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SCIENTIFIC PAPER

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pH CONTROL IN SODIUM CHLORATE CELL FOR ENERGY EFFICIENCY USING PSO-FOPID CONTROLLER

Article Highlights

- FOPID pH controller for energy efficiency in Sodium chlorate process
- Flexible, less time of computation, less parameter adjustment
- Can be utilized in the future for optimization of pH in sodium chlorate cell

Abstract

Industrial sodium chlorate production is a highly energy-intensive electrochemical process. If the pH of the chlorate cell is not controlled, the current efficiency drops from 99% to as low as 66.66%. Hence control of chlorate cell pH is very significant for energy-efficient sodium chlorate production. This study puts forward a fractional order PID controller for controlling the pH of the sodium chlorate cell. The tuning of FOPID controller variables is affected by employing particle swarm optimization. The highlight of the controller is that it is flexible, easy to deploy, and the time of computation is significantly low as few parameters are needed to be adjusted in PSO. The performance analysis of the suggested FOPID-PSO controller was studied and compared with the traditional PI controller and PID controller using time-domain provisions like settling time, rise time and peak overshoot and error indicators like integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE). FOPID controller employing PSO proved to perform well compared to conventional controllers with 0.5 s settling time and 0.1 s rise time. Thus, the FOPID-PSO controller has better setpoint tracking, which is essential for the process under consideration.

Keywords: fractional order PID controller, sodium chlorate process, particle swarm optimization, pH control.

Industrial manufacturing of sodium chlorate is one of the fastest-growing and highly energy-intensive processes, where power consumption accounts for over 70% of the production costs. The growth of the sodium chlorate industry is promising since it is globally used to manufacture chlorine- based bleaching agents and perchlorates (used as rocket oxidizers), besides its use in agricultural applications and milling applications. Hence, there have been constant efforts to improve sodium chlorate production in terms of quantity and quality.

Industrial sodium chlorate production from hot acidulated brine involves an electrochemical process in an undivided electrochemical cell [1]. Hydrogen and chlorine are liberated at the cathode and anode, respectively. Hydrogen bubbles and chlorine dissolves in the bulk solution, giving hypochlorous acid. This weak acid disintegrates into hypochlorite ions, also known as active chlorine. The transformation of active chlorine to chlorate in the bulk involves intermediate reactions. The kinetics of this reaction depends on the pH and local concentration of active chlorine [1]. If pH is not controlled, secondary parallel reactions occur in the cell, leading to a significant loss in the current efficiency [2-5]. Hence, it is essential to control the pH of the cell bulk to improve the current efficiency and power consumption. Several approaches have been employed to improve cell efficiencies, such as using different cell

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designs, selecting anode, and cathodes, adding sodium dichromate, etc. [2,6-9]. So far, to our knowledge, no studies have been reported on improving cell efficiency by controlling the pH of the chlorate cell. This work utilizes a PSO-based fractional order PID controller to maintain the cell bulk pH, promote auto-oxidation reaction, and improve energy efficiency.

Fractional order calculus and fractional order control have a comprehensive prospectus in science and engineering due to well-developed and well-explained theory and the drastic development of computing facilities. Fractional calculus is an extended version of integer-order calculus. It deals with integral and differential operators having fractional order. Recently fractional calculus has been widely used as many real-world systems exhibit a memory effect best described using fractional-order dynamics. Many interests are shown in designing controllers for such fractional-order systems [10]. Various kinds of literature can be seen in the field of fractional control in the last decade by its suppleness to meet the needs of control applications. Many recent works of literature demonstrate that fractional-order controllers outperform their integer-order counterparts for many real-life engineering applications.

Among the real-world industrial controllers, 99% are PID (Proportional Integral Derivative) controllers. It owes its popularity to the simplicity of design, easy tuning procedures, and ease of use for the layman. Hence there has been continuous research on improving the robustness and performance of the PID controller. Fractional order PID controllers can be enhanced with non-integer integration and derivation parts. Podlubny [11] has described the fractional order PID controller as an extended version of a conventional PID controller from point to the plane. The proposed $P I^{\lambda} D^{\mu}$ controller, where λ and μ have non-integer values giving more flexibility in controller design as well as better performance of controller compared to conventional PID controller. Recently, Puchalski *et al.* [12] have proposed a fuzzy fractional order PID controller to control the average thermal power of a nuclear reactor. In this work, the performance indices, like ISE, IAE, ITAE of the FMR FOPID, are compared with FOPID and conventional PID controller for robustness and smooth control signal. Rajesh [13] developed a FOPID controller for a single conical tank, a classical nonlinear problem. It proves the advantage of FOPID over conventional controllers in terms of better setpoint tracking and a smoother control signal for a nonlinear system. Tong *et al.* [14] proposed a state transition algorithm to address the optimization challenges in the design of the FOPID controller for the pH neutralization process. Recent literature shows a wide application of the fractional PID controller for various engineering fields [15-23]. All these prove undoubtedly that the FOPID controller is superior to its integer counterparts in terms of performance. Moreover, the flexibility to handle uncertainties and sudden changes in the control signal makes the FOPID concept a part of a more advanced control strategy [15,16,24-29].

The design and tuning procedures of the FOPID controller are complex compared to the conventional PID controller as two additional design parameters are involved. However, it is evident from recent literature that using an optimization algorithm is a perfect solution for the design problem [17,18,27,31-38]. Even though there have been many bioinspired algorithms, particle swarm optimization (PSO) algorithms are widely used because of their simplicity, flexibility for modification, and a smaller number of parameters for adjustment. PSO algorithm mimics the natural social behavior of a school of fish or swarm of birds or insects searching for food or location for migration. The individual learning of each team member is communicated with other members, and if anyone member finds food or location, then others in the team will follow the path quickly. This phenomenon is used for finding the optimum position for the particle. In this study, the design parameters of the FOPID controller are optimized by utilizing PSO. To tune the design variables of the FOPID controller, the performance indicator chosen is a weighted sum of integral square error (ISE), Integral absolute error (IAE), and Integral Time Absolute Error (ITAE). In addition, the time-domain variables, like settling time, rise time, and peak overshoot, are compared with those of conventional PI and PID controllers based on PSO to evaluate the performance of the proposed controller. The highlight of this proposed PSO-based FOPID controller is its flexibility and ease of implementation. This study can help implement online controllers for the industrial sodium chlorate process. Furthermore, it will lead to cost-effective and energy-efficient sodium chlorate technology development by improving cell efficiency and minimizing production costs.

The rest of this paper is framed in the following manner. In Section 2, the industrial sodium chlorate production process and the significance of pH for it are briefly explained. In Section 3, the Fractional PID controller is described. Section 4 elaborates on the PSO optimization. In Section 5, the tuning of the FOPID controller utilizing the PSO algorithm and the performances of PI, PID, and FOPID controllers are compared. Finally, in Section 6, the results are evaluated, and conclusions are drawn.

Industrial sodium chlorate manufacturing process

The industrial sodium chlorate process is an electrochemical process that involves high energy consumption. The global production rate of sodium chlorate is 3.6 million tons annually [39]. It is estimated that 5000-6000 kWh energy is required to produce a ton of sodium chlorate crystal [40]. This power consumption amounts to over 70% of the production costs. Hence, any means for improving efficiency will be beneficial from the economic and environmental points of view. The industrial process flow is given in figure1. This paper focuses on controlling the process taking place in the electrochemical cell. As per the equation, sodium chlorate is produced by electrolyzing hot acidulated brine [39]. The overall reaction is given by equation (1) [39].

$$NaCl + 3H_2O \rightarrow NaClO_3 + 3H_2 \quad (1)$$

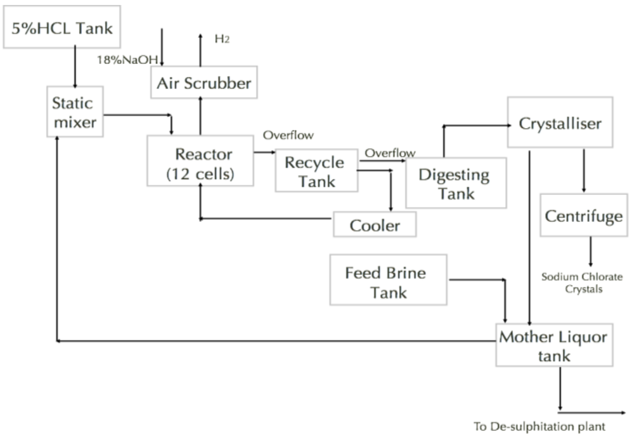

Figure 1. Block schematic of industrial sodium chlorate production plant.

The quantity and quality of the final product depend on various conditions prevailing in the electrochemical cell, especially the pH of the electrolyte bulk. Various studies on these aspects are available in the literature [6,39,41].

The primary reaction inside the cell is the liberation of chloride and hydrogen ions. The reduction at cathode releases H_2, and oxidation at anode release chlorine. The liberated hydrogen gas bubbles set up a circulation of the liquid electrolyte through the gap between the electrodes in the cell, leading to natural stirring action. As a result, chlorine gas formed dissolves in the bulk solution, giving hypochlorous acid, which partially disintegrates to form hypochlorite ions, otherwise called active chlorine. The kinetics of the transformation of active chlorine to chlorate in the bulk depends on the pH and local concentration of active chlorine [1]. If the pH of the electrolyte is congenial, i.e., pH value lies in the range 5.9 to 6, chlorate formation takes place by auto-oxidation with maximum energy efficiency:

$$2HClO + ClO^- \rightarrow ClO_3^- + 2H^+ + 2Cl^- \quad (2)$$

This reaction is not immediate, so if pH is not controlled, secondary reactions occur in the cell, leading to a significant loss in the current efficiency [2-5]. If the pH of the bulk is not in the required range, an undesirable parasitic reaction occurs, leading to anodic chlorate formation, and the cell efficiency can be as low as 66.66%. The reaction is given by equation (3) [39]:

$$ClO^- + 3H_2O \rightarrow 2ClO_3^- + 3O_2 + 6H^+ + 4Cl^- + 6e^- \quad (3)$$

Hence, control of the pH of the bulk is essential for energy efficiency and the quality of the product.

In this study, the control of the pH of bulk electrolyte is performed with the help of a FOPID controller tuned using particle swarm optimization for manipulating the NaOH flow rate.

The fundamentals of fractional-order proportional integral derivative controller (FOPID)

Fractional order PID controllers can be considered as improved PID controllers with non-integer integration and derivation parts. Fractional-order controllers were initially put forward by Igor Podlubny in 1997 and are denoted as $P\ I^{\lambda}D^{\mu}$, where λ and μ are non-integral orders. Figure 2 depicts the basis of the FOPID controller.

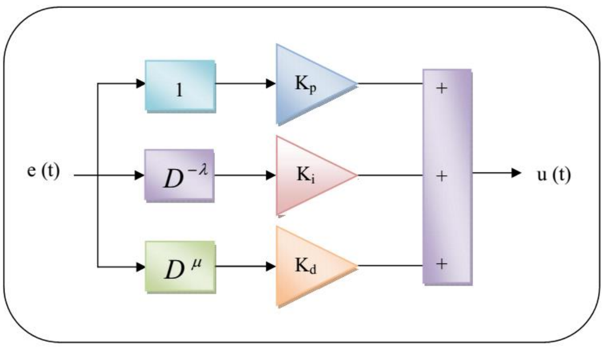

Figure 2. Block schematic of FOPID controller structure.

The fractional-order PID controller can be represented as:

$$G_{FOPID}(s) = \frac{u(s)}{e(s)} = K_C\left(1 + \frac{1}{T_i(s^{\lambda})} + T_d(s^{\mu})\right) \quad (4)$$

where λ and μ are real numbers, K_c is the gain, T_i is the integration constant and T_d is the differentiation constant. If λ=0 and μ=0, it becomes a proportional (P) controller. If λ=0 and μ=1, it becomes a PD (proportional and derivative) controller. If λ=1 and μ=0, the controller becomes the PI (proportional and integral) controller. If λ=1 and μ=1, then it becomes PID (proportional integral and derivative) controller. The non-integer order gives two additional degrees of freedom to the controller and creates the chance to improve the performance of the conventional PID controllers.

The FOPID controller is a generalized version of the integer-order PID controller. The value of λ and μ expands the controller from a point to plane in λ and μ, thus providing more flexibility and accuracy in the PID controller design. The proper choice of the five parameters of the FOPID controller will offer better performance. Since more parameters are tuned, the associated optimization problem will also be problematic. In this paper, the optimization problem is tackled using the PSO algorithm.

Optimization using particle swarm algorithm (PSO)

Particle swarm optimization (PSO) was put forward by Kennedy and Eberhart [42]. PSO is a bio-inspired stochastic optimization algorithm that mimics the social behavior of a school of fish or a swarm of birds. The communication between the birds about the location of food or location for migration based on individual learning is utilized to find the optimum value in the search space. For example, if a flock of birds is seeking food in a territory, all the birds may not know the food location. Therefore, the best approach is to chase the bird closest to the food [43]. The potential solutions to the problem form the group or population in PSO. Each solution member is called a particle having a fitness value, assessed using the fitness function. Each particle has an associated position and velocity, which guides the progression of the particles. They move in the problem search space, track the present optimum particles to find the most appropriate solution, and then save it in the memory.

PSO has been proved helpful in optimizing various engineering applications, like power system problems, power converters, controller design, etc. [13,17,19,26,31,44,45]. It initializes the population of a random solution as in evolutionary computation methods and searches for the optimum solution by updating generations. However, unlike GA, PSO does not have evolution operators.

The popularity of PSO is due to its simplicity, ease of modification, and very few parameters for adjustment. As there are no crossover and mutation operators, PSO takes less computation time than a genetic algorithm and is easy to implement. In the present study, the PSO algorithm calculates the controller design parameters by minimizing the error performance index. The FOPID controller parameters K_c, T_i, T_d, λ, μ are considered as particles, and the search space is a five-dimension space bounded by the limits of these parameters. PSO is booted up with a potential population of these particles. It is updated in each iteration based on fitness value. In each iteration of PSO, each particle is updated with the best fitness value the particle has acquired thus far, known as p_{best}, and the best fitness value obtained as yet by any particle in the population known as g_{best}. After storing p_{best} and g_{best}, the position and velocity of the particle are revised. The steps of PSO are detailed below.

Step 1:

The PSO initializes the population, a set of random solutions in the D dimension space bounded by the upper and lower limit. The location of the particle '*i*' is characterized as:

$$X_i = (x_1, x_2, \ldots\ldots x_n) \quad (5)$$

where, X_i- locality of the particle.

The particle encompasses memory of the prior best position, depicted by the relation below:

$$P_i = (p_1, p_2, \ldots\ldots p_n) \quad (6)$$

where, P_i- the prior best position.

The velocity of the particle is presented as per the expression:

$$V_i = (v_1, v_2, \ldots\ldots v_n) \quad (7)$$

where, V_i - velocity of the particle.

Step 2: Utilizing the relative equation concerning the whole particle, compute fitness value

$$F_i = \min(J) \quad (8)$$

The best fitness value attained so far is chosen as the global best.

Step 3: If the fitness is superior to the earlier p_{best}, set the present values as the novel p_{best}. The new populations are approximated according to the PSO algorithm's two specifications.

$$v_i^{(n+1)} \succ v_m^{(n+1)},\ then\ v_i^{(n+1)} = v_m^{(n+1)} \quad (9)$$

Step 4: Step 3 and step 4 for the whole particles were performed, and select the best particle as the g_{best}.

The velocity and position of the particles in the population need to be updated. Each particle has data about the g_{best} and p_{best} and it tends to vary its location employing data such as the distance among the present position and p_{best}, the distance among the present position, and g_{best}. The updating of velocity and position of the particle is done as follows:

$$velocity_i = velocity^c + \alpha(p_{best} - pos^c) + \beta(g_{best} - pos^c) \quad (10)$$

$$V_i^{(n+1)} = V_i^{(i)} + l_1 \cdot r_1 \cdot (pb_i - p_i^{(i)}) + l_2 \cdot r_2 \cdot (gb_i - p_i^{(i)}) \quad (11)$$

$$x_i^{(i+1)} = x_i^{(i)} + V_i^{(i+1)} \quad (12)$$

Step 5: If the maximum iteration is not met, continue steps after the fitness function calculation.

Since the problem dimension is small, the number of maximum iterations is a good choice for stopping criteria, compared to other commonly used criteria, like the minimum value of cost function, the maximum number of function evaluation, maximum CPU time, etc. On the other hand, there is no improvement in fitness value after a certain fixed number of iterations, so metaheuristics need to be stopped after that many iterations. In Figure 3 flow chart of PSO is explained.

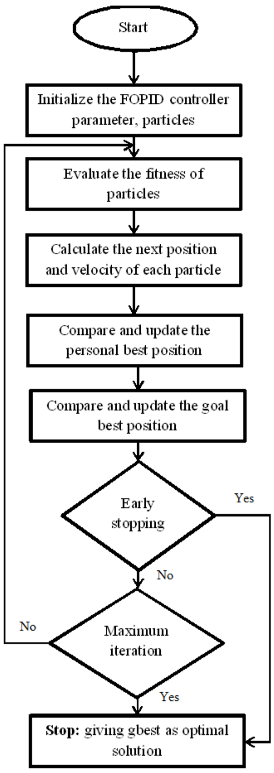

Figure 3. Flowchart of Proposed PSO algorithm.

Tuning of fopid controller for sodium chlorate cell using PSO algorithm

This paper proposes a FOPID controller to control pH in industrial sodium chlorate cells using the PSO algorithm. Figure 4 shows the proposed control strategy of the pH of chlorate cell bulk.

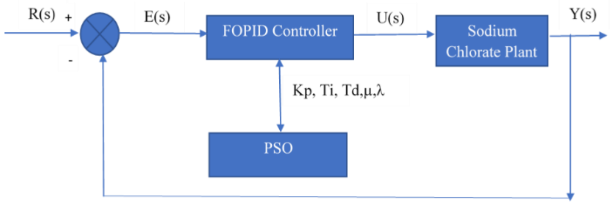

Figure 4. Schematic diagram of the suggested controller strategy.

PSO is utilized to find the optimal values of K_p, T_i, T_d, λ, and μ such that the controlled system exhibits the desired performance, evaluated using the performance specifications. These five parameters form a particle. The optimization using the PSO algorithm utilizes an objective function which is a weighted error performance indicator using the integral square error (ISE), the integral absolute error (IAE), and the integral time absolute error (ITAE). Even though the IAE and ISE indexes lead to a relatively minor overshoot, the settling time may be lengthy. This issue can be overcome by including the ITAE in the objective function. The weighting values are varied from 0 to 20, with a greater weighing for the ITAE. The following is the objective function for tuning of FOPID parameters:

$$J = w_1 ISE + w_2 IAE + w_3 ITAE \quad (13)$$

$$ISE = \int e(t)^2 dt \quad (14)$$

$$IAE = \int e(t) dt \quad (15)$$

$$ITAE = \int_0^T t\left|e(t)\right| dt \quad (16)$$

where *e(t)* is the error between the setpoint and output of the plant. The effectiveness of the suggested controller is assessed using the time-domain specifications like settling time, rise time, and peak overshoot and compared with traditional PI and PID controller tuned using PSO. The sodium chlorate cell model described in [46] is used in this paper. The model of the cell takes HCl flow rate, NaOH flow rate, electrolyte temperature, DC load current, and the pH of the feed as input to give the pH of the bulk electrolyte.

Simulation results

In this segment, the simulation details of the suggested FOPID controller and performance comparison with PI and PID controller are included. The MATLAB 2019b is employed to implement and test the proposed controller. The pH of the bulk should be regulated to 5.9-6.3 to improve the current efficiency of the cell and reduce power consumption. The proposed FOPID controller can be used for manipulating the

NaOH flow rate to maintain the pH of the bulk. Figure 5 presents the system in Simulink.

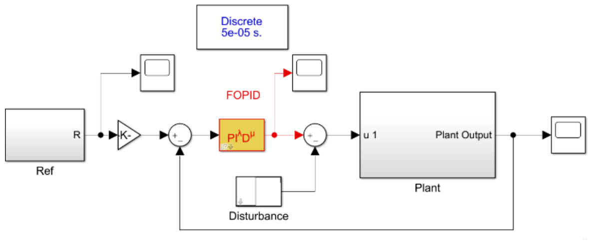

Figure 5. Simulink model of the proposed controller.

To optimally tune the FOPID controller employing the PSO algorithm, the FOPID variables bound are chosen, inspired from the practical requirements of the sodium chlorate plant, as $K_p \in [0, 60]$, $T_i \in [0, 15]$, $T_d \in [0, 40]$, $\lambda \in [0, 4]$, $\mu \in [0, 4]$. Table 1 lists the variables of the PSO algorithm.

Table 1. Variables of PSO Algorithm

Variables	Values used
Dimension	5
Population	100
Iterations	1000
c_1	1.5
c_2	2.0
Inertia weight	1

Figure 6 shows the pH value of cell bulk controlled using PI, PID, and FOPID-PSO controller. It is evident from the figure that the FOPID -PSO controller is capable of better regulation than the integral counterparts.

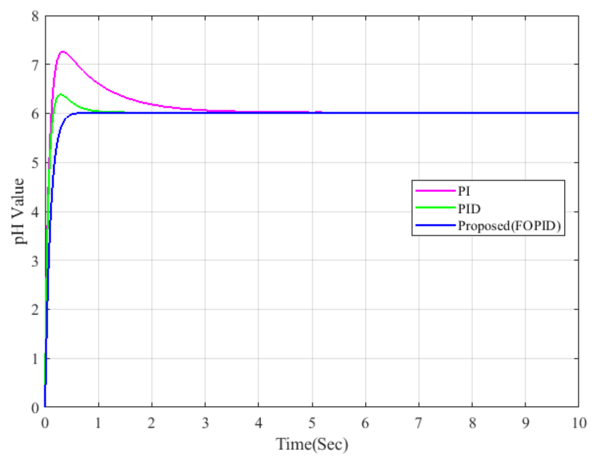

Figure 6. Performance comparison of different controller strategies for pH in sodium chlorate cell.

Table 2 reveals the values of time-domain performance indices and the error indicators of the system with PI, PID, and FOPID-PSO controllers, thus indicating that the FOPID-PSO controller gives superior performance compared to other control strategies. Figure 7 presents the bode diagram of the chlorate cell with the FOPID controller. The Bode plots are smooth, which is a pointer to the system's robustness. The comparison of the system's closed-loop performance for disturbance rejection is simulated using step changes in HCl flow rate. Figure. 8 shows that the setpoint tracking and settling ability of FOPID is better than other controllers. The figure also depicts the fact that the control signal is smoother in the case of FOPID. Table 3 gives the controller parameters obtained.

Table 2. Comparative analysis of the performance of different control strategies of pH of sodium chlorate cell bulk

Parameters	PI	PID	FOPID
IAE	0.8556	0.9076	0.8397
ISE	0.1755	0.1772	0.1743
ITAE	0.7591	0.9382	0.9027
Rise time (s)	0.05	0.03	0.01
Overshoot time (s)	0.45	0.8	-
Settling time (s)	4	1	0.5
J	1.0536	1.0644	1.01883

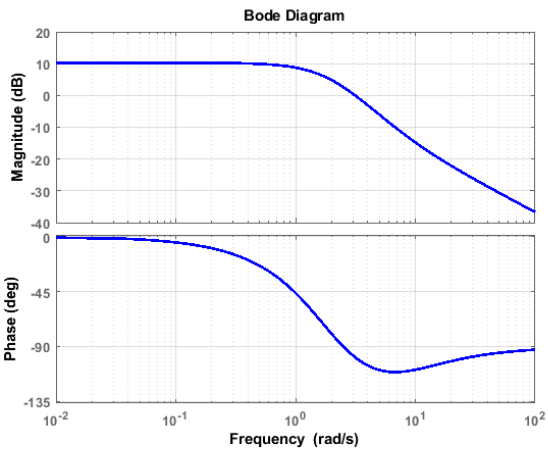

Figure 7. Bode diagram of chlorate cell model with FOPID controller.

The following conclusions are drawn, as it appears from the results obtained:

FOPID controller using PSO proved to have better control of the pH of chlorate cell than conventional controllers used in the plant concerning time-domain indicators, like peak overshoot, rise time, and settling

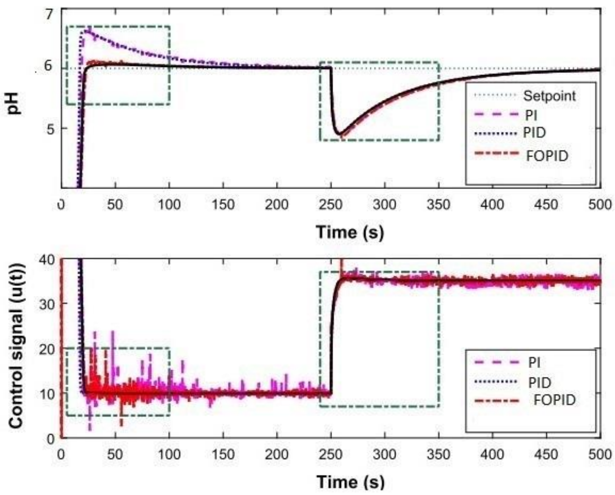

Figure 8. Comparison of controller performance for disturbance rejection.

Table 3. Controller parameters

Parameters	K_p	T_i	T_d	λ	μ
PI-PSO	1.3308	3.4222	0	1	0
PID-PSO	6.67134	7.50230	0.05440	1	1
FOPID-PSO	56.5	0.5	40	3.8336	1.1714

time, and error indicators, like ISE, IAE, and ITAE. For example, the PSO-based FOPID controller makes the plant settle in 0.5 s with a very low-rise time of 0.1 s. Also, the PSO-FOPID controller performance for disturbance rejection is better than PSO-PI and PSO-PID controllers.

The FOPID controller output is smooth to prevent the damage of delicate manipulating elements.

This work can facilitate achieving the maximum current efficiency of chlorate cells by favoring auto-oxidation and hence energy-efficient chlorate production. For future investigation, the proposed controller design can be used for inline control of cell pH, with online parameter updating

CONCLUSION

The pH of the sodium chlorate cell bulk is a key decisive factor for auto oxidation-based chlorate production in the cell, leading to maximum cell efficiency and thereby energy-efficient sodium chlorate production. Hence accurate pH control of sodium chlorate cell bulk is of utmost importance. In this study, a PSO-based FOPID controller for pH control in sodium chlorate cells has been investigated. The performance of the proposed FOPID controller using PSO was validated by comparing the time domain indices like settling time, rise time and peak overshoot and error indices like integral square error (ISE), integral absolute error (IAE), and integral time absolute error (ITAE) with the integer-order PI controller and PID controller. The motivation behind the controller design was the significance of the pH of cell bulk in improving the efficiency of sodium chlorate production. The highlight of the controller is that it is flexible, simple to realize, and the time of computation is minimal as few parameters need to be adjusted in PSO.

REFERENCES

[1] K. Viswanathan, J. Electrochem. Soc. 131 (1984) 1551.

[2] B. Endrődi, S. Sandin, V. Smulders, N. Simic, M. Wildlock, G. Mul, B.T. Mei, A. Cornell, J. Clean. Prod. 182 (2018) 529-537.

[3] G. Gordon, S. Tachlyashlki, Environ. Sci. Technol. 25 (1991) 468-474.

[4] M.M. Jaksic, J. Electrochem. Soc. 121 (1974) 70-79.

[5] Y.J. Jung, K.W. Baek, B.S. Oh, J.W. Kang, Water Res. 44 (2010) 5345-5355.

[6] L.R. Czarnetzki, N. Eindhoven University of Technology, Eindhoven, Doctoral T (1989) 154.

[7] L.R. Czarnetzki, L.J.J. Janssen, J. Appl. Electrochem. 22 (1992) 315-324.

[8] S. V. Evdokimov, Russ. J. Electrochem. 37 (2001) 786-791.

[9] J. Wulff, A. Cornell, J. Appl. Electrochem. 37 (2007) 181-186.

[10] A. Tepljakov, B.B. Alagoz, C. Yeroglu, E. Gonzalez, S.H. HosseinNia, E. Petlenkov, IFAC-PapersOnLine 51 (2018) 25-30.

[11] I. Podlubny, IEEE Trans. Automat. Contr. 44 (2002) 208-214.

[12] B. Puchalski, T.A. Rutkowski, K. Duzinkiewicz, ISA Trans. (2020).

[13] R. Rajesh, SN Appl. Sci. 1 (2019) 1-14.

[14] L.H. Tong, Y.G. Li, H.Q. Zhu, W.T. Li, IOP Conf. Ser. Earth Environ. Sci. 427 (2020) 12-26.

[15] M. Yaghi, M.O. Efe, IEEE Trans. Ind. Electron. 67 (2020) 4806-4814.

[16] E. Anbarasu, M.V. Pandian S, A.R. Basha, Microprocess. Microsyst. 74 (2020) 103030.

[17] N.M.H. Norsahperi, K.A. Danapalasingam, ISA Trans. 102 (2020) 230-244.

[18] A. Sikander, P. Thakur, R.C. Bansal, S. Rajasekar, Comput. Electr. Eng. 70 (2018) 261-274.

[19] F.A. Hasan, L.J. Rashad, Int. J. Power Electron. Drive Syst. 10 (2019) 1724-1733.

[20] S.K. Swain, D. Sain, S.K. Mishra, S. Ghosh, AEUE - Int. J. Electron. Commun. 78 (2017) 141-156.

[21] P. Roy, B.K. Roy, ISA Trans. 63 (2016) 365-376.

[22] I. Shivakoti, G. Kibria, P.M. Pradhan, B. Bahadur, A. Sharma, Mater. Manuf. Process. 00 (2018) 1-10.

[23] R. Ranganayakulu, G. Uday Bhaskar Babu, A. Seshagiri Rao, D.S. Patle, Resour. Technol. 2 (2016) S136-S152.

[24] M.-K. Salehtavazoei, Mohammad, IET Control Theory

Appl. 8 (2014) 319-329.

[25] T. Binazadeh, M.H. Shafiei, Mechatronics 23 (2013) 888-892.

[26] Y. Tang, X. Zhang, D. Zhang, G. Zhao, X. Guan, Neurocomputing 111 (2013) 122-130.

[27] M.P. Aghababa, Soft Comput. 20 (2016) 4055-4067.

[28] R. Sharma, K.P.S. Rana, V. Kumar, Expert Syst. Appl. 41 (2014) 4274-4289.

[29] H. Delavari, R. Ghaderi, A. Ranjbar, S. Momani, Commun. Nonlinear Sci. Numer. Simul. 15 (2010) 963-978.

[30] H. Delavari, R. Ghaderi, A. Ranjbar, S. Momani, Commun. Nonlinear Sci. Numer. Simul. 15 (2010) 963-978.

[31] R. Pradhan, S.K. Majhi, J.K. Pradhan, B.B. Pati, Ain Shams Eng. J. 11 (2019) 281-291.

[32] K. Bingi, R. Ibrahim, M.N. Karsiti, S.M. Hassan, Arab. J. Sci. Eng. 43 (2018) 2687-2701.

[33] A. Djari, T. Bouden, A. Boulkroune, Int. Conf. Syst. Control 1 (2013) 1-6.

[34] M.C. Heredia-Molinero, J. Sánchez-Prieto, J. V. Briongos, M.C. Palancar, J. Process Control 24 (2014) 1023-1037.

[35] S. Tufenkci, 2018 Int. Conf. Artif. Intell. Data Process. (2018) 1-6.

[36] S.K. Prince, K.P. Panda, V.N. Kumar, G. Panda, 2018 IEEMA Eng. Infin. Conf. ETechNxT 2018 (2018) 1-6.

[37] M. Zamani, M. Karimi-ghartemani, N. Sadati, M. Parniani, Control Eng. Pract. 17 (2009) 1380-1387.

[38] A. Kumar, V. Kumar, AEU - Int. J. Electron. Commun. 79 (2017) 219-233.

[39] K. Viswanathan, B. V. Tilak, J. Electrochem. Soc. 131 (1984) 1551-1559.

[40] R.K.B. Karlsson, A. Cornell, Chem. Rev. 116 (2016) 2982-3028.

[41] L.C. Adam, G. Gordon, Inorg. Chem. 38 (1999) 1299-1304.

[42] R. Eberhart, J. Kennedy, Proc. Int. Symp. Micro Mach. Hum. Sci. (1995) 39-43.

[43] N. Nalini, G. Raghavendra Rao, Inf. Sci. (Ny). 177 (2007) 2553-2569.

[44] L.T. Le, H. Nguyen, J. Dou, J. Zhou, Appl. Sci. 9 (2019) 1-23.

[45] I. Pan, S. Das, ISA Trans. 62 (2016) 19-29.

[46] S. Sreekumar, A. Kallingal, V. Mundakkal Lakshmanan, Chem. Eng. Commun. 208 (2021) 256-270.

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NAUČNI RAD

KONTROLA pH U NATRIJUM-HLORATNOJ ĆELIJI POMOĆU PSO-FOPID REGULATORA RADI POBOLJŠANJA ENERGETSKE EFIKASNOSTI

Industrijska proizvodnja natrijum hlorata je visoko energetski intenzivan elektrohemijski proces. Ako se pH hlaratne ćelije ne kontroliše, trenutna efikasnost pada sa 99% na čak 66,66%. Stoga je kontrola pH hlaratne ćelije veoma značajna za energetski efikasnu proizvodnju natrijum hlorata. Ova studija predlaže frakcioni PID regulator (FOPID) za kontrolu pH ćelije natrijum hlorata. Optimizacija rojem čestica (PSO) utiče na podešavanje varijabli FOPID regulatora. Ovaj regulator je fleksibilan, jednostavan za primenu i sa malim vremenom izračunavanja, jer je potrebno podešavanje nekoliko parametara optimaizacijom rojem čestica. Analizirane su performanse predloženog PSO-FOPID regulatora u poređenju sa tradicionalnim PI i PID regulatorima koristeći mere u vremenskom domenu, kao što su vreme poravnanja, vreme porasta i prekoračenje maksimuma, i indikatori greške, kao što su integralna kvadratna greška (ISE), integralna apsolutna greška (IAE), i apsolutnu grešku integralnog vremena (ITAE). FOPID regulator koji koristi PSO radi dobro u poređenju sa konvencionalnim regulatorima sa vremenom podešavanja od 0,5 s i vremenom porasta od 0,1 s. Dakle, FOPID-PSO regulator ima bolje praćenje zadate vrednosti, što je od suštinskog značaja za proces koji se razmatra.

Ključne reči: frakcioni PID regulatorr, natrijum-hlorat, optimizacija rojem čestica, pH kontrola.