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Non integer order PID controller tuning using grey wolf optimization method for Sea Water Reverse Osmosis Desalination process

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Abstract

The optimal integer order and fractional order controller setting are designed for the Sea Water Reverse Osmosis Desalination plant model. The Controller settings are tuned using the grey wolf optimization method to minimize the time absolute integrated error values. The interaction measures are analyzed for the design of pairing in the multiloop controller settings. The comparative simulation response are demonstrated between the integer order PID and non integer order PID controller. The simulation results show the improvement of closed loop performance with the non integer order controller settings. It is observed that Improved grey wolf optimization based FOPID provides slightly improved performance in the controller tuning compared to PID controller.
Keywords—*desalination; multiloop control; non integer order PID control, grey wolf optimization.*

I. INTRODUCTION

With the expanding shortage of regular freshwater sources, a higher measure of vitality is expected to give clean water from elective sources. Seawater is one of the developing non-conventional water hotspots for human use. The necessity of generating fresh water can be achieved by computerizing the desalination plants. Numerous strategies have been utilized for desalination, however turn around assimilation is spotlight procedures in light of low energy requirement, simple design and low water creation cost [1].The reverse osmosis process is progressively response to change in load contribution just as the working conditions. So it is important to keep up the working condition and liquid progression of the procedure in as far as possible control limit [2][3][4].The profitability of reverse osmosis can be improved by legitimate controlling strategies. Many control procedures have been actualized in the reverse osmosis process, yet multi-loop control scheme is preferable for industrial process for easy implementation and failure tolerance [5][6].

The multiloop controller design is challenging becomes of the coupled interaction effect. The multiloop control scheme such as detuning, sequential loop closing, relay auto tuning, decoupled based design methods are mostly used design procedures. Designs of PID controller have analytical methods with potential results in the literature. But, non-integer order PID controller is marginally studied and implemented. Vinoth Kumar (2019) introduced fractional order PID (FOPID) controller for fractional order system [7]. Shalini et. al (2019) investigated the new meaning of integral and derivative actions, and gains, resulting by the concern of non-integer integration and differentiation orders. [8] Fabrizio Padula and Antonio Visioli (2011) developed tuning policy of Integer and non integer order PID controller in order to minimize the Integral Absolute Error (IAE) with constraint on maximum sensitivity [9]. Recently, the evolutionary optimization techniques have been widely used in all kinds of control engineering problems to find the optimal controller parameter. May different optimization methods are applied in the controller tuning problems. Lakshmanaprabu et al (2019) proposed the designing procedure for the multi-loop PID and non-integer order

PID controller using optimization techniques such as genetic algorithm, cuckoo search algorithm and bat optimization algorithm. [10],[11][12],[13]. Numerous engineering requirements will have several local optimum and one global optimum result. Recently, The Grey Wolf Optimization Algorithm (GWOA) is extensively used in many engineering, nonlinear, multimodal problems [14][15]. Mirjalili, S et.al (2014) proposed GWOA which is inspired from the hunting strategies of wolf [16]. The algorithm is uncomplicated to implement and flexible to work out many complex problems.

II. PROCESS DESCRIPTION

The sea water reverse osmosis desalination process is illustrated in the figure 1. The sea water is pumped up to the pre processing units to remove the big sized particles from the sea water. Then TDS of the sea water must be removed to produce fresh water. This can be done using the semi-permeable membrane which allows only the water molecules and restrict the other particles. The osmotic pressure across the membrane is very important to obstacle to the desalination process. The high pressure pump is used to overcome the restriction due to the osmotic pressure. The output of the fresh water ph values has to be maintained with any control system. Also the input feed of water to the RO can be controlled such that to increase the efficiency of the fresh product outcome.

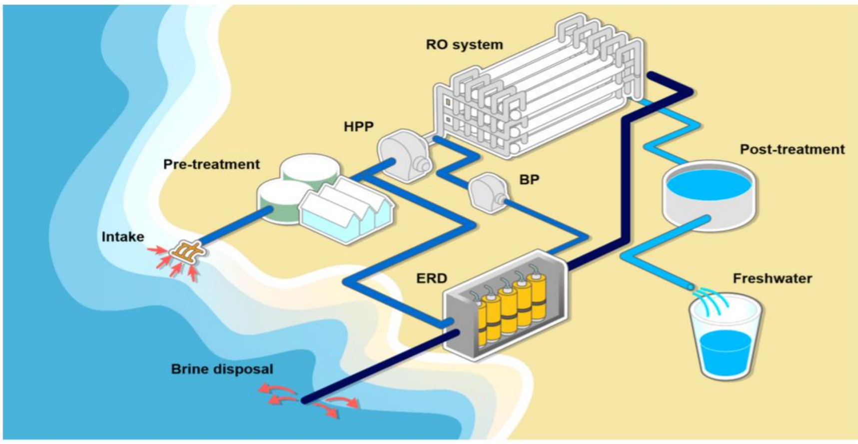

Figure 1. Sea Water Reverse Osmosis Desalination Process **[17]**

The desalination system contains of equalization tank and reverse osmosis membrane and collection tank. Membrane was used for the purification of the sea water with the support of pumps and filter. The pump pressure and reverse ratio are the input for the RO plant which can be varied to get the final fresh water as the product optimally.

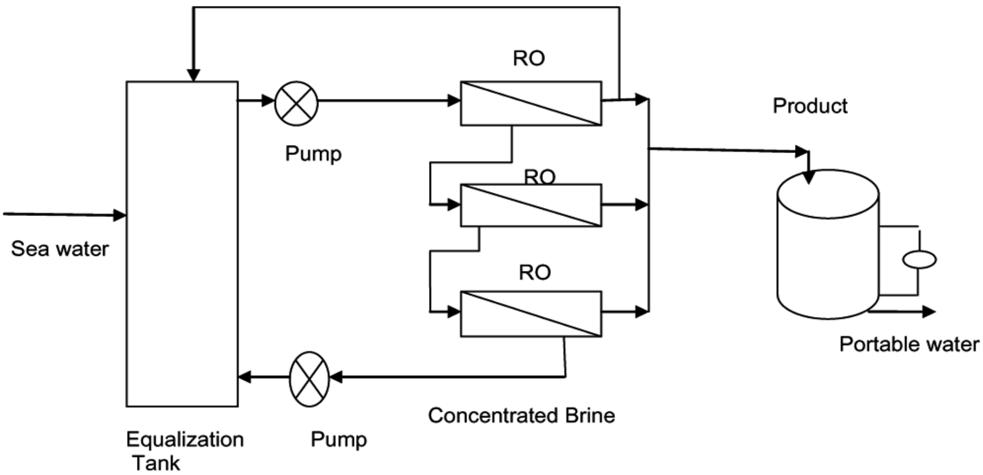

Fig.2. Schematic diagram of Reverse osmosis process

The first principle model is developed for sea water reverse osmosis system. Sobana and panda identified the multivariable model is with the real time data of RO plant is used in the paper for design of controller [2][3].

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The linear state model is obtained for the operating region and given in the equation 1. The transfer function for feed tank, brine tank, permeate tank also modelled and the higher order process is converted into reduced order transfer function model. Here, two input two output is consider for controller design. The inputs for the system are pump pressure and ratio of flow rates of seawater feed to that of brine stream. The output of the process are permeate flow rate and permeate pH.

$$\begin{bmatrix} F_p \\ pH_p \end{bmatrix} = \begin{bmatrix} \frac{1.4944e^{-0.55s}}{0.71615s+1} & \frac{0.092857e^{-0.3666s}}{1.1875s+1} \\ \frac{0.114411e^{-0.55s}}{7s+1} & \frac{0.1781e^{-0.15s}}{2.5s+1} \end{bmatrix} \begin{bmatrix} \Delta P \\ R_{FB} \end{bmatrix}$$

III. MULTI-LOOP CONTROLLER DESIGN

The multiloop Control scheme of Two Input Two Output system is shown in the figure 3. The $G_{11}(s)$, $G_{12}(s)$, $G_{21}(s)$ and $G_{22}(s)$ are the process transfer function model. The controller transfer function is denoted by the $g_{c1}(s)$ and $g_{c2}(s)$. Multiloop controller is easy to implement and the failure tolerance of the closed loop will be good. The controller needs to take of interaction as well as other disturbances. Then the controller is tuned using single loop transfer function without taking into account of interaction effect. At last, the detuned factor is tuned to design a controller to balance the interaction effect of other loops.

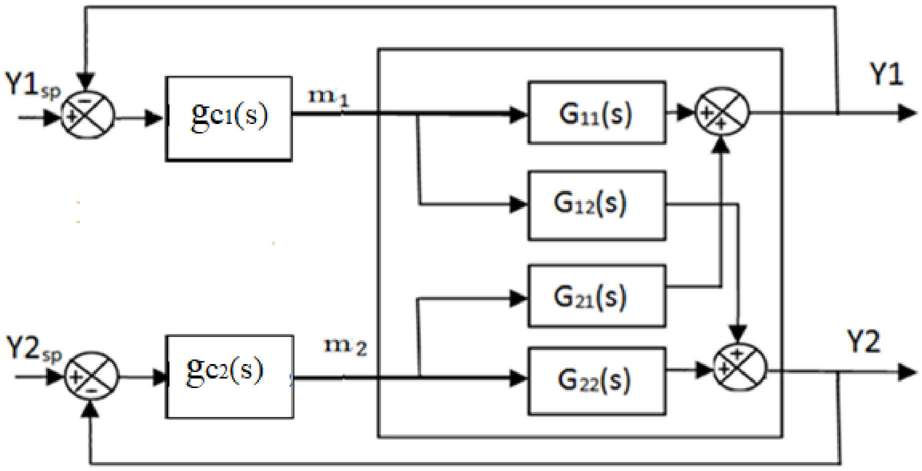

Fig.3 Multiloop control scheme

The structure of TITO Process is G(s) represented in equation 1,

$$G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{1}$$

The multiloop FOPID controller Gc(s) is,

$$G_c(s) = \begin{bmatrix} g_{c1}(s) & 0 \\ 0 & g_{c2}(s) \end{bmatrix} \tag{2}$$

The multiloop FOPID controller can be expressed as,

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$$G_c(s) = \begin{bmatrix} K_{p1} + \frac{K_{i1}}{s} + K_{d1}s & 0 \\ 0 & K_{p2} + \frac{K_{i2}}{s} + K_{d2}s \end{bmatrix} \quad (3)$$

where Kp_1 and Kp_2 are the proportional gains, K_{i1} and K_{i2} are the integral gain, K_{d1} and K_{d2} are the derivative gain, λ_1 and λ_2 are the order of integrator, μ_1 and μ_2 are the order of differentiator.

$$G_c(s) = \begin{bmatrix} K_{p1} + \frac{K_{i1}}{s^{\lambda_1}} + K_{d1}s^{\mu_1} & 0 \\ 0 & K_{p2} + \frac{K_{i2}}{s^{\lambda_2}} + K_{d2}s^{\mu_2} \end{bmatrix} \quad (4)$$

$G_c(s)$ is the control law of multivariable FOPID controller, where K_{p1} , K_{p2} are the proportional gains, k_{i1}, k_{i2} are the integral gains, k_{d1}, k_{d2} are the derivative gains, λ_1, λ_2 are the integrator order and μ_1, μ_2 are the derivative orders of multiloop FOPID controller.

The tuning of multiloop controller is difficult because of the interaction effect. Many controller tuning procedure have been proposed in the literature. The single loop controller is easy for PID controller. Many tuning algorithm is available in the literature. But , design of non integer order PID controller is difficult due to the additional two parameters called integrator order and differentiator order parameter.

The tuning of FOPID controller parameters using optimization techniques are depends on the selection of objective function for controller tuning. The different kind of objective function gives different values of FOPID controller parameters. The ITAE based indices provide better controller with faster servo tracking and disturbance rejection without offset. The main reason for selection of ITAE for the FOPID controller design is that the order of integrator produce offset for a long time. Hence, the ITAE is utilized for providing more penalties to the offset error. TheITAE is a better performance indicator of the closed loop control scheme where overshoot, setting time, rise time, offset are considered. Therefore, the ITAE is used as the objective function of multiloop FOPID controller design. The controller with small values of ITAE considered as best controller for system and also it indicates that the controller response is fast.

In this study, multi objective optimization problem is converted into the single objective control problem by assigning proper weightage to sub objective function.

The objective function for controller design problem is formulated and the constraint bounds are given below,

$$J = \int_0^T \left[w_1.t \left|e_1(t)\right| + w_2.t \left|e_2(t)\right| \right] dt$$

Minimize J, subject to
$k_{p_1}^{\min} \le k_{p_1} \le k_{p_1}^{\max}; k_{i_1}^{\min} \le k_{i_1} \le k_{i_1}^{\max}; k_{d_1}^{\min} \le k_{d_1} \le k_{d_1}^{\max}; \lambda_1^{\min} \le \lambda_1 \le \lambda_1^{\max}; \mu_1^{\min} \le \mu_1 \le \mu_1^{\max}; k_{p_2}^{\min} \le k_{p_2} \le k_{p_2}^{\max};$
$k_{i_2}^{\min} \le k_{i_2} \le k_{i_2}^{\max}; k_{d_2}^{\min} \le k_{d_2} \le k_{d_2}^{\max}; \lambda_2^{\min} \le \lambda_2 \le \lambda_2^{\max}; \mu_2^{\min} \le \mu_2 \le \mu_2^{\max}$; where the simulation is run from time $t=0$ to T; w_1, w_2 are the weight to each loop objective function which is fixed with same weightage 0.5. The lower and upper bound of controller parameters kp_1, k_{i1}, λ_1, k_{d1}, μ_1, kp_2, k_{i2}, λ_2, k_{d2}, μ_2 are fixed based on the initial guess.

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IV. IMPROVED GREY WOFL OPTIMIZATION ALGORITHM

GWO algorithm is developed by Mirjalili et al., [4] in 2014, stimulated from the hunting behavior of grey wolves. Grey wolves live in group and hunt food with their group with some unique roles and responsibilities. Each have to follow the social hierarchy and social dominants. The top level wolves are named as Alpha types which decide the main strategy of hunting similar to the functionality as a manager. Next level will be beta type wolves which follows the leader also support the decision making. These beta wolves are kind of assistant managers. Next level wolves are the Delta wolves which needs the submit reports to alpha and beta. The Delta wolves dominate the omega wolves because of the social hierarchy. These Delta type wolves have different team with different functionality such as Scouts, Sentinels, elders, hunders and caretakers. The Scouts wolf responsible for watching the boundaries of the territory and warning the team in the emergency conditions. The sentinels type wolf responsible for protecting the team. The elder type of wolves are experienced who might be in the team of alpha and beta. The hunters type wolves responsibility is to for helping alpha and beta while hunting. The caretakers are similar to doctors who are the responsible for carrying the ill, weak and wounded wolves. The fourth level is the lowest level is called omega type wolves are considered as a scapegoat in the team. This type does not have important responsibilities. Figure 4 illustrates the different stage of hunting. The flow chart of grey wolf optimization algorithm is shown in figure 6.

Figure 4 Hunting behavior: (A) chasing prey, (B–D) pursuing, harassing, and encircling, (E) attack

In the wolf optimization algorithm, the hunting is supervised by the alpha beta and gamma. The omega type follows these three wolves.

$$\vec{D} = |\vec{C}.\overrightarrow{X_p}(k) - \vec{X}(k)| \quad (6)$$

$$\vec{X}(k+1) = \overrightarrow{X_p}(k) - \vec{A}.\vec{D} \quad (7)$$

Where k specify the current round, $\vec{A}$ and $\vec{C}$ are coefficient vectors, position vector of the prey is denoted as is the position vector, || is the absolute value and (.) is an element by element multiplication. The vectors A and C are determined as:

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (8)$$

$$\vec{C} = 2.\vec{r} \quad (9)$$

The grey wolf hunts with random values in the initial stage. After the first iteration of the optimization the values will be updated based on the objective function i.e, food location. The minimum distance between the wolves and hunting space is considered as the beta wolf. The hunting strategy is given shown in the equation.

$$\vec{D}_\alpha = |\vec{C}_1 * \vec{X}_\alpha - \vec{X}|$$
$$\vec{D}_\beta = |\vec{C}_2 * \vec{X}_\beta - \vec{X}|$$
$$\vec{D}_\delta = |\vec{C}_1 * \vec{X}_\delta - \vec{X}| \quad (10)$$

Where D ⃗_α , D ⃗_β , and D ⃗_δ are the modified space vector among the α, β and γ location to the other wolves.

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 * \vec{D}_\alpha$$
$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 * \vec{D}_\beta$$
$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 * \vec{D}_\delta \quad (11)$$

where X ⃗_1 is an reached fresh location vector by the use of α position X ⃗_α and distance vector D ⃗_α. A_1, A_2 and A_3 are three coefficient vectors determined.

$$\vec{X}(k+1) = \frac{\sum_{i=1}^{n} \vec{X}_i}{n} \quad (12)$$

where $\vec{X}(k+1)$ is new finalized new position vector is determined by the average total of all positions attained by the use of α, β and δ (n=3).

The bacterial foraging mechanisms utilized in the grey wolf algorithm for an enhancement of searching performance. The fresh positions are found by the use bacterial foraging algorithm (BFO)[19]. In the IGWO algorithm, the grey wolves follow the chemotactic progress of bacterium as equated in Eq. (7)

$$x_i^t = x_i^{t-1} + \vec{X}(k+1)\frac{\Delta_i}{\sqrt{\Delta_i^T \times \Delta_i}} \quad (13)$$

Where $\vec{X}(k+1)$the new finalized position vector is computed from Eq. (8), and Δ_i is the randomly generated values from -1 to +1.

The flow chart of gray wolf optimization is shown in the figure. The integer and non-integer PID controller parameter are tuning to get optimum hunting location. (i.e. Integral Time Absolute Error). The Kp, Ki , Ki , order of integrator and differentiator are updated by the alpha, beta and gamma wolves. The multiloop non-integer order tuning strategy is illustrated in the figure 6.

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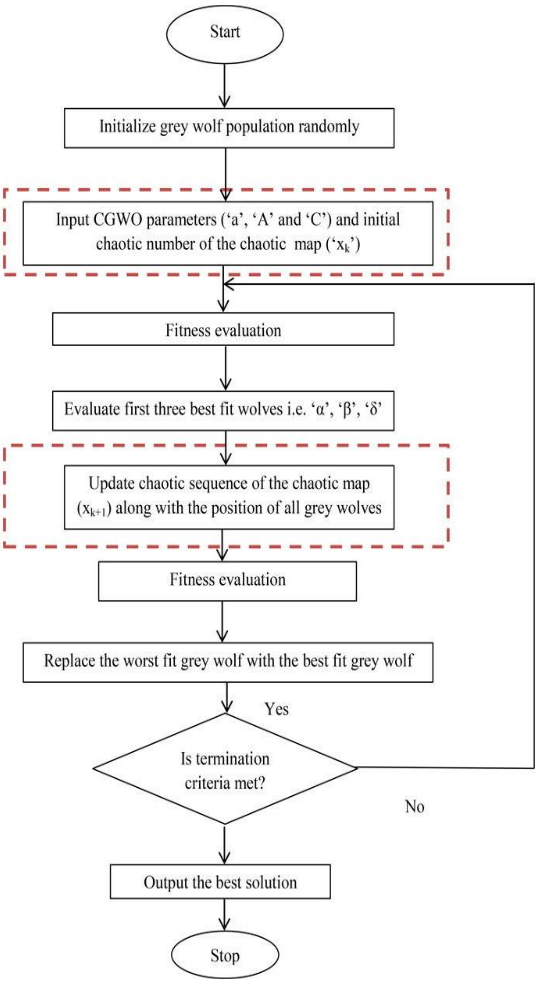

Figure 5. Gray wolf Optimization Algorithm [14]

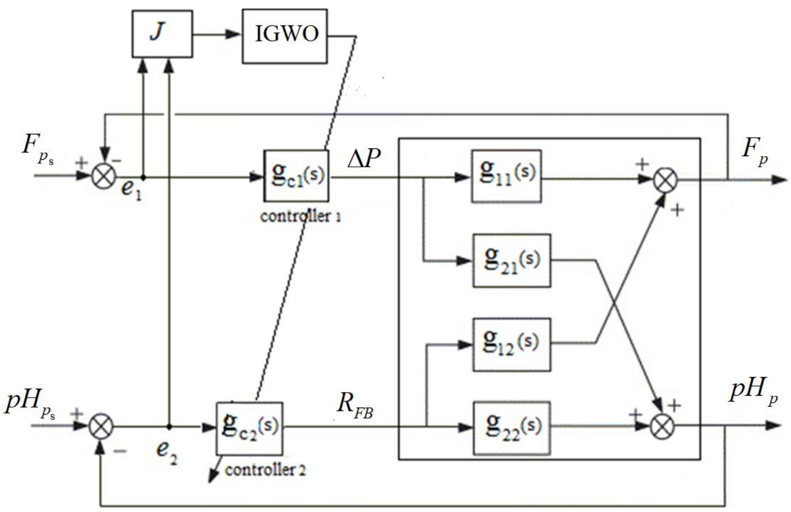

Fig 6. The Improved GWOA based Multiloop non-integer order PID controller tuning.

Table 1 The optimal multiloop PID and FOPID controller values based on ITAE

		K_p	K_i	λ	K_d	μ	J
PID(IGWO)	Loop1	0.52	0.83	-	0.104	-	84.81
	Loop2	22.43	9.3	-	0.35	-	
FOPID(IGWO)	Loop1	0.76	0.681	1.0015	0.0055	0.96	76.52
	Loop2	22	8.3	1.002	0.6	0.0540	

V. RESULT AND ANALYSIS

The closed loop servo and regulatory response of RO desalination process with multiloop controller is shown in figure 7 and 8. The closed loop RO desalination system is simulated for the set point change in flow rate (80 m3/h) and pH (7.0). Fig.6 shows how the output flow rate and pH values track the set points using integer order PID and non-integer order PID control. The non integer order PID control tracks the setpoint faster than the integer order PID control with lesser overshoot. The settling time also less for the non-integer order control which is tabulated in the Table 2. The reference point of flow rate also affects the pH value. The controller regulating the disturbance due to the flow rate changes. The servo regulator response of multiloop integer and non integer order PID control is shown in the figure. 7. The loop2 non integer order control regulates faster than the integer order PID controller. It is clearly seen from the table 2 is that, the performance index such as Integrated Absolute Value (IAE), Integrated Square Error (ISE) and Integrated Time Absolute Error (ITAE) is lesser for the non-integer order controller.

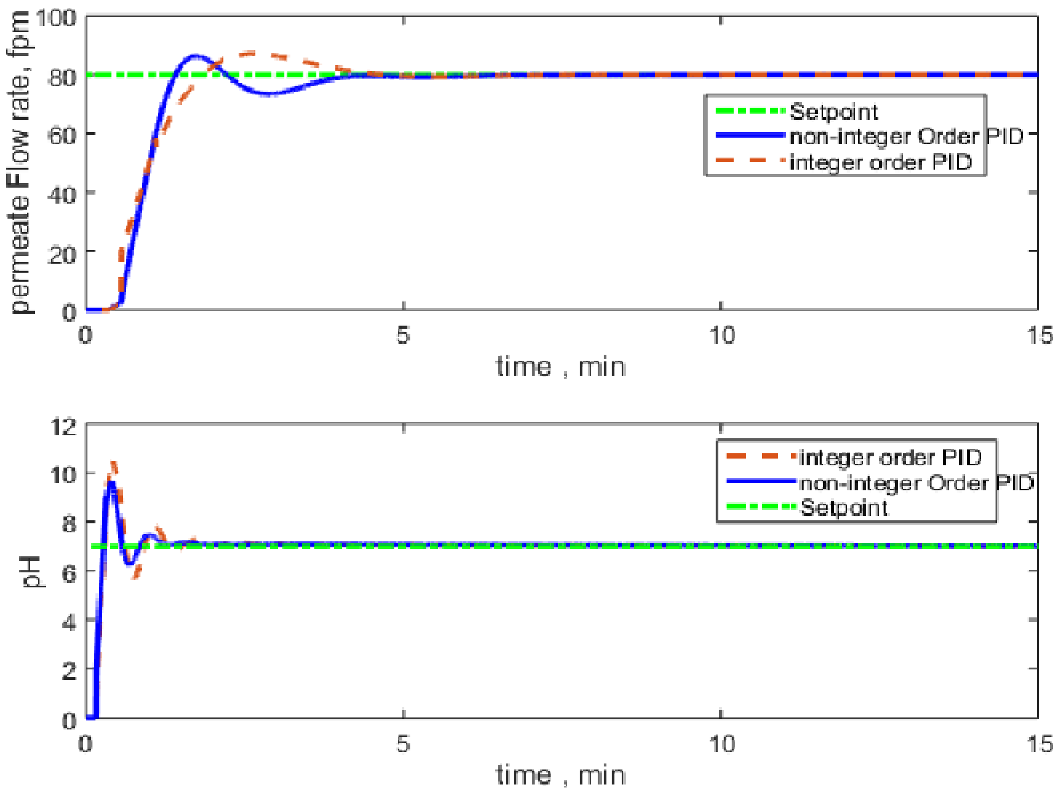

Fig.7. Servo response of multiloop IMC-PID controller

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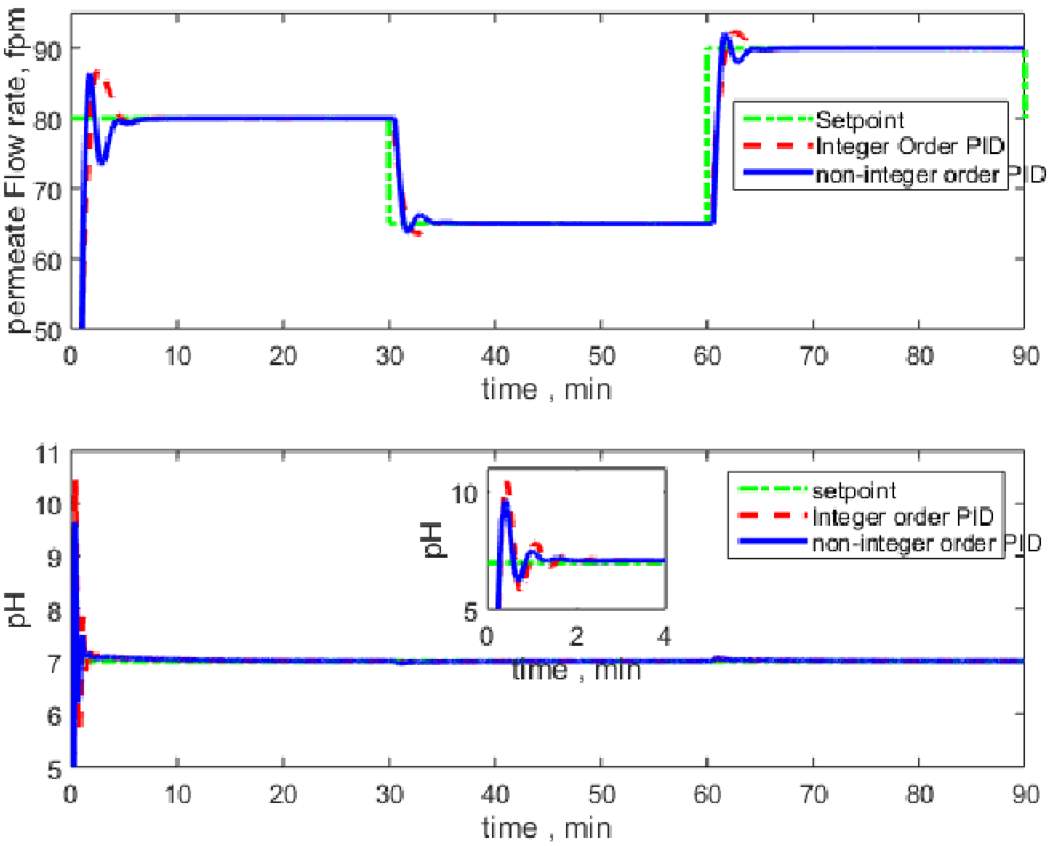

Fig.8. Servo and regulatory response of multiloop IMC-PID controller

TABLE.II
CLOSED LOOP PERFORMANCE (IAE, ISE,ITAE) OF DESALINATION PROCESS USING IMC-PI FOR DIFFERENT FILTER VALUES.

		PID (IGWO)	Non-integer order PID(IGWO)
LOOP1	IAE	86.8	84.59
	ISE	5701.2	4961.4
	ITAE	80.15	71.79
	Settling time	8.03 minutes	6.42 minutes
LOOP2	IAE	11.36	2.834
	ISE	19.94	10.04
	ITAE	4.77	4.05
	Settling time	2.87 minutes	2.24 minutes

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VI. CONCLUSION

The fractional order controller setting is designed for the sea water desalination plant. The transfer function was used as the plant model, the multiloop controller pairing is designed with the relation gain array method. The controller tuning parameters are tuned using IGWO algorithm with the time absolute integral error as an objective function. The closed loop simulation studies are carried out to obtain the output responses and the corresponding ITAE, IAE and ISE values. The qualitative and quantitative comparison of the closed loop simulation studies conducted by adjusting reference set point values. The simulation results clearly shows

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that the non integer order PID controller performance was better than the integer order PID controller. But, the important inference is that, the order of integrator for the non-integer order control is approximately equals to 1. This shows that order of integrator perform better when it is integer order equal to 1. The order of differentiator play important role in the enhancement of non-integer PID control performance. It is concluded that non-integer order control can perform better than integer order control but optimal integrator order is around 1.

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