

DYNAMIC PERFORMANCE ENHANCEMENT OF PEM FUEL CELL USING PSO OPTIMIZED FRACTIONAL ORDER PI CONTROLLER

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Abstract

This study presents the designing of conventional PI, FOPI, Particle-Swarm-Optimization (PSO) algorithm optimized PI and FOPI control schemes for the performance enhancement of PEMFC system. The PSO artificial intelligence technique searches for optimal PI and FOPI parameters intelligently. The simulation results show that in comparison with conventional PI, FOPI, PSO-PI control schemes there is a remarkable improvement in rise time, settling time, overshoot and steady state error in PEMFC output with PSO-FOPI controllers. This ensures far superior and robust system output under uncertain input conditions with PSO-FOPI control scheme.

Keywords: PI (Proportional and Integral) Controller, PSO (Particle Swarm Optimization), FOPI (Fractional Order PI) Controller, PEMFC

Introduction

Proton Exchange Membrane Fuel Cells (PEMFC) is attaining huge attentiveness due to their high energy power density, compact size and efficiency. The commercialization of PEMFCs is hindered by issues including suboptimal performance, unregulated voltage and fuel starvation. Thus, a suitable control design is required to overcome the problems associated with PEMFC. In today's world, fossil fuels are depleting at alarming rate and the current reserves may not suffice in meeting the growing future energy demands (Daud *et al.*, 2017). Experimental optimization has been investigated to increase the performance, efficiency, and development of models and simulations of PEM fuel cells (Taner, 2018). This will create an unbalanced

demand-supply gap while catering energy needs in the near-future. This energy gap will hamper energy security. PEMFC is attracting extensive interest, courtesy its high efficiency and power density; however, its industrialization is adversely impacted by issues such as poor voltage control and power quality limitations. The performance and durability of a PEMFC can be improved with suitable designing of controller to balance the reactants flow, stack of cells humidity and temperature of the membrane (Javaid *et al.*, 2020). Fuel Cell has various subsystems, thus from control aspects, it needs fine control with proper air flow subsystem, fuel supply subsystem, humidity and temperature management systems. By adjusting the flow rate

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parameters and pressure, the thermal efficiency of PEMFC might be improved (Taner, 2021).

A PID controller is designed (Dwivedi and Tayal, 2017) for integrated AFC (Alkali Fuel Cell) system by taking loading uncertainties into consideration. The Fuzzy-proportional-integral-derivative controller has been proposed by (Rakhtala and Roudbari, 2016) for controlling a stand-alone system. The underlying aspiration is to design and control a suitable power line conditioning-unit (PCU) made up of DC/AC inverter and DC/DC converter. A different model based approach for PEMFC was classified consisting of black, white and grey box (Petrone *et al.*, 2013). To circumvent the starvation of oxygen and expand the existing life of fuel cells, the flow of air has been regulated (Dhanya and Paul, 2014). To obtain the constant voltage, Fuzzy Logic (FL) and a PID controller are designed incorporating the mathematical model of PEMFC. In order to ensure accuracy, stability and meliorating the efficiency of PEMFC, regulation of air supply is of paramount importance (Chonglin and Shaoyuan, 2016). This reduces steady state errors and refines dynamic performance of the system. (Duan *et al.*, 2006) designed a non-linear PID controller where controller gains are optimized by using Ant Colony Optimization Algorithm. The FO-PID is tuned by Grouped GWO (Grey Wolf Optimization) (Yang *et al.*, 2018) to verify the productiveness and effectiveness of the controller.

Farhadi and Sojoudi (2014) proposed that output voltage of PEMFC can be controlled by PSO based PID controller, where PSO is selected for its simplicity and fast performance. To control the output power of PEMFC, (Ren *et al.*, 2006) designed a predictive control technique based on PSO. This algorithm was prioritized due to its easy implementation and effectiveness. For controlling the sub-models of PEMFC viz.-cathode back pressure regulation, membrane hydration and anode pressure following control, hybrid dynamic model is proposed (Penga *et al.*, 2019). Terminal voltage of PEMFC was regulated by classical Linear Quadratic Regulator (LQR) (Cao *et al.*, 2020) controller. PSO algorithm is developed with the intent to achieve superior PEMFC performance (Dezvarej, and Morovati, 2016). PEMFC cannot be directly pertained (Hu *et al.*, 2017) owing to its soft electrical properties that can be improved by using FO-PID controller. By this technique, regulated output can be achieved. For controlling microgrids, PSO based PI controller have been developed by (Qazi *et al.*, 2017). This controller is capable of regulating voltage, frequency and mitigating harmonics. The unstable processes (Vastrakar and Padhy, 2013) and reduction of error is carried out by simplified PSO with PI-PD

controller. Nazelan *et al.* (2017) proposes PSO-PI controller for controlling permanent magnet synchronous motor (PMSM) to achieve the target of desirable speed.

The conventional integer order PID controllers are incapacitated of optimally controlling real world objects or fractional processes. These classical controllers are inefficient for non-linear systems. In contrast to other classical methods, Fractional order controllers are more flexible, robust and accurate. They perform more preciously for real time dynamic processes may also revamp the system performance remarkably. The sub optimal dynamic performance of PEMFC can be enhanced by using FO-PID controller. Further, FO-PID controller can be tuned by an artificial intelligence technique to optimize the gains of the controller (Qi *et al.*, 2020). Mehrabi *et al.* (2012) modelled a PEMFC control scheme optimized by Genetic Algorithm. In this GA has been used with polynomial neural network.

However, higher accuracy can't be obtained from Genetic Algorithm technique. GA has quite high processing time and indispensable enormous designing iterations (Khalaf *et al.*, 2020). Theoretical analysis of Ant Colony Algorithm is difficult, and its probability distribution can change with each iteration. Further, the time required by ACO algorithm for convergence is uncertain. Grey Wolf Optimization (GWO) Algorithm is less reliable and has low level of fault tolerance. GWO is exceedingly complex technique with low speed operation. In contrast to other optimization techniques, PSO is simple, efficient and can be implemented easily. It can process multiple computations simultaneously while giving precise results.

This paper presents performance enhancement of PEMFC system subjected to uncertainty in input with conventional PI, FOPI, PSO based PI and PSO-FOPI controllers. The performance evaluation parameters-overshoot, steady state error, rise time and settling time are used to compare the effectiveness of proposed control schemes. The quantitative comparison of all the controllers indicates that FOPI controller appreciably improves the system performance. This paper is organized as follows-Section II describes the PEMFC and various reactions involve in it. Section III explains the concepts and approximations of Fractional Order Controllers. Section IV enumerates implementation of PSO technique while Section V discusses the evaluation of fitness function. Section VI deliberates about the control strategy involved in this work. Simulation results are presented in Section VII represents the simulation results that assure applicability and robustness of the proposed

technique. Finally the conclusions are discussed in Conclusions.

Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFC conducts proton and is impenetrable to electrons and gas, for instance, Nafion or per-flouro-sulfonic acid. These fuel cells operate at very low temperature (nearly 80-90°C). Protons are conducted by membrane from anode to cathode to complete the electrical circuit with electrons. These electrons were conducted from anode, on other hand, at cathode side water is formed by chemical reaction between protons and electrons of oxygen and positive ions of hydrogen. PEMFC is best suited for transportation, portable devices and small scale applications (Wee, 2007; Swain and Jena, 2015). PEMFCs have emerged as significant source of electricity generation because of eminence excellence like high throughput, low operating temperature, quick startup time and high energy density. The schematic representation of the fuel cell is detailed in Figure 1.

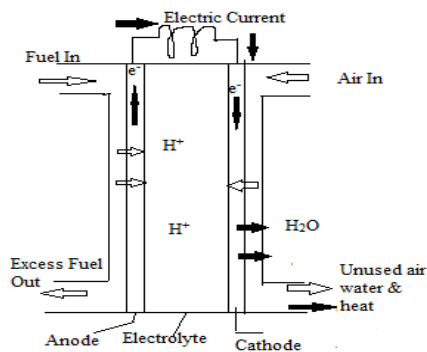
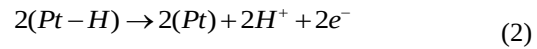
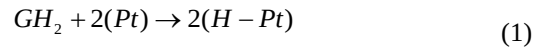


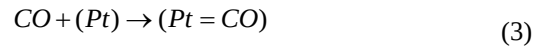
Figure 1. Shows Schematic Diagram of PEM Fuel cell

Hydrogen is used as fuel in PEMFCs and is continuously fed to the anode. At the anode, it dissociates into free electrons and positive hydrogen ions. Positive hydrogen ions enter the electrolyte, from where they permeate to the cathode electrode. Now, at the cathode electrode, oxygen is fed from air, thus oxygen and positive ions of hydrogen combines to form water as a by-product. At the anode, free electrons advance towards the external circuit to produce electrical output.

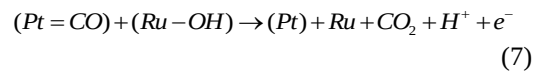
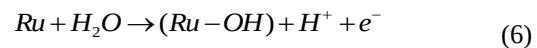
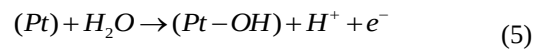
To reduce the carbon monoxide adsorption on the surface of the catalyst of Pt (Platinum), a catalyst of alloy Pt-Ru (Platinum-Ruthenium) can be employed at PEMFCs anode (Qi and Kaufman, 2003). For pure hydrogen, chemical reactions (at anode) are expressed in Equations (1) and (2):



If hydrogen is mixed with carbon monoxide (CO), the chemical reaction at the anode electrode can take place in two ways, as given in Equations (3) and (4):



The alloy catalyst (Pt-Ru) reduces the adsorption of CO remarkably on the catalyst platinum at the anode electrode of a PEMFC. This permits a water-gas shift reaction to take place. Equations (5)-(7) represents chemical reactions at the anode side.



The transfer function model (Subhasree and Kotteswaran, 2016) of PEMFC is mathematically represented by Equation (8)

$$G(s) = \frac{591.6s^4 + 1472s^3 + 451.3s^2 + 0.9748s + 1.847 \times 10^{-5}}{s^5 + 21.72s^4 + 52.59s^3 + 16.12s^2 + 0.03318s + 4.35 \times 10^{-7}} \quad (8)$$

Fractional Order Controllers

Fractional order controllers have attained momentum in the recent past from commercial and academic perspectives. FOPI controllers are more flexible, robust and accurate in contrast to classical PI controllers as they have three tuning parameters for optimizing the output (instead of two). Fractional calculus is the combination of non-integer order integrals and derivatives (Bhisikar et al., 2014). Mathematicians interpret fractional order derivatives and integrals in their own way. Cauchy gave the definition of integration as shown in Equation (9)

$${}_0^J t^n f(t) = \frac{1}{(n-1)!} \int_0^t (t-\tau)^{n-1} f(\tau) d\tau \quad (9)$$

where, and it is a n order of integration. Riemann-Liouville gave the fractional order integration by generalising the definition given by Cauchy. In Equation (10), factorial function is replaced by lambda function that allows non integer value of n .

$${}_0 J_t^\lambda f(t) = \frac{1}{\lambda!} \int_0^1 (t-\tau)^{\lambda-1} f(\tau) d\tau \quad (10)$$

Fractional Order systems operates at unlimited dimensions, as a result, their realization is a very complex procedure especially in industries. Thus, it mandates to execute a transfer function of limited band and higher order. There are numerous approximations to resolve the purpose of high order transfer function namely Matsuda, Oustaloup and Carlson. Matsuda's approximation (Matsuda and Fujii, 1993) is expressed in continuous form of fractions. These are the frequency response of the FO systems at different frequencies. If $\rho_0 < \rho_1 < \dots < \rho_n$ then the approximation for fractional order system $G(s)$ is given in Equation (11)

$$H_n(s) = b_0 + \frac{s - \rho_1}{b_1 + \frac{s - \rho_1}{b_{n-1} + \frac{s - \rho_n}{b_n}}} \quad (11)$$

$$\text{where } b_k = \begin{cases} |G(j\rho_0)| & k=0 \\ \frac{\rho_k - \rho_{k-1}}{d_{k-1}(\rho_k) - d_{k-1}(\rho_{k-1})} & k=1,2,3,\dots,n \end{cases}$$

In Oustaloup approximation (Podlubny, 1998), the poles and zeros are calculated in frequency domain where several compensators are multiplied. The transfer function in this case is expressed in Equation (12)

$$s^\mu = A \prod_{k=-n}^n \frac{s + \rho'_k}{s + \rho_k} \quad 0 < \mu < 1 \quad (12)$$

$$\text{where } \rho'_k = \rho_b \left(\frac{\rho_h}{\rho_b} \right)^{\frac{k+n+\frac{1}{2}(1-\mu)}{2n+1}}$$

$$A = \rho_h^\mu$$

The approximation of fractional order system using Carlson approximation (Carlson and Halijak, 1964) is based on Newton Raphson technique. It is represented in Equation (13)

$$G(s) = (H(s))^\alpha \quad (13)$$

where $H(s)$ is an integer function and α lies in the interval of (0,1). $G_i(s)$ is given in Equation (14),

$$G_i(s) = \frac{\left(\frac{1}{\alpha}-1\right)(G_{i-1}(s))^{\frac{1}{\alpha}} + \left(\frac{1}{\alpha}+1\right)H(s)}{\left(\frac{1}{\alpha}+1\right)(G_{i-1}(s))^{\frac{1}{\alpha}} + \left(\frac{1}{\alpha}-1\right)H(s)} G_{i-1}(s) \quad (14)$$

Particle Swarm Optimization Algorithm

Kennedy and Eberhart (1995) developed the Particle Swarm Optimization technique. The PSO (Ahmadi *et al.*, 2017) has sharp accuracy and efficiency, works on an elementary principle and redefines system accomplishments. Mukhtar *et al.* (2019) used this technique for process liquid control wherein controlling parameters have high computational efficiency and are sturdy in nature. A swarm of particles flies through a problem space, where each particle represents a solution to the optimization problem. The fitness function is bounded by an objective function which is defined and derived for each particle. For every iteration, particle upgrades its velocity, which depends on the premier position attained so far and is known as the particle best or p_{best} . Thus, the particle progresses towards its optimal location. Global best or g_{best} is defined as the overall best position acquired by any particle. Particles update their velocity and position, with every iteration by following individual's local best and global best. Table 1 represents the PSO parameters considered in this work. The new position and velocity (Wu *et al.*, 2020) of all the particles can be expressed according to the Equations (15) and (16).

$$V(t+1) = V(t) + C_1 R_1 (p_{best} - X(t)) + C_2 R_2 (g_{best} - X(t)) \quad (15)$$

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1) \quad (16)$$

Table 1. Shows PSO Parameters

S. No.	PSO parameter	Values
1	C_1	2.0
2	C_2	2.0
3	Inertial Weight, w	0.9
4	Population Size	49

where, t is the algebra of the current evolution; C_1 and C_2 are accelerating factors, usually with a value of 2; factors R_1 and R_2 are the random numbers between 0 and 1; The inertia coefficient 'w' is added to intensify the ability of particles to come out of the local best so that the Equation (16) can be changed to Equation (17)

$$V(t+1) = wV(t) + C_1R_1(p_{best} - X(t)) + C_2R_2(g_{best} - X(t)) \quad (17)$$

$$\text{where } w = w_{\max} - \frac{(w_{\max} - w_{\min})t}{T_{\max}} \quad (18)$$

The PSO algorithm consists of following steps: (Latha *et al.*, 2013) and its shown in Figure 2.

1) Swarm Initialization: If population size is considered as N, then particles randomly assumes position, ranging from minimum to maximum value of parameters.

2) Calculation of Objective Function: It is done by performance criteria for algorithm convergence.

3) p_{best} and g_{best} - Initialisation: Values are termed as p_{best} and are obtained from the initial values. g_{best} are the values that are attained from the p_{best} values.

4) Computation of velocity & position: The new velocity and position for every particle is evaluated.

5) Swarm Upgrade): If the current values are superior to the last local best then the current value is set as new p_{best} . Thus, accordingly global best is updated.

6) Stop Criteria: If the stop criterion is satisfied then p_{best} represents the optimal value, otherwise repetition of above method takes place from 4th step till the designated iteration is completed.

Fitness Function Selection

PSO algorithm makes use of fitness function for the evaluation of merits of an individual or solution in the process of optimal search (Solihin *et al.*, 2011). In this work, Integral Time Absolute Error (ITAE) performance index is used as a fitness function. The ITAE criterion is mathematically described by Equation (19)

$$ITAE = \int_0^{\infty} t |e(t)| dt \quad (19)$$

The PSO algorithm sets the controller gains of the proposed controllers such that the performance index ITAE is the minimum.

Control Strategy

The objective of Control system is to stipulate error to zero between starting point and actual value (Eswaran and Kumar, 2017). PI control is required for the non-integrating processes PI control is required for the non-integrating processes. For integrating processes, P-controllers gives adequate results and offsets can be removed by Integrator controller (Yadav and Tayal, 2018). P-I controller may be used to circumvent major disruptions and noise arising during the process. Figure 3 represents the block diagram of PSO optimised PI controller.

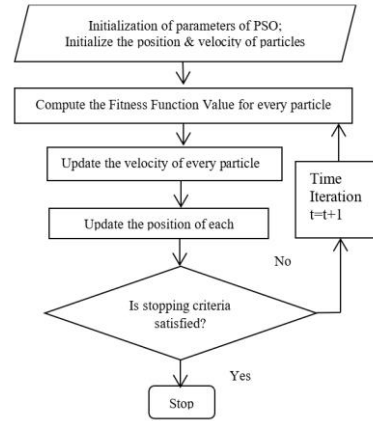


Figure 2. Shows flowchart for PSO-algorithm

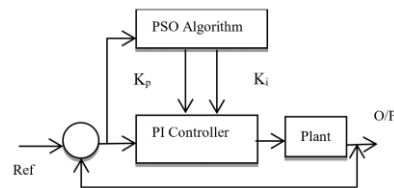


Figure 3. Shows PI controller with PSO

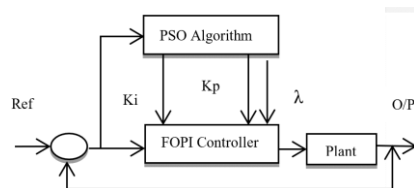


Figure 4. Shows FOPI Controller with PSO

PI controller is a feedback control mechanism that requires an error signal to be actuated. It generates the control signal based on this error signal. In s-domain PI controller can be expressed by Equation (20)

$$G(s) = K_p + \frac{K_i}{s} \quad (20)$$

FOPI controllers have four tuning parameters. In contrast to PI controllers, FOPI controllers are more robust, flexible; give better performance and real world processes can be controlled more adequately and accurately. Figure 4 represents a typical FO-PI controller with PSO. The FOPI controller can be defined by Equation (21)

$$G(s) = \frac{U(s)}{R(s)} = K_p + K_i s^{-\lambda}, \quad \lambda \geq 0 \quad (21)$$

In Equation (21), λ can be any real number and thus infinite number of FOPI controllers can be produced. If λ is kept as 1, then it will represent a PI controller (Mehra *et al.*, 2010). There is a need to tune three parameters in case of FOPI controllers. The tuning of the controller depends on following parameters (Desai *et al.*, 2015):

- Integral gain K_i
- Proportional gain K_p
- Order of integrator (λ)

This paper employs PSO technique to determine the values of K_p , K_i and λ by using a repetitive search process.

Simulation Results

In order to evaluate the effectiveness of proposed control schemes, step disturbance is introduced in PEMFC input at $t = 1, 1.1, 1.2, 1.3, 1.4$, and 1.5 seconds as outlined in Figure 5. Table 2 shows the values of controller gains which are obtained by optimization. The PEMFC output in the absence of any controller is shown in Figure 6. From Table 3, it is observed that without controller steady state error is too high (324.177).

To control the output of PEMFC with PI and FOPI controllers, selection of controller parameters K_p , K_i , and λ is carried out by conducting number of computer experiments. The output of PEMFC with PI controller is depicted in Figure 7. With PSO optimized PI controller, the PEMFC output is illustrated in Figure 8. The PEMFC output with FOPI controller is shown in Figure 9. The controlled

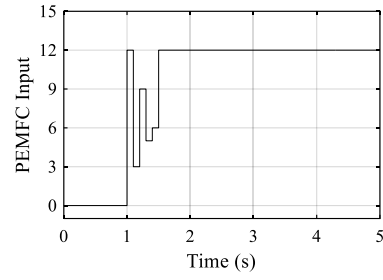


Figure 5. Shows input of PEMFC

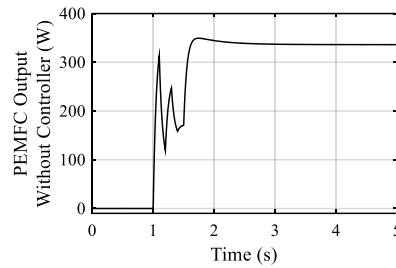


Figure 6. Shows PEMFC output without controller

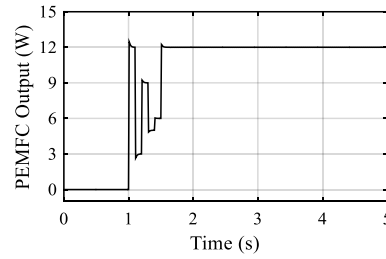


Figure 7. Shows PEMFC output with PI controller

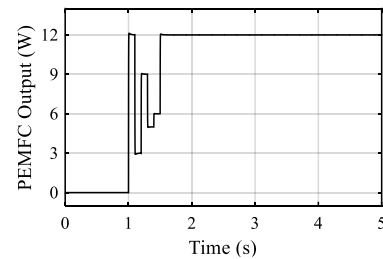


Figure 8. Shows PEMFC output with PSO-PI controller

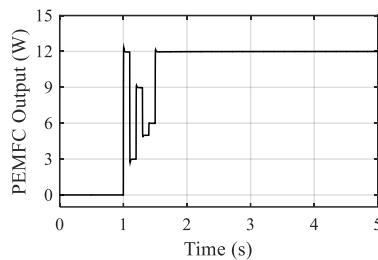
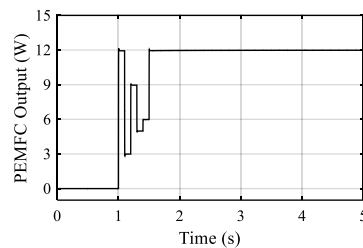
Table 2. Shows controller parameters

Controller parameter values	Controller type			
	PI	FOPI	PSO-PI	PSO-FOPI
K_p	0.9	1.21	1.407	2.101
K_i	45.7	10.75	42	6.864
λ	-	0.61	-	0.4831

Table 3. Shows comparison among PEMFC output with different controllers

Parameters	Without Controller	Type of Controller			
		PI	PSO-PI	FOPI	PSO-FOPI
Settling Time (ms)	1800	22.397	11.786	7.477	1.806
Rise Time (ms)	85.727	3.631	2.475	2.503	1.515
Overshoot (%)	3.467	3.646	2.567	2.577	1.531
Steady State Error (%)	2.7×10^3	0	0	0	0

output of PEM fuel cell exhibited in Figure 10

**Figure 9. Shows PEMFC output with FOPI controller****Figure 10. Shows PEMFC output with PSO-FOPI controller**

represents FOPI controller tuned with PSO technique. PEMFC output with PI, PSO-PI, FOPI and PSO-FOPI controller are being compared on the basis of various time domain performance evaluation parameters viz.-settling time, overshoot, steady state error and rise time. Table 3 represents the comparison of PEMFC output with different controllers. With the implementation of controllers, the steady state error is completely eliminated. The settling time, rise time and overshoot for PEMFC output with PI controller are 22.397 ms, 3.631 ms and 3.646% respectively; with PSO-PI controller, the settling time, rise time and overshoot values are 11.786 ms, 2.475 ms, and 2.567% respectively. The value of settling time for FOPI and PSO-FOPI controller are 7.477 ms and 1.806 ms respectively. With PSO-FOPI controller, the rise time and overshoot improves from 2.503 ms to 1.515 ms and from 2.577% to 1.531% respectively.

Conclusions

PEMFCs are being widely adopted due to their high efficiency, portability and low operating temperature. However, their dynamic performance is degraded under varying input and loading conditions. This results in large unregulated output voltage. In this paper, PI, FOPI, PSO-PI and PSO-FOPI controllers are proposed for the performance enhancement of PEMFC. This has been observed that the system results in degraded performance without any controller, but the fuel cell system gains stability and robustness with proposed controllers. In the absence of any controller, steady state error is too high, which hampers the system performance. The steady state error is completely removed by employing controller designs (PI, FOPI, PSO-PI, and PSO-FOPI). The simulation results obtained from PSO optimized PI and FOPI controllers outperforms the PI and FOPI controllers in terms of settling time, rise time, overshoot and steady state error.

PSO tuned FOPI controller remarkably improves the settling time of the PEM fuel cell. The PSO-FOPI controller substantially improves the dynamic performance of PEM fuel cell in contrast to FOPI controller. The PEMFC output with PSO-FOPI controller is far superior in comparison with PI, FOPI and PSO-PI controllers.

References

- Ahmadi, S., Abdi, Sh., and Kakavand, M. (2017). Maximum power point tracking of a proton exchange membrane fuel cell system using PSO-PID controller. *Science Direct*, 42:20,430-20,443.
- Bhisikar, K.K., Vyawahare, V.A., and Tare, A.V. (2014). Design of fractional-order pi controller for linear unstable systems. In: 2014 IEEE Students' Conference on Electrical, Electronics and Computer Science, 14:1-6.
- Cao, Y., Li, Y., Zhang, G., Jermittiparsert, K., and Nasser, M. (2020). An efficient terminal voltage control for PEMFC based on an improved version of whale optimization algorithm. *Energy Reports*, 6:530-542.
- Carlson, G. and Halijak, C. (1964). Approximation of fractional capacitors $(1/s)^{1/n}$ by a regular Newton process. *IEEE Trans. Circ. Theory*, 11(2):210-213.

- Chonglin, Z. and Shaoyuan, Li. (2016). Control strategies for the air supply system in PEMFC. In: Proceedings of the 35th Chinese Control Conference, IEEE, 50(1):96-101.
- Daud, W.R.W., Rosli, R.E., Majlan, E.H., Hamid, S.A.A., and Mohamed, R. (2017). PEM fuel cell system control: A review. *Renewable Energy, Int. J.*, 113:620-638.
- Desai, R., Kadu, C., and Parvat, B. (2015). Design Of FOPI controller for time delay system. In: International Conference on Energy Systems and Applications (ICESA 2015) p. 375-378.
- Dezvarei, M. and Morovati, S. (2016). Optimization of proton exchange membrane fuel cell parameters based on modified particle swarm algorithms. *Int. J. Energ. Power Eng.*, 10(10):1,315-1,320.
- Dhanya, S. and Paul, V. (2014). Fuzzy-PID controller for PEM fuel cell in automobile application. *OSR J. Elect. Commu. Eng.*, (IOSR-JECE), p. 63-68.
- Duan, H., Wang, D., and Yu, X. (2006). Novel approach to nonlinear pid parameter optimization using ant colony optimization algorithm. *J. Bio. Eng.*, 3(2):73-78.
- Dwivedi, Y. and Tayal, V.K. (2017). Dynamic stability improvement of alkali fuel cell integrated system using PSO optimized PID control design. In: IEEE International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), p. 499-504.
- Eswaran, T. and Kumar, V.S. (2017). Particle swarm optimization (PSO)-based tuning technique for PI controller for management of a distributed static synchronous compensator (DSTATCOM) for improved dynamic response and power quality. *J. Appl. Res. Technol.*, 15(2):173-189.
- Farhadi, P. and Sojoudi, T. (2014). PEMFC voltage control using pso-tuned-pid controller. In: Proceedings of the 2014 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference, p. 32-35.
- Hu, D., Qi, Z., and Tong, Y. (2017). Research on fractional order PID controller applied to PEMFC pre-stage power conversion. In: 29th Chinese Control And Decision Conference (CCDC), IEEE., p. 1,016-1,020.
- Javaid, U., Mehmood, A., Arshad, A., Imtiaz, F., and Iqbal, J. (2020). Operational efficiency improvement of pem fuel cell_a sliding mode based modern control approach. *IEEE Access*, 8:95,823-95,831.
- Kennedy, J. and Eberhart, R. (1995). Particle swarm optimization. In: Proceedings of IEEE International Conference on Neural Networks (Perth, Australia) (IEEE Service Center, Piscataway, NJ., p. 1,942-1,948.
- Khalaf, O.I., Abdulsahib, G.M., and Sabbar, B.M. (2020). Optimization of wireless sensor network coverage using the bee algorithm. *J. Inform. Sci. Eng.*, 36:377-386.
- Latha, K., Rajinikanth, V., and Surekha, P.M. (2013). PSO-Based PID controller design for a class of stable and unstable systems. *ISRN Artificial Intelligence*, Hindawi Publishing Corporation. 13:1-12.
- Matsuda, K. and Fujii, H. (1993). H (infinity) Optimized Wave-Absorbing Control-Analytical and Experimental Results. *J. Guid. Cont. Dyn.*, 16(6):1,146-1,153.
- Mehra, V., Srivastava, S., and Varshney, P. (2010). Fractional-order PID controller design for speed control of DC motor. In: Third International Conference on Emerging Trends in Engineering and Technology, IEEE., p. 422-425.
- Mehrabi, M., Rezazadeh, S., Sharifpur, M., and Meyer, J. (2012). Modeling of proton exchange membrane fuel cell (PEMFC) performance by using genetic algorithm-polynomial neural network (Ga-Pnn) hybrid system. In: Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference Fuel Cell., p. 447-452.
- Mukhtar, A., Tayal, V.K., and Singh, H.P. (2019). PSO Optimized PID controller design for the process liquid level control. In: 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), NOIDA, India., p. 590-593.
- Nazelan, A.M., Osman, M.K., Samat, A.A.A., and Salim, N.A. (2017). PSO-Based PI controller for speed sensorless control of PMSM. In: 1st International Conference on Green and Sustainable Computing (ICoGeS), p. 1-11.
- Penga, F., Renb, L., Zhaob, Y., and Li, L. (2019). Hybrid dynamic modeling-based membrane hydration analysis for the commercial high-power integrated pemfc systems considering water transport equivalent. *Ener. Conv. Manage.*, 205:1-19.
- Petrone, R., Zheng, Z., Hissel, D., Pera, M.C., Pianese, C., Sorrentino, M., Becherif, M., and Yousfi-Steiner, N. (2013). A review on model-based diagnosis methodologies for PEMFCs. *SciVerse Science Direct*, 38(17):7,077-7,091.
- Podlubny, I. (1998). Fractional differential equations: an introduction to fractional derivatives, fractional differential equations, to methods of their solution and some of their applications. *Math. Sci. Eng.*, 198(1):1-340.
- Qazi, S.H., Mustafa, M.W., Hussain, N., and Sultana, U. (2017). Performance evaluation of PI and PI-PSO in improving power quality of an autonomous microgrid. In: IET International Conference on Resilience of Transmission and Distribution Networks, p. 1-6.
- Qi, Z. and Kaufman, A. (2003). CO-tolerance of low loaded Pt/Ru anodes for fuel cells. *J. Power Source*, 113(1):115-123.
- Qi, Z., Tang, J., Pei, J., and Shan, L. (2020). Fractional controller design of a DC-DC converter for PEMFC. *IEEE Access*. 8:120,134-120,144.
- Rakhtala, S.M. and Roudbari, S. (2016). Fuzzy PID control of a stand-alone system based on PEM fuel cell. *International J. Elect. Pow. Ener. Sys.*, 78:576-590.
- Ren, Y., Cao, G.Y., and Zhu, X.J. (2006). Particle swarm optimization based predictive control of proton exchange membrane fuel cell (PEMFC). *J. Zhejiang Univ. Sci. A.*, 7(3):458-462.
- Solihin, M.I., Moey, L.K., and Kean, M.L. (2011). Tuning of PID controller using particle swarm optimization (PSO). In: Proceeding of the International Conference on Advanced Science, Engineering and Information Technology, 1(11):458-461.
- Subhasree, S.V. and Kotteswaran, R. (2016). Modelling and control of polymer membrane fuel cell. *Indian J. Sci. Technol.*, 9(13):1-7.
- Swain, P. and Jena, D. (2015). PID control design for the pressure regulation of PEM fuel cell. In: 2015 International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE), IEEE., p. 286-291.
- Taner, T. (2018). Energy and exergy analyze of PEM fuel cell: A case study of modeling and simulations. *Energy*, 143:284-294. doi: 10.1016/j.energy.2017.10.102.
- Taner, T. (2021). The novel and innovative design with using H2 fuel of PEM fuel cell: Efficiency of thermodynamic analyze. *Fuel*, 302:121109. doi: 10.1016/j.fuel.2021.121109.
- Vastrakar, N.K., and Padhy, P.K. (2013). Simplified PSO PI-PD controller for unstable processes. In: 4th International Conference on Intelligent Systems, Modelling and Simulation., p. 350-354.
- Wee, J.H. (2007). Applications of proton exchange membrane fuel cell systems. *Renew. Sustain. Ener. Rev.*, 11:1,720-1,738.
- Wu, T., Zhou, C., Yan, Z., Peng, H., and Wu, L. (2020). Application of PID optimization control strategy based on particle swarm optimization (PSO) for battery charging system. *Int. J. Low Carb. Technol.*, p. 1-8.
- Yadav, V. and Tayal, V.K. (2018). Optimal controller design for a DC motor using PID tuner. In: IEEE International

- Conference on Power Energy. Environment and Intelligent Control (PEEIC), p. 442-445.
- Yang, B., Yu, T., Shu, H., Zhu, D., Zeng, F., Sang, Y., and Jiang, L. (2018). Perturbation observer based fractional-order PID control of photovoltaics inverters for solar energy harvesting Via Yin-Yang-Pair optimization. *Ener. Conv. Manage.*, 171:170-187.