TID Controller for Valve Control

4.4 Unit Step Response of ASDA and APSO Tuned PID Controller

The unit step response for PID and TID controllers tuned using ASDA and APSO are shown in Figure 16 and figure 17 respectively. In Figure 16, PID_ASDA has a better response compared

to PID_APSO. It can be seen that slower response with zero overshoots were obtained when PID_ASDA was deployed, unlike the PID_APSO having a slower response [26, 27, 28].

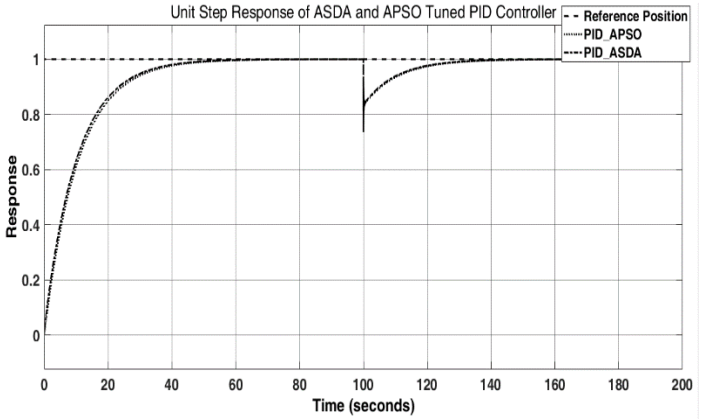

Figure 16. Unit Step Response of ASDA and APSO Tuned PID Controller

In Figure 17, faster response with zero overshoots were seen when the PID controller was replaced with TID controller irrespective of the tuning algorithms. With the TID_ASDA, the response is better and faster compared to the TID_APSO [26, 29]. Hence one can say that the TID controller has good performance and better speed of response in terms of transient behaviour as compare to PID controller.

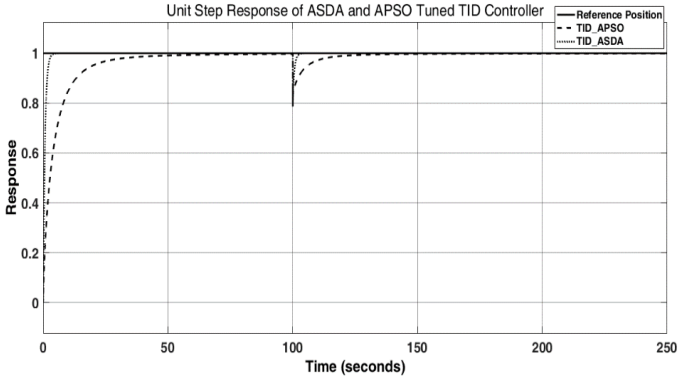

Figure 17. Unit Step Response of ASDA and APSO Tuned TID Controller

To test the robustness of these controllers, a disturbance of magnitude 10000 was introduced at 150 seconds in each controlled loop. Figure 18 and Figure 19 show the error signal and the control signal for tuned PID and TID controller respectively. In Figure 18, tuned PID was not able to maintain the same control signal when subjected to disturbance until after about 140 seconds [26]. But it was able to reject the disturbance and maintain steady state after 164 seconds.

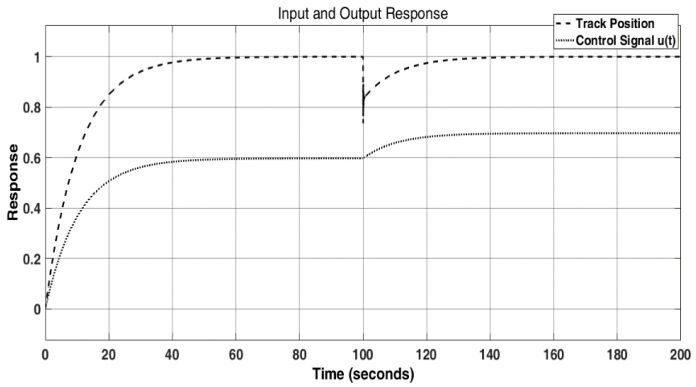

Figure 18. Input and Output Response of Tuned PID Controller

In Figure 19, the TID controller was able to maintain the same signal even in the presence of disturbance. It was observed that the TID controller which was tuned using ASDA rejected the disturbance faster and settles almost immediately as compared to PID controller.

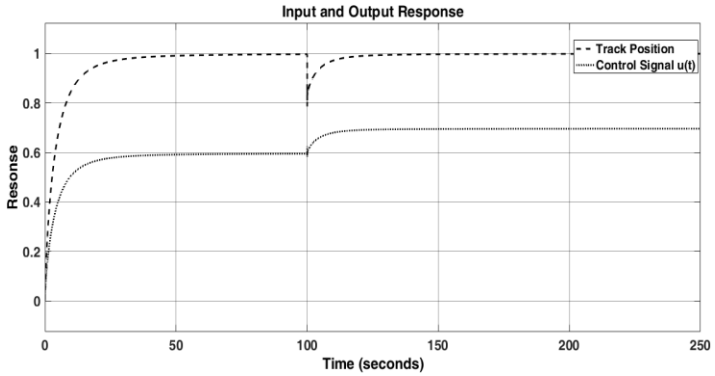

Figure 19. Input and Output Response Tuned TID Controller

4.5 Combine Unit Step Response of ASDA and APSO Tuned PID and TIDController

The combine unit step responses of PID and TID controllers tuned using ASDA and APSO algorithms is shown in Figure 20. From the response, it is clear that the TID controller tuned with ASDA has the fastest speedof response, followed by TID controller tuned with ASPO. PID controller tuned with ASDAand PID controller tuned with APSO having the least performance in terms of speed of response. For robustness, it was observed that the ASDA tuned TID controller rejected the disturbance faster so it can conclude that ASDA tuned TID has the best transient responseand it is more robust as compare to APSO tuned TID and PID controllers.

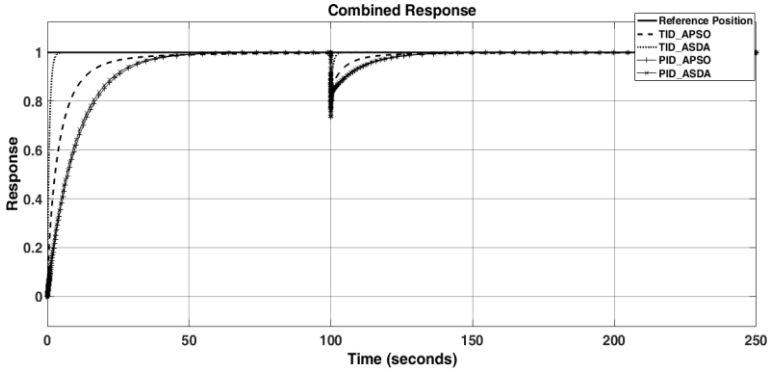

Figure 20. Combine Response of ASDA and APSO Tuned PID and TID Controller

Table 1 gives the numerical values of the controllers' gains using ASDA and APSO algorithm. In table 1, TID_ASDA has higher controller gain parameters as it was able to maintain steady-state with those values as compared TID_APSO, PID_APSO and PID_ASDA. TID_ASPO comes next, then PID_ASDA and then PID_APSO. Beyond these controllers gain parameters, these three controllers could not maintain steady-state due to high oscillations. This shows the superiority of the TID_ASDA control over the rest of the three controllers.

Table 1. Controllers gains using APSO and ASDA Algorithms

Algorithm	PID Controller			TID Controller			
	Kp	Ki	Kd	Kt	Ki	Kd	N
APSO	0	5663.996	0.000108	8636.4	9260.5	133.8	1.6
ASDA	1415.22	6000	0	30179	53801	4430	1.3

Table 2 gives the numerical values of the controllers' performance using ASDA and APSO algorithm. The performance of these algorithms was tested in terms of the rise time, settling time and peak overshoot. TID_ASDA had the minimum rise time and settling time, followed by TID_APSO, then PID_ASDA, and finally PID_ASPO. This shows that TID_ASDA is faster in terms of speed of response and maintaining steady-state. This in turn implies that the rest of the combinations are slower. This also proves the superiority of the TID_ASDA control over the rest of the three control algorithms. Although, these controllers had 0% peak overshoot in all ramifications. This result is further presented in Figures 21 and 22 and proves the superiority of the TID_ASDA over the rest of the control algorithms as it has the minimum rise time and settling time.

Table 2. Transient Parameters of Controllers using APSO and ASDA Algorithms

Algorithms	PID Controller			TID Controller		
	Rise Time	Settling Time	Peak Overshoot	Rise Time	Settling Time	Peak Overshoot
APSO	23.25	123.46	0.00	13.00	112.93	0.00
ASDA	22.47	121.59	0.00	1.53	101.51	0.00

The bar charts in figure 19 and figure 20 show the comparison for the rise time and the settling time of PID and TID controller using APSO and ASDA tuning algorithms. In Figure 21, TID_ASDA takes the shortest time to rise than TID_APSO. This means that it is faster in response compared to TID_APSO. The same thing applies to PID_ASDA with PID_APSO. In Figure 22, TID_ASDA takes the shortest time to settle or stabilize than TID_APSO. This means that it can be able to return to stability after been affected by a disturbance compared to TID_APSO. The same thing applies to PID_ASDA with PID_APSO.

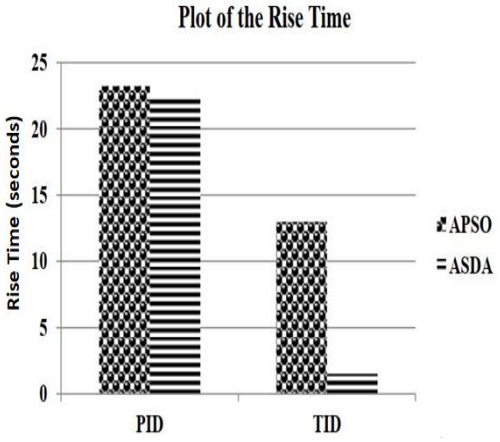

Figure 21. Rise Time of the Controllers

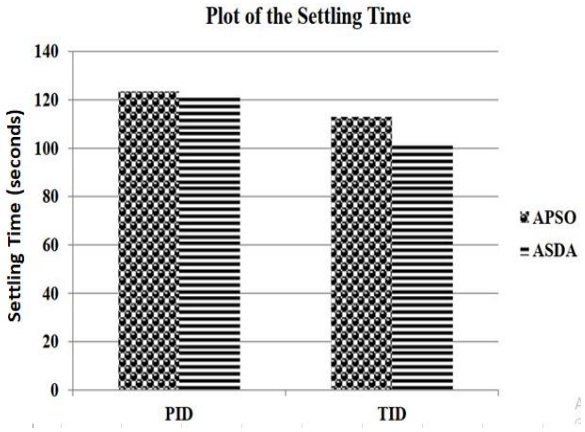

Figure 22. Settling Time of the Controllers

Results obtained from Figure 14 shows the faster convergence of the APSO compared to the ASDA in the tuned PID controller within the first 5 iterations. ASDA achieved steady convergence until after the 26th iteration, but APSO has a higher fitness value of 111. In Figure 15, the tuned TID controller shows APSO maintaining its convergence speed but not reaching the global optimum as fast as ASDA, which achieved the smallest possible fitness value. Despite APSO's faster convergence in all scenarios, it does not reach the global optimum as fast as ASDA [13, 30]. Figure 16 reveals that PID_ASDA controllers have better response and faster transient behavior compared to PID_APSO controllers, with slower responses and zero overshoots. TID controllers show faster responses and reject disturbances faster, indicating better performance and faster response speed. The robustness of these controllers was tested with a 10000 disturbance at 150 seconds in each controlled loop. This agrees with [13]. The study compared the performance of TID and PID controllers tuned using APSO and ASDA. The TID controller with ASDA showed the fastest response speed, followed by ASPO. PID controllers with ASDA and APSO had the least performance. ASDA-tuned TID controllers had the best transient response and were more robust compared to APSO-tuned TID and PID controllers. TID_ASDA had higher controller gain parameters and was able to maintain steady-state compared to TID_APSO, PID_APSO, and PID_ASDA. TID_ASDA had a minimum rise time of 1.53 seconds and a settling time of 101.51 seconds, outperforming other algorithms with 0% peak overshoot. This superior control over the other three controllers is demonstrated in Figures 21 and 22 as demonstrated by [13].

5 CONCLUSIONS

In conclusion, the following were achieved in valve control using TID and PID controllers with ASPO and ASDA algorithms. The TID controller for the valve control was modeled both in mechanical and electrical aspects using mathematical equations. In the optimal tuning and sizing of the TID controller parameters using ASDA based algorithms, K_t was found to be 30,179, Ki = 53,801, K_d = 4430 and N = 1.3 as against that of APSO where K_t = 8636.4, Ki = 9260.5, K_d = 133.8 and N = 1.6. TID_ASDA controller was found to have performed better with rise and settling time of 1.53sec and 101.51sec respectively when compared to PID_ASDA having risen and settling time of 22.47sec and 121.59sec respectively. Future research would be focused on designing a control system that will continuously monitor and adjust the control parameters, eliminating human intervention and allowing prompt action when necessary.

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