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RESEARCH ARTICLE

PID Control Design Using AGPSO Technique and Its Application in TITO Reverse Osmosis Desalination Plant

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ABSTRACT Desalination plants have an important concern regarding controlling the permeate flow rate and *pH* during operability. This paper proposes the proportional integral derivative (PID) control design using modified Particle Swarm Optimization (PSO) techniques called autonomous groups PSO (AGPSO) in the two-input two-output (TITO) RO desalination plant to control the permeate flow rate and *pH*. Here, three different versions (AGPSO1, AGPSO2, and AGPSO3) of the AGPSO algorithm are utilized to design PID control for the same TITO plant. In addition, an integral time absolute error (J_{ITAE}) based objective function is utilized to design a PID controller. The simulation results suggest that the proposed controller designs are flexible, self-tuning, and have stable characteristics, while the AGPSO3-PID control design attained a robust design for optimum tuning compared to existing improved grey wolf optimization PID (IGWO-PID) and other versions of AGPSO based PIDs (AGPSO1-PID, AGPSO2-PID). The design of AGPSO-PID achieved a minimum objective function than existing IGWO-PID and other versions of AGPSO based PIDs {AGPSO1-PID, AGPSO2-PID}. Finally, the proposed controller designs outperform the existing IGWO-PID design in literature in terms of control performance, demonstrating a precise control for and the improvement of plant performance.

INDEX TERMS Desalination, reverse osmosis (RO), PID controller, autonomous groups particle swarm optimization (AGPSO), optimization.

I. INTRODUCTION

A. BACKGROUND

For humans, animals, and plants to survive, water is one of the most precious natural resources on the earth [1], [2], [3]. According to WHO and UNICEF reports [4], [5], water covers 70% of our planet, but only 3% of it is freshwater; as a result, approximately 1.1 billion people worldwide lack access to water. They are susceptible to diseases such as typhoid, cholera, and other water-borne ailments. Due to this, two million people, mainly children, die from diarrheal illnesses every year [4], [5]. This problem will only get worse if the consumption continues at its current rate. Water shortage may affect two-thirds of the world's population by 2025 [4].

Desalination and water treatment plants have gained attention to meet freshwater needs in the face of a water shortage [6], [7], [8]. Desalination is a process that removes dissolved salts and pollutants from saltwater, brackish water, or wastewater, creating freshwater that can be used for various anthropogenic activities [9], [10]. In present times, desalination is seen as a critical method for meeting water demands in the Middle East, Saudi Arabia, UAE, Singapore, USA, India, Maldives, and other nations [9], [10]. There

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are ∼18,000 desalination plants installed with 97.2 million m^3/day capacity around the world [11]. The Minjur reverse osmosis (RO) desalination plant in Chennai, which is built on a 60-acre, is the largest plant in India, producing ∼100 megalitres clean water per day [12].

Literature suggests that commonly two types of desalination techniques are widely used during treatment: thermal-based and membrane-based [11]. The thermal-based desalination techniques like multi-effect distillation (MED) and multi-stage flash (MSF) involve evaporating saline water and then condensing the resulting steam to recover freshwater [11]. These techniques have been installed mainly in the Middle East, particularly in Saudi Arabia. The membrane techniques like ultrafiltration (UF), nanofiltration (NF), RO, forward osmosis (FO), and membrane distillation (MD) use semipermeable membranes to separate freshwater from saline water [11]. Among them, the RO-based desalination is the most widely used water-treatment technique, with more than 60% installed capacity worldwide [13].

According to the literature, several model-based designs have been presented to evaluate the performance of desalination plants in the last few decades [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. Modeling, simulation, optimization, control, and verifications are the essential phases of such designs [26], [27]. Due to the globalization of businesses and freshwater demand, desalination plants are facing stiff competition worldwide. They seek to improve their existing systems to reduce costs, energy, and processing time [9], [10]. To achieve this, they are swiftly shifting towards soft computing tools to evaluate plant performance in a small space [9], [10]. These soft computing tools are more reliable, user-friendly, flexible, and capable of redesigning, reassessing, and decision-making for plant engineers at a low cost and energy [28], [29], [30], [31], [32], [33], [34], [35].

The type of process controlling action plays a vital role in the desalination plant. This requires manipulating the process variables like speed, pressure, flow, temperature, etc., to improve the plant performance [36], [38], [39], [39], [40]. According to the literature, various controllers such as ON-OFF, proportional (P), integral (I), derivative (D), PI, PD, and PID have been utilized earlier in the plant's design [36], [37], [38], [39], [41], [42], [43], [44], [45]. Though, every controller has unique characteristics, PID is the most widely used controller in the plant. It is simple and performs more precise outcomes than others. But, some literature articles suggest that the tuning of PID is also a critical issue for improving the robustness and performance of the control system [36], [37], [38], [39]. Hence, there are still possibilities to enhance the robustness and performance of processes by the proper tuning of the PID. Recently, many researchers have worked on the tuning of the PID controllers using various nature-inspired algorithms [36], [37], [38], [39]. Some nature-inspired-techniques based PID controller designs for the RO desalination plants have been discussed in the next section to understand this research area more clearly. Literature suggests that these are more capable of achieving faster and smoother responses for the higher-order systems.

Park et al. [46] presented a PID control design using a genetic algorithm (GA) of the Doha RO desalination plant of Kuwait. It includes two input parameters: feed pressure (800–1000 psig) and *pH* (6–7), while permeate flux (0.85–1.25 gpm) and conductivity (400–500 μs/cm) are the output parameters. They have reported improved settling time ($t_s = 91224$ s and $t_s = 452$ s) of the proposed design compared to Ziegler-Nichols (ZN) proposed PID setting ($t_s = 1939269$ s and $t_s = 454$ s) for permeate flux and conductivity, respectively. Further, Kim et al. [47] proposed a PID control design using an immune GA (IGA) of the same Doha RO desalination plant of Kuwait. They have also reported a better settling time ($t_s = 147$ s and $t_s = 25$ s) of the proposed design than the ZN PID ($t_s = 529000$ s and $t_s = 82$ s) for permeate flux and conductivity, respectively. Recently, Guna et al. [48] presented PID control designs for a single-stage pilot-scale RO process using particle swarm optimization (PSO) and bacterial foraging optimization (BFO) algorithms. To examine controller designs, they used four objective functions: integral absolute error (IAE), integral squared error (ISE), integral time absolute error (ITAE), and integral time squared error (ITSE). Finally, they reported minimum settling times for PSO and BFO tuned PIDs ($t_s = 20.3$ s and $t_s = 17.3$ s, respectively).

These nature-inspired algorithm-based PID controllers are a part of optimization of controlling action. Thus, optimization is a systematic process that allows the plant engineer to design a precise controller for a stable and optimal solution. It aims to achieve the "best" design and maximize factors such as efficiency, reliability, productivity, strength, and utilization. With the motivation of the literature mentioned above, we have proposed a PID control design using a nature-inspired algorithm called autonomous groups PSO (AGPSO) to control the permeate flow rate (m^3/h) and *pH* in the two-input two-output (TITO) RO desalination plant in this paper.

Why AGPSO algorithm to design PID controller:

Mirjalili et al. [49] developed the modified PSO technique called the AGPSO algorithm. They employed 23 benchmark functions to analyze this algorithm. The results demonstrated that the AGPSO algorithm outperforms the conventional PSO in terms of escaping local minima and convergence speed. It has gained much interest in solving optimal control problems and providing a globally optimized solution. Therefore, we have utilized this algorithm in this research.

B. MAJOR OBJECTIVES, CONTRIBUTIONS, AND PAPER OUTLINES

Based on the above discussions, we have concluded that AGPSO algorithm has not been explored for PID control design in the literature. In addition, the proposed control design has also not been implemented for the RO desalination plants. Thus, with this apparent literature gap, we have utilized the AGPSO technique to design a PID controller

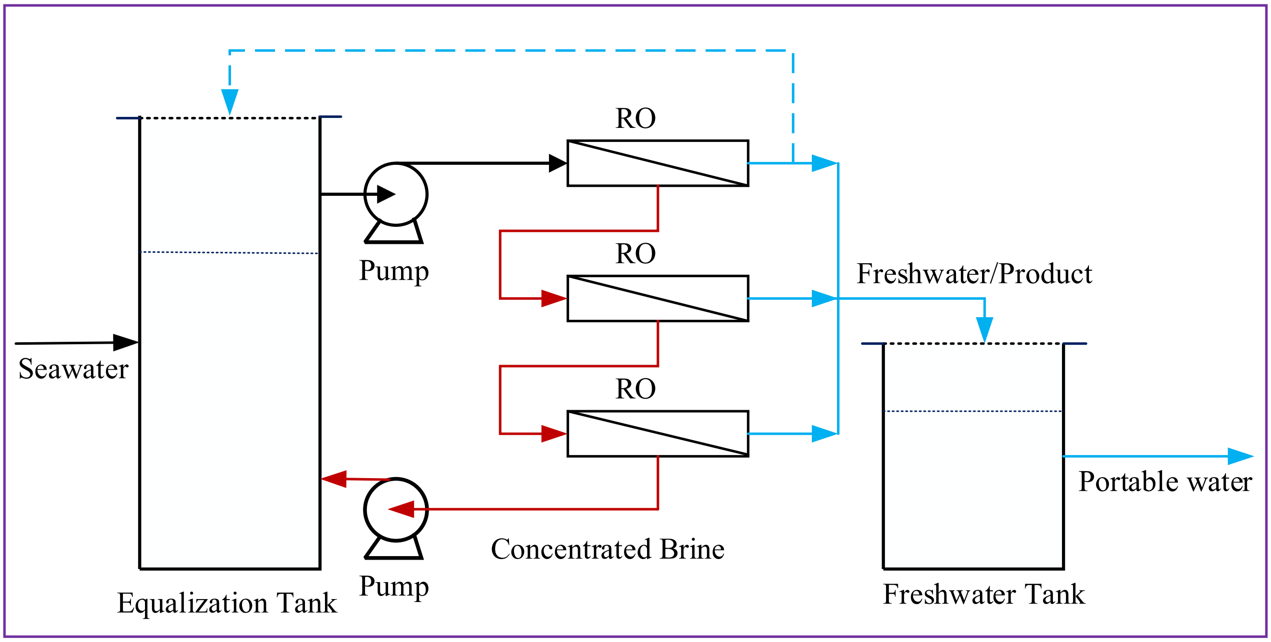


FIGURE 1. Schematic diagram of a RO desalination plant. Photo: courtesy Sobana and Panda [38].

for the first time for desalination systems. Hence, the major objectives and contributions are as follows: (1) This paper explores implementation of the PID control design assisted with modified PSO techniques called AGPSO and improved grey wolf optimization based PID (IGWO-PID) in the TITO RO desalination plant to control the permeate flow rate (m^3/h) and *pH*. (2) The tuning of PID controller is done using three different versions (AGPSO1, AGPSO2, and AGPSO3) of the AGPSO algorithm for the same TITO plant. (3) The proposed controller design is compared and found to show better control performance than the IGWO-PID based design [39].

The outlines of this paper are as follows: The desalination plant's process, along with a relevant schematic diagram, is described in Section 2. It involves the technical input-output parameters of the plant. In Section 3, the AGPSO algorithm is described in detail. The proposed controller designs with an appropriate flow diagram and objective function are presented in Section 4. Section 5 provides the results and discussion. Finally, Section 6 presents the conclusion.

II. RO DESALINATION PLANT'S PROCESS DESCRIPTION

Sobana and Panda [38] have designed a transfer function model (shown in equation 1) for control of a RO desalination plant with a capacity of 3.80 MLD drinking water in the Village of Narippaiyur, District Ramanathapuram, Tamil Nadu, India. Here, two-input two-output (TITO) parameters were considered for PID controller design [39]. The input parameters considered were pump pressure (ΔP) and the ratio of flow rates of seawater feed to that of brine stream (R_{FB}), while the output parameters ware permeate flow rate F_p (m^3/h) and *pH*. The schematic diagram of the RO desalination plants is shown in Figure.1 [38].

The primary components involved in the RO desalination plant are an equalization tank, high-pressure pumps, RO, and freshwater tank. Initially, raw seawater is pretreated and stored in an equalization tank. Then, it is pumped to the RO tubular membrane chamber using the high-pressure pump and separated into freshwater and brine. In this plant, the RO membrane is made by Dow Filmtech with a diameter of 2.5 inches [38]. Finally, the freshwater collected into the freshwater tank is ready for portable water, while the concentrated brine is returned to the equalization tank for reuse.

The transfer function representation of the TITO RO Desalination plant is given as follows [38]:

$$\underbrace{\begin{bmatrix} F_p \\ pH_p \end{bmatrix}}_{Outputs} = \underbrace{\begin{bmatrix} G_{p11}(s) & G_{p12}(s) \\ G_{p21}(s) & G_{p22}(s) \end{bmatrix}}_{Process\ transfer\ function\{G_p(s)\}} \underbrace{\begin{bmatrix} \Delta P \\ R_{FB} \end{bmatrix}}_{Inputs} \quad (1)$$

where, ΔP indicates the feed pump pressure; R_{FB} denotes the ratio of flow rates of seawater feed to that of brine stream; F_p represents the permeate flow rate (m^3/h); and *pH* indicates the permeate *pH*. The individual process transfer functions in the laplace domain are described as follows [38]:

$$\frac{F_p}{\Delta P} = G_{p11} = \frac{1.4944e^{-0.55s}}{0.71615s + 1} \quad (2)$$

$$\frac{F_p}{R_{FB}} = G_{p12} = \frac{0.092857e^{-0.3666s}}{1.1875s + 1} \quad (3)$$

$$\frac{pH_p}{\Delta P} = G_{p21} = \frac{0.114411e^{-0.55s}}{7s + 1} \quad (4)$$

TABLE 1. Details of updating techniques of different versions of the AGPSO algorithm [49]. Here, T = maximum number iterations and Small t = current iteration.

Versions of the AGPSO algorithm	Algorithm's group	Updating formula	
		c_1	c_2
AGPSO1	Group 1	$(-2.05/T)t+2.55$	$(1/T)t+1.25$
	Group 2	$(-2.05/T)t+2.55$	$(2t^3/T)+0.5$
	Group 3	$(-2t^3/T^3)+2.5$	$(1/T)t+1.25$
	Group 4	$(-2t^3/T^3)+2.5$	$(2t^3/T^3)+0.5$
AGPSO2	Group 1	$2.5-(2\log(t)/\log(T))$	$(2\log(t)/\log(T))+0.5$
	Group 2	$(-2t^3/T^3)+2.5$	$(2t^3/T)+0.5$
	Group 3	$0.5+2\exp[-(4t/T)^2]$	$2.2-2\exp[4t/T)^2]$
	Group 4	$2.5+2(t/T)^2-2(2t/T)$	$0.5-2(t/T)^2+2(2t/T)$
AGPSO3	Group 1	$1.95-2t^{1/3}/T^{1/3}$	$2t^{1/3}/T^{1/3}+0.05$
	Group 2	$(-2t^3/T^3)+2.5$	$(2t^3/T^3)+2.5$
	Group 3	$1.95-2t^{1/3}/T^{1/3}$	$(2t^3/T^3)+2.5$
	Group 4	$(-2t^3/T^3)+2.5$	$2t^{1/3}/T^{1/3}+0.05$

$$\frac{pH_p}{R_{FB}} = G_{p22} = \frac{0.1781e^{-0.15s}}{2.5s+1} \tag{5}$$

III. AGPSO ALGORITHM

Kennedy and Eberhart [50], [51], [52] invented a nature-inspired algorithm called the PSO technique. It is inspired by the social behavior of birds flocking and is initialized by a group of random particles. Particles move around in a multidimensional space, adjusting their positions based on their own best positions, called individual best (*pbest*), and another best value achieved by a neighbor, called as global best (*gbest*). In this technique, every particle searches for its best position in space with its own knowledge and guides the best positions towards each other. Thus, the mathematical equations for the best velocity and position of every particle are represented as below [20], [50]:

$$v_i^{n+1} = \omega v_i^n + c_1 r_1^n \left[x_{i,p}^n - x_i^n\right] + c_2 r_2^n \left[x_g^n - x_i^n\right] \tag{6}$$

$$x_i^{n+1} = x_i^n + v_i^{n+1} \tag{7}$$

where, i is the particle index; v_i^n and v_i^{n+1} are the velocity of i^{th} particle at n^{th} and $n+1^{th}$ iteration, respectively; x_i^n and x_i^{n+1} are the particle i position at n^{th} and $n+1^{th}$ iteration, respectively; n is the number of iterations; $x_{i,p}^n$ is the individual best position associated with particle *i (pbest);* x_g^n is the global best value, obtained by the particle (*gbest*); c_1 and c_2 are the acceleration factors; r_1^n and r_2^n are the random values and ω is the weight of inertia.

Further, Mirjalili et al. [49] found some limitations in acceleration factors (c_1 and c_2) of the conventional PSO algorithm and developed a modified PSO algorithm called autonomous groups PSO (AGPSO). It fine-tunes the acceleration factors to identify the global minima of the problems relatively more quickly. With the fine-tuning of c_1 and c_2 through a unique strategy, the authors assigned four independent groups wherein and each group of particles attempts to find the best on its own. Based on these unique strategies, the authors developed three versions (AGPSO1, AGPSO2, and AGPSO3) of this algorithm with their updating formulas, illustrated in Table 1. All versions of the AGPSO have unique capabilities and perform different outcomes. Besides, the authors suggested that the AGPSO3 algorithm shares better performance than other versions of AGPSO (AGPSO1 and AGPSO2).

IV. PROPOSED CONTROLLER DESIGN

This section has been divided into three subsections for ease of understanding of the proposed controller design. The first subsection explains the structure of the PID controller design of the TITO RO desalination plant, and then the second subsection explains the objective functions in detail. Finally, the last subsection defines the complete step-by-step proposed controller (AGPSO-PID) design using a suitable flow diagram.

A. *PID CONTROLLER DESIGN*

As stated earlier in the introduction section, the PID controller is the most widely used one in industrial applications. It is simple and automatically optimized, regulates different parameters like pressure, temperature, and speed of the plant, and performs precise outcomes. It estimates error by computing the difference between the actual and desired values and adjusting the decision parameters accordingly [36], [37]. This error is calculated continuously until the process

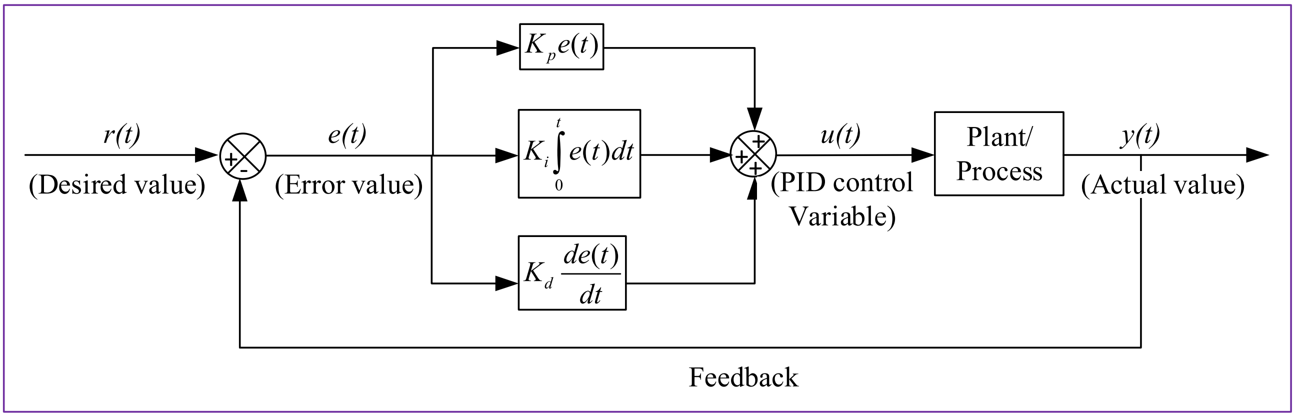


FIGURE 2. Block diagram representation of the PID controller [36], [37].

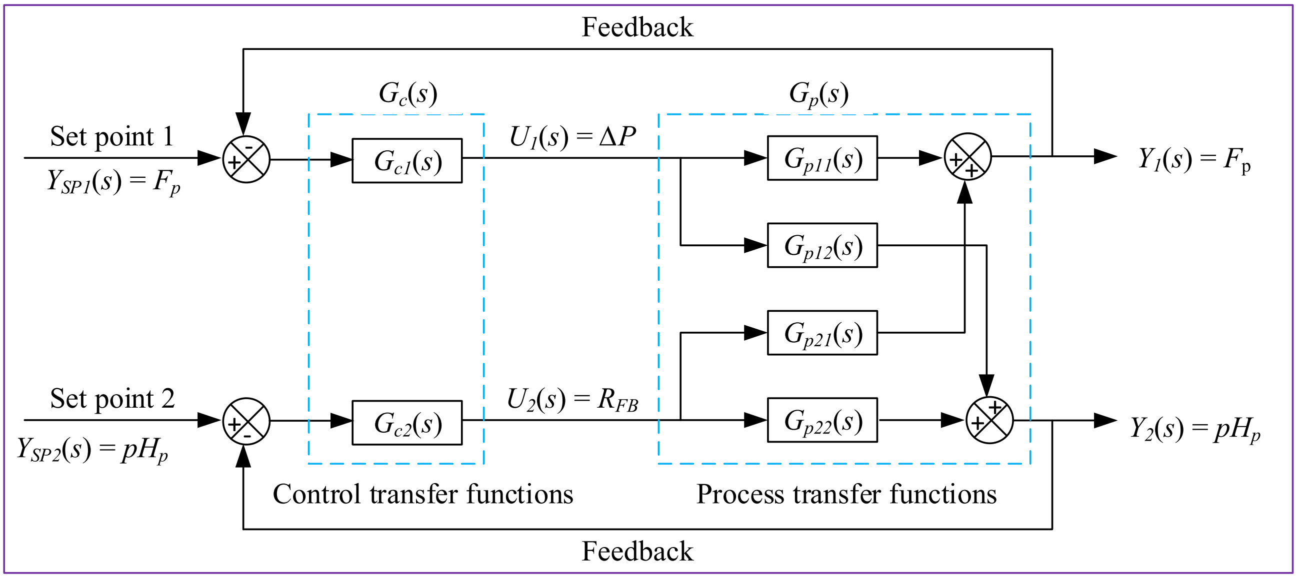


FIGURE 3. TITO control system of RO desalination plant [39].

is terminated. The mathematical formulation of the PID controller is as follows [36], [37]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{8}$$

where, $u(t)$ is the PID control variable; $e(t)$ is the error value $\{e(t) = r(t) - y(t)\}$ or the difference between the desired value $r(t)$ and the actual value $y(t)$; K_p, K_i and K_d are the proportional, integral, and derivative coefficients, respectively. The basic block diagram representation of the PID controller is shown in Figure. 2.

The main aim of this investigation is to design a PID controller for the TITO RO desalination plant. In the present case RO desalination plant, the proposed TITO system has two inputs ($U_1(s) = \Delta P$ and $U_2(s) = R_{FB}$) and two outputs ($Y_1(s) = F_p$ and $Y_2(s) = pH$). The TITO control system has been designed based on these input-output parameters and shown in Figure. 3. Here, PID controllers have been employed in the whole control design. As illustrated in Figure. 3, the system presents two loops: the first loop is for the permeate flow rate F_p (m^3/h), and the second loop is for the pH. The control transfer function $G_c(s)$ controls the process transfer function $G_p(s)$ of the system. Here, two control transfer functions $G_{c1}(s)$ and $G_{c2}(s)$ have been employed to control the four process transfer functions $G_{p11}(s)$, $G_{p12}(s)$, $G_{p21}(s)$, and $G_{p22}(s)$ represented in equations 9 and 10, also in Figure. 3.

The control transfer functions $\{G_c(s)\}$ and the process transfer functions $\{G_p(s)\}$ of the system are given below as follows:

$$G_c(s) = \begin{bmatrix} G_{c1}(s) \\ G_{c2}(s) \end{bmatrix} \tag{9}$$

$$G_p(s) = \begin{bmatrix} G_{p11}(s) & G_{p12}(s) \\ G_{p21}(s) & G_{p22}(s) \end{bmatrix} \tag{10}$$

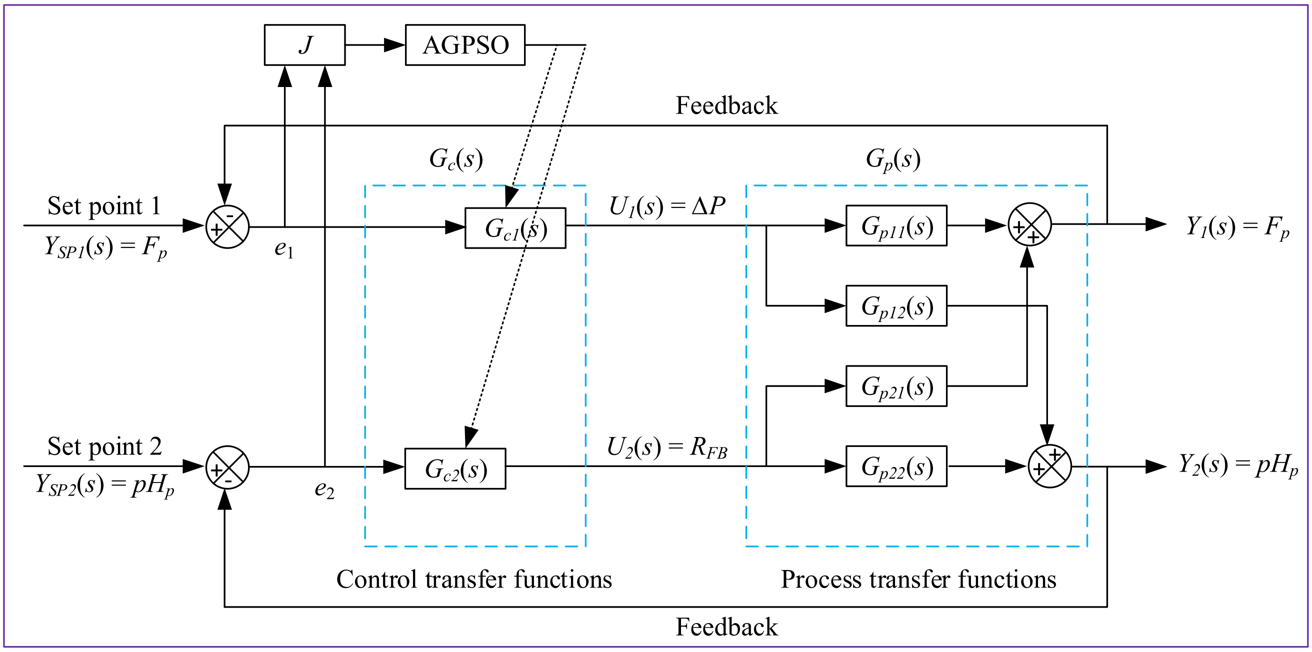


FIGURE 4. **The AGPSO based PID controller tuning.**

where, $G_{c1}(s)$ and $G_{c2}(s)$ are the first and second control transfer functions of the TITO RO desalination plant;$G_{p11}(s)$, $G_{p12}(s)$, $G_{p21}(s)$, and $G_{p22}(s)$ are the four process transfer functions of the same TITO plant.

B. OBJECTIVE FUNCTION

The tuning of the PID controller of the TITO RO desalination plant is more complex because of the interaction effect. Literature suggests numerous nature-inspired tuning algorithms (GA [46], IGA [47], PSO, and BFO [48]) for the PID controller to tune easily. The tuning using these techniques depends on the selection of objective functions. This research utilizes the integral time absolute error (ITAE) objective function to tune the AGPSO based PID controller of the TITO RO desalination plant, as illustrated in Figure. 4. The mathematical formulation of this objective function is given below as follows:

$$\text{Minimize} \quad J_{ITAE} = \int_{0}^{\infty} t\,|e(t)|\,dt$$

$$\text{subject to}: \tag{11}$$

$$k_{p1},\text{min} \leq k_{p1} \leq k_{p1},\text{max} \tag{12}$$

$$k_{i1},\text{min} \leq k_{i1} \leq k_{i1},\text{max} \tag{13}$$

$$k_{d1},\text{min} \leq k_{d1} \leq k_{d1},\text{max} \tag{14}$$

$$k_{p2},\text{min} \leq k_{p2} \leq k_{p2},\text{max} \tag{15}$$

$$k_{i2},\text{min} \leq k_{i2} \leq k_{i2},\text{max} \tag{16}$$

$$k_{d2},\text{min} \leq k_{d2} \leq k_{d2},\text{max} \tag{17}$$

where, $e(t)$ is the error; J is the objective function; ITAE is the integral time absolute error; k_{p1}, k_{i1}, k_{d1} are the gains of PID controller for permeate flow rate (m^3/h); k_{p2}, k_{i2}, k_{d2} are the gains of PID controller for pH. The main reason for selecting this objective function for the PID controller design is that the order of integrator produces offset for a long time. It may provide a better controller with faster servo tracking and disturbance rejection without offset.

C. FLOW DIAGRAM OF AGPSO-PID CONTROLLER

In the initial two subsections, we designed the AGPSO based PID controller and defined the objective function. In this subsection, we have described the step-by-step AGPSO-PID approach by a suitable flow diagram (shown in Figure. 5) summarized as follows:

V. RESULTS AND DISCUSSION

The results and discussion section has been divided into five subsections to understand the fruitful findings of the AGPSO based PID controller for the TITO RO desalination system. The first subsection deliberates the optimal gains of the IGWO-PID (Existing) [39], AGPSO1-PID, AGPSO2-PID, and AGPSO3-PID control design based on the ITAE objective function. The second and third subsections discuss the servo and regulatory response analysis of the PID controller design, respectively. The fourth subsection described the servo and regulatory response with disturbance of the same system. Finally, the last subsection gives a comparative study between AGPSO based PID and existing IGWO based PID performance of the TITO RO desalination plant.

A. PID CONTROL DESIGN

In this study, the simulation results suggest to employ AGPSO based PID control design of the TITO RO desalination plant

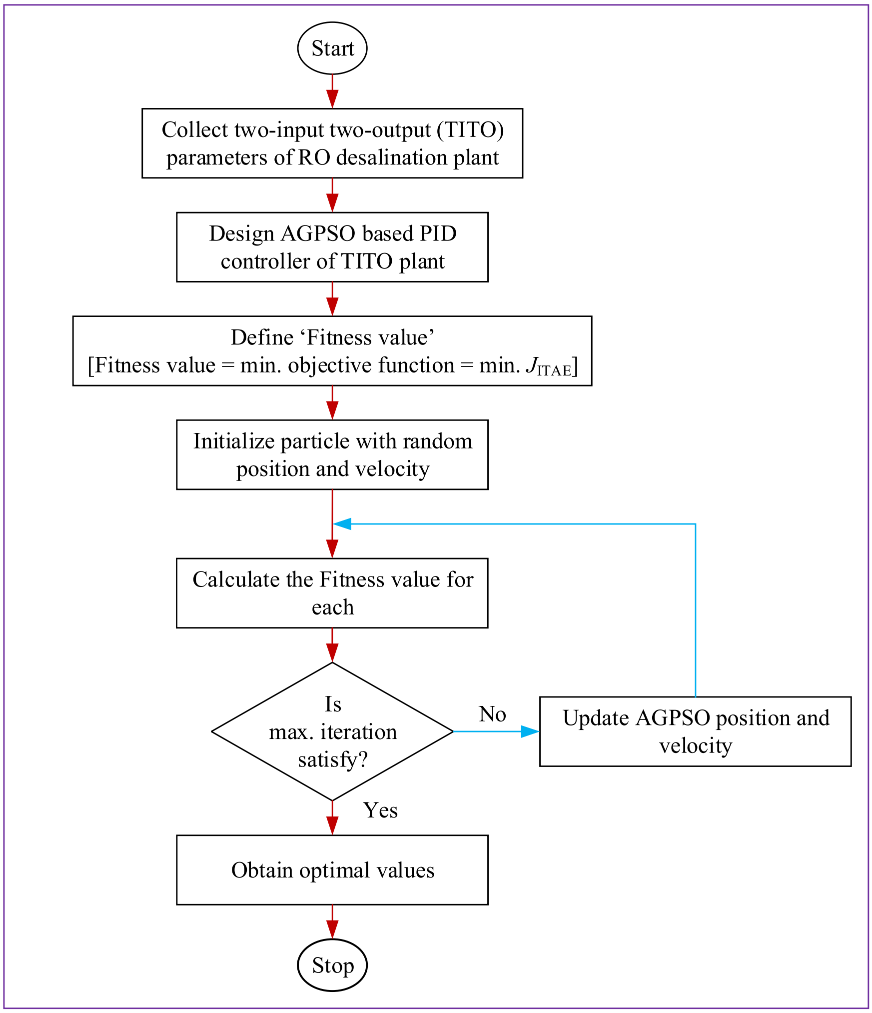


FIGURE 5. Flow diagram of the AGPSO based PID controller design.

work for an accurate control. The proposed design explored the optimal gain by using the 10 number of particles and the 30 maximum iterations. The lower (*lb*) and upper bound (*ub*) ranges employed in this design as below (18) and (19), shown at the bottom of the next page.

The optimal gains obtained for IGWO-PID (Existing) [39], AGPSO1-PID, AGPSO2-PID, and AGPSO3-PID control design based on ITAE objective function are shown in Table 2. As apparent from Table 3, the AGPSO3-PID gave the minimum objective function ($J_{\text{ITAE}} = 19.303$) than the existing IGWO-PID (84.810) [39] and other versions of AGPSO PIDs ($J_{\text{ITAE}} = 20.305$ for AGPSO1-PID and $J_{\text{ITAE}} = 21.105$ for AGPSO2-PID) for permeate flow rate (m^3/h) and *pH*. Overall, all proposed designs based on AGPSO variants performed better gains compared to the existing IGWO-PID design.

B. SCENARIO I: SERVO-RESPONSES ANALYSIS

The simulation results illustrated in Figure. 6 for a unit step response to change in permeate flow rate, clearly show that the proposed control design performed better with a shorter settling time ($t_s = 2.740$) for permeate flow rate (m^3/h) compared to the existing IGWO-PID ($t_s = 8.030$) design. Similarly, we have also noted a marginally shorter settling time ($t_s = 4.024$) for permeate *pH* than the existing IGWO-PID ($t_s = 4.048$) design. The transient response analysis of AGPSO1-3 and IGWO based PID control designs for permeate flow rate (m^3/h) and *pH* are shown in Table 4. Finally, simulation findings suggested that the proposed AGPSO based PID controllers are the most suitable for the RO desalination plant.

C. SCENARIO II: REGULATORY RESPONSES ANALYSIS

For further analysis of the proposed PID control design, the integral absolute error (IAE), the integral squared error (ISE), and the integral time absolute error (ITAE) have been checked. Thus, the regulatory response analysis of the listed errors and their performances for the permeate flow rate (m^3/h) and permeate *pH* of the RO desalination

TABLE 2. Optimal gains obtained for IGWO-PID (Existing) [39], AGPSO1-PID, AGPSO2-PID, and AGPSO3-PID control design based on ITAE objective function.

Name of tuning methods	**Optimal gains of PID parameters**		
	For permeate flow rate (m^3/h)		
	K_{p1}	K_{i1}	K_{d1}
IGWO-PID tuned [39]	0.520	0.830	0.104
AGPSO1-PID tuned	0.722	0.812	0.095
AGPSO2-PID tuned	0.789	0.950	0.100
AGPSO3-PID tuned	0.771	0.841	0.100
	For pH_p		
	K_{p2}	K_{i2}	K_{d2}
IGWO-PID tuned [39]	22.430	9.300	0.350
AGPSO1-PID tuned	9.002	2.573	0.257
AGPSO2-PID tuned	10.074	2.875	0.607
AGPSO3-PID tuned	18.101	4.380	0.722

TABLE 3. Obtained minimum objective function value for IGWO-PID (Existing) [39], AGPSO1-PID, AGPSO2-PID, and AGPSO3-PID control design based on ITAE objective function.

Name of tuning methods	**Obtained minimum objective function value (J_{ITAE})**
IGWO-PID tuned [39]	84.810
AGPSO1-PID tuned	20.305
AGPSO2-PID tuned	21.105
AGPSO3-PID tuned	**19.303**

TABLE 4. Transient response analysis of AGPSO1-3 and IGWO based PID control using ITAE objective function for permeate flow rate and permeate *pH*.

Name of tuning methods	**Settling time (sec)**
(For permeate flow rate (m^3/h))	
IGWO-PID tuned [39]	8.030
AGPSO1-PID tuned	3.307
AGPSO2-PID tuned	**2.740**
AGPSO3-PID tuned	4.847
(For permeate *pH*)	
IGWO-PID tuned [39]	4.048
AGPSO1-PID tuned	5.930
AGPSO2-PID tuned	5.163
AGPSO3-PID tuned	**4.024**

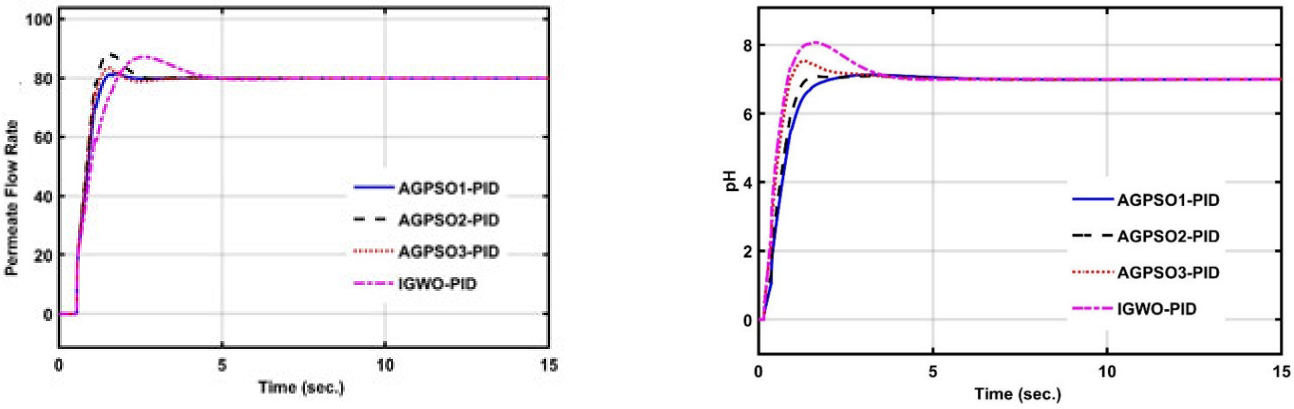
plant is illustrated in Table 5. We have recorded that the AGPSO3-PID controller design performs minimum errors for IAE, ISE, and ITAE than the existing IGWO-PID and other versions of the AGPSO-PIDs. In addition, we have also noted that the ITAE recorded a minimum of minimum errors for permeate flow rate (m^3/h) (ITAE = 33.91) and *pH* (ITAE = 3.31) than IAE and ISE. However, the literature suggests that the performance errors may vary according to the plant's transfer function model and the design of the control system.

D. SERVO AND REGULATORY RESPONSES ANALYSIS WITH DISTURBANCES

For the deep analysis of the proposed AGPSO based PID control design, we have employed the disturbances and observed numerous outcomes, as shown in the graphical form in Figure.7 and the recorded form in Table 6. We have observed that the proposed controllers (ASPSO1-3 PIDs) perform better than the existing (IGWO-PID) control design when employing disturbances for both measurements, permeate flow rate (m^3/h) and *pH*. We have also recorded much smaller

$$lb = [\, k_{p1}\min \;\; k_{i1}\min \;\; k_{d1}\min \;\; k_{p2}\min \;\; k_{i2}\min \;\; k_{d2}\min \,] = [\,0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0\,] \tag{18}$$

$$ub = [\, k_{p1}\max \;\; k_{i1}\max \;\; k_{d1}\max \;\; k_{p2}\max \;\; k_{i2}\max \;\; k_{d2}\max \,] = [\,1 \;\; 1 \;\; 0.1 \;\; 25 \;\; 10 \;\; 1\,] \tag{19}$$

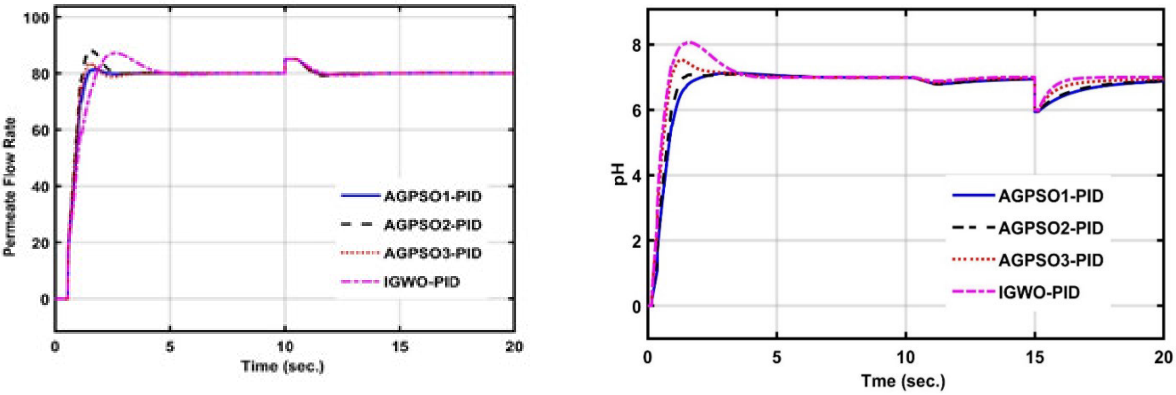


(a) (b)

FIGURE 6. Unit step response of AGPSO1-3 and IGWO based PID control using ITAE objective function for disturebances in: (a) Permeate flow rate (m^3/h) and (b) Permeate *pH*.

TABLE 5. Servo and Regulatory responses analysis using IAE, ISE, and ITAE in the PID control design measures the permeate flow rate and *pH* of the TITO RO desalination plant.

Output	Error	IGWO-PID [39]	AGPSO1-PID	AGPSO2-PID	AGPSO3-PID
Permeate flow rate (m^3/h)	IAE	86.80	66.92	68.88	**66.09**
	ISE	5701.20	4420.00	4332.00	**4328.00**
	ITAE	80.15	33.99	39.08	**33.91**
pH	IAE	11.36	5.16	4.54	**4.06**
	ISE	19.94	23.50	21.34	**17.33**
	ITAE	4.77	4.24	3.44	**3.31**



(a) (b)

FIGURE 7. Servo and the regulatory unit step response of the AGPSO1-3 and IGWO based PID TITO controllers of RO desalination plant for disturbances in: (a) Permeate flow rate (m3/h) and (b) Permeate pH.

error (IAE, ISE, and ITAE) for all proposed controllers than previously modeled IGWO-PID controller, as shown in Table 6. In addition, we have noted that the AGPSO3-PID has performed better than the existing IGWO-PID and other versions of AGPSO-PIDs. Finally, we conclude that the disturbances have not affected the proposed PID control designs performance. Thus, the proposed PID control designs are the most suitable for the RO desalination plant performance.

E. COMPARATIVE STUDY BETWEEN AGPSO BASED PID AND PREVIOUSLY MODELED IGWO BASED PID

Finally, this section presents the comparative analysis between the proposed AGPSO based PID and the existing IGWO based PID control designs of the TITO RO desalination plant. We have observed that the proposed control design ensures a smoother but quicker servo and regulatory response. It has also been noted that the proposed design clearly performed better than the existing IGWO-PID

TABLE 6. Servo and Regulatory response analysis for disturbances using IAE, ISE, and ITAE in the PID control design to measure the permeate flow rate (m3/h) and pH of the TITO RO desalination plant.

Output	**Error**	**IGWO-PID** [39]	**AGPSO1-PID**	**AGPSO2-PID**	**AGPSO3-PID**
Permeate flow rate (m^3/h)	IAE	93.37	72.16	74.29	**71.25**
	ISE	4792.00	4441.00	4352.00	**4347.00**
	ITAE	154.30	91.29	98.86	**90.90**
Permeate *pH*	IAE	5.66	7.61	6.68	**5.52**
	ISE	18.00	24.68	22.37	**17.92**
	ITAE	**16.52**	42.83	38.54	25.82

design [39]. Some fruitful comparative findings are listed as follows:

(1) The AGPSO3-PID achieved the minimum objective function value ($J_{\text{ITAE}} = 19.303$) than the IGWO-PID (84.810) [39] and other versions of AGPSO PIDs ($J_{\text{ITAE}} = 20.305$ for AGPSO1-PID and $J_{\text{ITAE}} = 21.105$ for AGPSO2-PID) (Table 3).

(2) The AGPSO-PD2 and AGPSO3-PID recorded a shorter settling time $\{(t_s = 2.740)$ and $(t_s = 4.024)\}$ compared to the existing IGWO-PID $\{(t_s = 8.030)$ and $(t_s = 4.048)\}$ for permeate flow rate (m^3/h) and *pH*, respectively.

(3) The AGPSO-PID achieved minimum errors for IAE, ISE, and ITAE than the existing IGWO-PID in the mostly cases. (Table 5).

(4) The AGPSO-PID also achieved minimum errors for IAE, ISE, and ITAE than the existing IGWO-PID in the mostly cases with disturbances. (Table 6).

(5) The proposed AGPSO1-3 PID performs better than the existing IGWO-PID control design for disturbances made in permeate flow rate (m^3/h) and *pH* measurements.

VI. CONCLUSION

In this work, the modified particle swarm optimization (PSO) technique called autonomous groups PSO (AGPSO) was used to tune the proportional integral derivative (PID) controller of the two-input two-output (TITO) reverse osmosis (RO) desalination plant. The plant's permeate flow rate (m^3/h) and the *pH* have been considered for the analysis. At the same time, three versions of the AGPSO algorithm with different updating formula have been employed to tune PID (AGPSO1-PID, AGPSO2-PID, and AGPSO3-PID) for a deeper investigation. The simulation results show that the proposed controller designs perform better than the existing IGWO-PID in terms of responses to disturbances. The proposed AGPSO3-PID achieved a minimum value of objective function ($J_{\text{ITAE}} = 19.30$) than that from the earlier proposed IGWO-PID ($J_{\text{ITAE}} = 84.81$) and other versions of AGPSO2-PID ($J_{\text{ITAE}} = 20.30$) and AGPSO3-PID ($J_{\text{ITAE}} = 21.10$). In addition, the AGPSO3-PID recorded a shorter settling time $\{(t_s = 2.740\text{ s})$ and $(t_s = 4.024\text{ s})\}$ compared to the existing IGWO-PID $\{(t_s = 8.030\text{ s})$ and $(t_s = 4.048\text{ s})\}$ for permeate flow rate (m^3/h) and *pH*, respectively. Thus, we summarised that the proposed controllers are more flexible and provide faster servo tracking and disturbance rejection without offset and are most suitable for the TITO RO desalination plant.

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