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Optimal Design of Fractional Order PID Controllers for Solid Oxide Fuel Cell System Employing PSO Algorithm

Swati Singh, Vijay Kumar Tayal, Hemender Pal Singh, and Vinod Kumar Yadav

***Abstract*— Solid Oxide Fuel Cells (SOFCs) are gaining attraction in order to facilitate various applications owing to portability, low pollution and high efficiency. However, due to strong nonlinearity, fast variations in loading conditions and sluggish dynamics, regulation of the output voltage of SOFCs is disturbed. This paper aims to enhance the dynamic performance of SOFC by employing PI, PI Fast, PIDF, 2-DOF PID and PSO optimized FO-PID controllers under uncertain input conditions. The PID tuner is used for tuning the PI, PI fast, PIDF and 2-DOF PID controller parameters. The PSO technique is utilized for optimizing of FO-PID controller. The SOFC output with various controllers is compared in terms of performance specifications such as peak overshoot, settling time, steady state error and rise time. The comparison of computer simulation results manifests that the proposed PSO-FOPID controller scheme yields in far better performance with SOFC subjected to uncertain input.**

***Index Terms*—FOPID-Fractional Order PID, PI-Proportional-Integral, PID- Proportional–Integral–Derivative, PIDF- Proportional–Integral–Derivative with filter, SOFC- Solid Oxide Fuel Cell, 2DOF-Two Degree of Freedom**

I. INTRODUCTION

Technological breakthroughs in renewable energy technology have established fuel cells as a significant resource of energy for the future aspects. Over the last decade, generation of fuel cell electricity has attracted increasing attention due to minimal noise pollution, negligible amount of heat with higher energy efficiency than fossil fuel combustion plants. Dwivedi and Tayal designed a PID controller for integrated AFC (Alkali Fuel Cell) system by taking loading uncertainties into consideration [1]. Distinguished by its solid polymer electrolyte and higher working temperature, the SOFC has the added benefit of fuel adaptability, continuous stability [2]. The SOFCs appears to be most viable, as it decreases the significant start-up times. The SOFC has a variety of benefits, including cell/stack design flexibility, diverse manufacturing choices, multi-fuel capabilities, and the ability to operate at different temperatures. In Phosphoric Acid Fuel Cell, design flexibility operating temperature has been the biggest issue [3]. Alkaline Fuel Cell faces issues viz. sensitivity to CO_2 in fuel and air; and management of electrolyte [4]. Boldrin and Brandon proposed SOFC application for the continuous functioning of vehicles [5]. Fuel cell has been proved to be a great source of providing electric energy however it produces uncontrolled output voltage, current and power [6]. A fuel flow and heat analysis is being carried out to boost the efficiency of the SOFC stack [7]. For pressure and voltage control of SOFCs, feedback linearization controllers and gain scheduling have been developed [8]. This system utilizes P-I based fuel control system without power. To optimize the proper functioning of the affecting its operational feasibility and capacity for monitoring SOFC power system a supervisory controller comprising of two PI and four feed forward controllers is proposed [9].

To improve the small signal dynamic behaviour of a grid-connected SOFC system, P-I controller-based strategy is proposed [10]. The controller parameters are optimized by the Differential Evolution (DE) algorithm. The fluctuations in the output voltages due to varied power demand are considered [11]. They designed PID and Fuzzy controllers to overcome the issues related with varying power. In order to optimize the temperature control within the furnace to increase the life of the micro tubular SOFCs, a control system has been developed. The efficiency of the pilot power plant simulator 300 kW SOFC Gas Turbine (SOFC-GT) is enhanced by a fixed set of robust Proportional Integral Derivative (PID) controllers [12]. Darjat et al. conducted a simulation of control and fuel used in solid oxide fuel cells (SOFC) [13].

The constant regulation of fuel utilization scheme maintains the fuel utilization ratio. This leads to oscillations in SOFC output voltage. As the internal partial pressures can change considerably, the membrane may also get affected. Electrical current is used as feedback signal in a current feedback control device that may not be an effective method to regulate the partial and internal pressures. Modified FO-PI and 2-DOF-PI controllers are designed for the regulated functioning of an autonomous micro grid (MG) [14]. The autonomous MG consists of a distributed generation (DG) system of SOFC & photo-voltaic (PV) systems, various loads of AC & DC and a

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Swati Singh,
Amity University, Noida.
Email: singh.swati2703@gmail.com

Vijay Kumar Tayal,
Amity University, Noida.
Email: vktayal@amity.edu

Hemender Pal Singh,
Amity University, Noida
Email: hpsingh2@amity.edu

Vinod Kumar Yadav,
Delhi Technological University, New Delhi
Email: vinodkumar@dtu.ac.in

battery energy storage system (BESS) as a storage unit. Adar and Kozan compared the performance of 2-degree-of-freedom PID controller and traditional PID controllers [15]. 2DOF PID controller appears to be more effective than PID controller because of reduced settling time and error. The tuning of 2-DOFPID controller (both for feed forward and feedback structures) is done by Bacterial Foraging Optimization algorithm, to intensify the performance of delayed unstable systems [16].

SOFC bi-directional DC-DC Converter Control is designed to increase the speed of the SOFC system's power control. PI controller provides better system stability and is capable of eliminating offset [17]. It has good transient response and stabilizes controller gains. The PID controller is feasible, simple in implementation and one of the most robust controller. Zamani et. al. has modeled a fractional order PID controller capable of regulating the dynamics of stability margins, transient, and steady-state response [18]. The PSO multi-objective methodology is used to progressively change the controller gain of the FOPID controller depending on the error discrepancy between the plant model and reference model [19]. For the second order system with delayed time, PSO technique is used to configure the PID and FOPID parameters [20]. FOPID controllers promise strong merits over the classical PID controllers as shown by both simulation and real time experiments [21]. In comparison with integer order PID controller, FOPID controllers possess more flexibility, better robustness, and improve the system performance in time and frequency domain. Further, in industrial control processes, the FOPID controller application results in reduction of control efforts.

SOFC control design is proposed to minimize power oscillations in the optimal stabilizer system [22]. The multi-objective PSO methodology is intended to enhance the system efficiency. In order to optimize the operational specifications of the SOFC and μ-gas turbine (MGT) hybrid systems under different loads, the improved recursive particle swarm optimization (PSO) algorithm has been developed [23]. The SOFC-Gas Turbine (SOFC-GT) has been presented to overcome the non-linear and multi-objective optimization issues by using GA (Genetic Algorithm) and PSO [24]. For the SOFC-GT issues, PSO provides better stability and reliability than GA technology. The ACO (Ant Colony Optimization) algorithm is unable to solve discrete optimization problems, whereas the PSO technique is flexible and an effective technique to face the challenges of stochastic optimization. Artificial Bee Colony (ABC) algorithm has uncertain time to convergence and probability distribution can change for each iteration. In contrast to other perceptual optimization techniques, PSO is simple in definition and coding implementation. In contrast with other heuristic methodologies, PSO is easier to implement, requires less parameters and reduced computation time.

In this paper PI, PID with filter, 2-DOF PID and artificial intelligence technique (PSO) optimized Fractional order PID control schemes are employed for the performance enhancement of SOFC system subjected to variations in input. The efficacy of various control schemes is compared on the basis of time domain performance specifications viz. steady state error, peak overshoot, settling time and rise time. This paper is structured as follows, section 2 identifies system modeling, advantages and challenges associated with SOFC Technology. Section 3, discusses the designing of various control schemes viz. PI, PI Fast, PIDF and 2-DOF PID controllers. Section 4 outlines the tuning of parameters of PI, PI Fast, PIDF and 2DOF PID controllers by PID tuner. Explanation of construction of FO-PID controller is detailed in Section 5. Optimization of FOPID controller gain with PSO technique is illustrated in Section 6. Section 7, describes and compares the simulation results of proposed controllers while the conclusions are drawn in Section 8.

II. SOLID OXIDE FUEL CELL

In SOFCs, the circuit loop is closed by transporting negative oxygen ions to anode from cathode, unlike other fuel cells where positive hydrogen ions permeates to the cathode from the anode [25]. The schematic diagram of S-O fuel cell is detailed in Fig. 1.

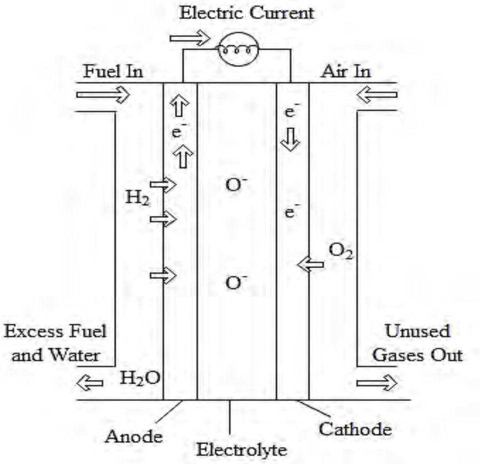

Fig. 1. Schematic Diagram of SOFC

Through electro-chemical reactions, the SOFC system can continuously supply electricity. Eqn (1) -(3) denotes the chemical reactions involved at anode, cathode and the overall reaction, respectively.

At Anode end:

$$2O^{2-} + 2H_2 \rightarrow 4e^- + 2H_2O \tag{1}$$

At Cathode End:

$$4e^- + O_2 \rightarrow 2O^{2-} \tag{2}$$

Cumulative Reaction:

$$O_2 + 2H_2 \rightarrow 2H_2O \tag{3}$$

The SOFC system makes it possible to turn a wide variety of fuels into electrical energy, such as hydrogen, biofuels and hydrocarbon gases. The device works at elevated temperatures (600-1000 °C) and employs three main elements: anode, a dense ceramic solid electrolyte, and a cathode. The high operating temperature increases the performance of the device and creates an incentive for the recycling of waste heat. TABLE I represents the parameters involved for modelling in the SOFC system.

The partial oxygen, hydrogen, steam (*Pa*) pressures in the cell are referred to as p_{O_2} , p_{H_2} and p_{H_2O} respectively [26].

The output dc voltage, v_{FC}, across the stack of the fuel cell at current I_{FC} is given by Nernst's equation, as shown in Eqn (4)

$$v_{FC}=n_0\left[\frac{r_0T_0}{2F_0}\ln\left(\frac{p_{H_2}p_{O_2}^{0.5}}{p_{H_2O}}\right)+e_0\right]-rI_{FC} \tag{4}$$

The partial pressure can be represented roughly in the following transfer functions: Eqn (5)-Eqn (7)

$$p_{H_2}=\frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(\frac{1}{1+\tau_f s}q_f-2K_rI\right) \tag{5}$$

$$p_{O_2}=\frac{1/K_{O_2}}{1+\tau_{O_2}s}\left(\frac{1/\tau_{H-O}}{1+\tau_f s}q_f-K_rI\right) \tag{6}$$

$$p_{H_2O}=\frac{1/K_{H_2O}}{1+\tau_{H_2O}s}2K_rI \tag{7}$$

TABLE I
SOFC MODEL PARAMETERS

Parameter	Unit	Description
T_0	K	Absolute Temperature
F_0	$Cmol^{-1}$	Faraday's constant
v_{FC}	V	Output DC voltage at fuel cell stack
n_0	-	Number of stacked cells
e_0	V	Standard reversible cell potential
I_{FC}	A	Stack Current
R	Ω	Internal resistance of the stack
r_0	J/molK	Universal gas constant
K_r	Mol/sA	Constant
K_{H_2}	Mol/sPa	Hydrogen molar constant for valve
K_{O_2}	Mol/sPa	Oxygen molar constant for valve
K_{H_2O}	Mol/sPa	Water molar constant for valve
τ_{H_2}	s	Hydrogen-flow reaction time
τ_{O_2}	s	Oxygen flow reaction time
τ_{H_2O}	s	Water flow response time
τ_{H-O}	-	Hydrogen to Oxygen Ratio
τ_f	s	Constant Time of the Fuel Processor

The transfer function of SOFC [27] is mathematically described by Eqn (8):

$$G(s)=\frac{2.417s+0.8276}{s^3+0.716s^2+0.1808s+0.006914} \tag{8}$$

III. CONTROL STRATEGY

SOFCs are one of the most efficient fuel cell technologies and proved to be a great source of providing electric energy. However, it produces uncontrolled output voltage, current and power. The SOFCs have degraded performance due to non-linearity, uncontrolled voltage, limited fuel flow, and rapid variations in load. Thus, it becomes necessary to have suitable control design to overcome these drawbacks. In this paper, the enhanced dynamic performance of SOFC has been explored by utilizing classical control schemes viz.-PI, PI Fast, PIDF, 2DOFPID and Fractional Order PID controllers. To achieve better results, the gains of classical controllers (PI, PI Fast, PIDF, 2DOFPID) are tuned using PID Tuner GUI available in MATLAB. To optimally tune the Fractional Order PID (FO-PID) controllers, the Particle Swarm Optimization (PSO) technique is implemented.

A. P-I (Proportional-Integral) controller

The P-I controller comprises of the Integral and Proportional controllers and is mathematically represented by Eqn (9)

$$u(t)=K_i\int_0^t e(t)\,dt+K_pe(t) \tag{9}$$

Where, the integral and proportional gains are designated as K_i and K_p, respectively, error signal is represented by $e(t)$, y is output signal and the reference signal is denoted as r [28]. The P controller is a gain element; higher gain results in increased speed of system response, reduced steady-state error (e_{ss}) and reduced system stability. Undesired increase in K_p may results in an unstable system. The impact of an Integral controller is superior to the Proportional controller to remove steady-state error. Further, rise in K_p and K_i results in an increase in the speed of response. The block diagram of PI controller is depicted in Fig. 2.

In order to achieve higher speed of response, the PI controller design is modified (PI Fast Controller) with higher gain crossover frequency.

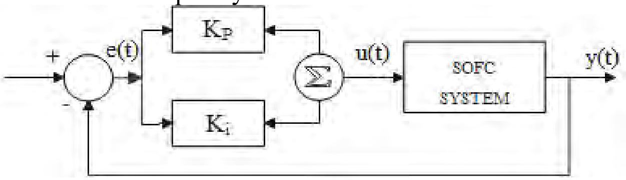

Fig. 2. Block Diagram of PI Controller

B. P-I-D (Proportional-Integral-Derivative) Controller

P-I-D controller is closed loop mechanism that comprises of three basic controllers that differ to obtain optimal response [29]. In industrial applications, it is the most prevalent control system used. In a broad range of operating conditions, robust reliability and practical simplicity can be credited to the performance of PID controllers. A PID controller gives the smallest steady state error and the most reliable response. The block diagram representation of PID controller is detailed in Fig. 3.

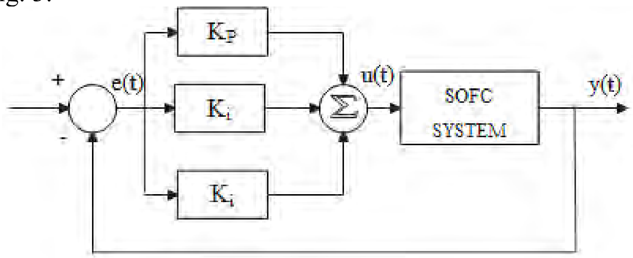

Fig. 3. Block Diagram Representation of PID Controller

The P-I-D controller is mathematically expressed by Eqn (10):

$$u(t) = K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} + K_p e(t) \tag{10}$$

C. Proportional-Integral-Derivative controller with Filter (PIDF)

A four-parameter PIDF controller is known as a filtered derivative action PID controller. The transfer function for PIDF controller is described in Eqn (11):

$$C(s) = \frac{K_i}{s} + K_P + \frac{K_d s}{T_f s + 1} \tag{11}$$

Where, integral, derivative and proportional gains are designated by K_i, K_d and K_p, respectively. T_f is the filter time constant. T_f can have real, non-negative and finite values. Fig.4 illustrates the structure of Proportional-Integral-Derivative controller with Filter (PIDF) [30]. Here N represents derivative filter coefficient mathematically given by Eqn (12),

$$N = \frac{1}{T_f} \tag{12}$$

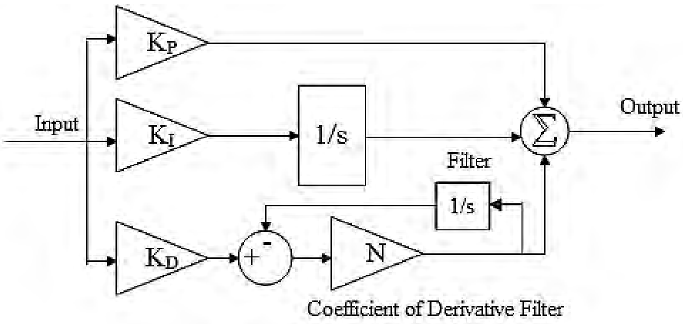

Fig. 4. Structure of PIDF Controller

The derivative action filter of the controller is absent when the value of T_f is zero ($T_f = 0$). If the value of T_f is very small, then in eqn (7), the term $\frac{K_d s}{T_f s + 1}$, will tends to become an ideal derivative term. For high frequency signals, this ideal derivative term has high gains and this is the major drawback of derivative action. Wide variations in the control signals will be produced by high frequency noise level. To avoid this, the value of T_f is approximately taken as $\left(0.05 < T_f < 0.5\right)$.

D. 2-DOF PID controller

2DOF-PID controller incorporate set point weighting on the derivative and proportional terms. In set point monitoring, a 2 DOF PID controller shown in Fig. 5 is responsible for the rapid disturbance rejection without a substantial increase in overshoot. 2-DOF PID controllers are also helpful in minimizing the effect on the control signal of changes in the reference signal [31].

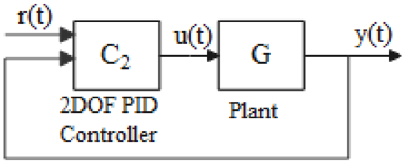

Fig. 5. Simple Block Diagram of 2-DOF PID Controller

It is possible to model the arrangement between the output of the 2DOF controller (u) and its two inputs (r and y) either in parallel or classification scheme. The two types vary in the parameters used to express the controller's proportional, integral, and derivative behaviour, embodied respectively in Eqn (13) and Eqn (14). This controller enhances the overall performance of the process.

$$u = K_p\left(br - y\right) + \frac{K_i}{s}\left(r - y\right) + \frac{K_d s}{T_f s + 1}\left(cr - y\right) \tag{13}$$

$$u = K_p\left[\left(br - y\right) + \frac{1}{T_i s}\left(r - y\right) + \frac{T_d s}{\frac{T_d}{N} s + 1}\left(cr - y\right)\right] \tag{14}$$

where, K_p, K_i and K_d are proportional gain, integral gain and derivative gain respectively, b is weight of set point on proportional term, c is weight of set point on derivative term, derivative filter divisor is denoted by N and T_f designates time of derivative filter.

The 2 degree of freedom PID controller can be equivalently transformed into feedback structure and Feed Forward structure of 2 D-O-F PID Controller. Fig. 6 and Fig. 7 respectively illustrates the block diagram of feedback and feed forward structures. In this paper, feedback structure of two D-O-F PID controller is used.

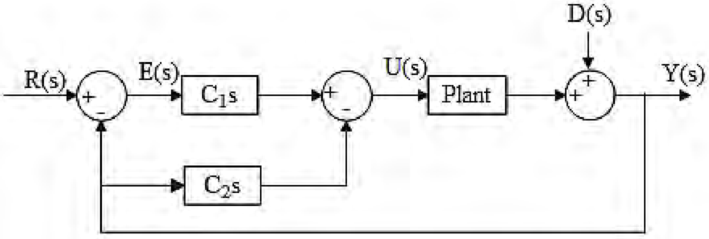

Fig. 6. Feedback Structure for 2 DOF PID Controller

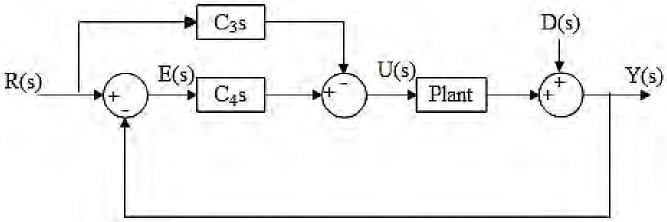

Fig. 7. Feed Forward Structure for 2 DOF PID Controller

In Fig. 6, the feedback path is applied to the traditional PID controller straight from y to u. $C_2(s)$ is termed as feedback compensator. The value of $C_1(s)$ and $C_2(s)$ are detailed in Eqn (15) and Eqn (16), respectively.

$$C_1(s) = K_i + K_p(1-\alpha) + D_f(s)K_d(1-\beta) \tag{15}$$

$$C_2(s) = K_p\left(\alpha + \tau_d \beta D_f(s)\right) = K_d \beta D_f(s) + K_p \alpha \tag{16}$$

The feed forward structure is acquired by attaching the y-to-u feed forward direction to the classical PID controller. *C₃(s)* and *C₄(s)* are mathematically represented by Eqn (17) and Eqn (18) respectively.

$$C_3(s) = K_p\left(1 + \frac{1}{\tau_i s} + \tau_d D_f(s)\right) = K_i + K_d D_f(s) + K_p \tag{17}$$

$$C_4(s) = \left(\beta \tau_d D_f(s) + \alpha\right)K_p = K_i + K_p + K_d D_f(s) \tag{18}$$

where, β & α are controller weight parameters ranged from 0 to 1; and Derivative Filter term is given by $D_f(s)$.

IV. TUNING OF PI, PI FAST AND 2DOF- PID CONTROLLER WITH PID TUNER

In the Control System Toolbox, by using P-I-D tuner, user can carry out interactive, automated tuning of PID controllers for plants. For designing the controller automatically for any given plant, the PID Tuner is used. The user has to define the type of controller, such as P, I, D, PI, PD, PID, PIDF. The plant blocks can include nonlinear effects. As automatic tuning involves a linear model, a linearized approximation of the plant in the user model is determined by the PID tuner.

PID tuning algorithm is capable to optimizing the controller gains of PI, PI-fast and 2-DOF PID controller. In order to attain a reasonable balance between efficiency and dynamism, the PID tuning algorithm tunes the gains. The tuning algorithm chooses a controller configuration for a given robustness (minimum step margin) that combines the two performance metrics, reference tracking and rejection of disturbance. PID tuning's main goals are as follows:

- Closed-loop stability: The performance of the closed-loop system remains limited to limited inputs.
- It should provide sufficient output, which implies that the device should detect reference changes and remove disruptions as quickly as possible.
- It ought to be robust. This implies that computational errors or deviations in system dynamics should be allowed.

These objectives can be fulfilled by PID tuning algorithm by tuning PID controller so as to attain steadiness between robustness and performance. The tuning algorithm has the capability to select a controller configuration that can balance performance-reference tracing and disruption rejection measurements.

V. FRACTIONAL ORDER (FO) PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLER

The differentiation-integration operator, denoted by ${}_bD_t^p$, is used in fractional calculus [32]. The concepts widely used are the definitions of Riemann-Liouville, Caputo, and Grunwald-Letnikov. The description of Grunwald-Letnikov is given in Eqn (19)

$${}_bD_t^p f(t) = \frac{d^p f(\mathrm{t})}{d(\mathrm{t}-b)^p} = \lim_{N\to\infty}\left[\frac{t-b}{N}\right]^{-p}\sum_{i=0}^{N-1}(-1)^i\binom{p}{i} f\left(t - i\left[\frac{t-b}{N}\right]\right) \tag{19}$$

The shortest and the simplest definition to use is the Riemann-Liouville definition. This definition is detailed in Eqn (20)

$${}_bD_t^p f(t) = \frac{d^p f(\mathrm{t})}{d(\mathrm{t}-b)^p} = \frac{1}{\Gamma(n-p)}\frac{d^n}{dt^n}\int_0^t (t-\tau)^{n-p-1} f(\tau)\,d\tau \tag{20}$$

where n is the first integer which is not less than p i.e. $n-1 \le p < n$ and Γ is the Gamma function that is presented in Eqn (21)

$$\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt \tag{21}$$

Unfortunately, because the Riemann-Liouville fractional derivative involves information of the function's non-integer order derivatives at t = 0, it seems inappropriate for the Laplace transformation technique to be carried out. In the Caputo definition, which is often referred to in literature as a seamless fractional derivative, this problem does not exist. Eqn (22) defines this definition of derivative.

$${}_bD_t^p f(\mathrm{t}) = \begin{cases} \dfrac{1}{\Gamma(m-p)}\displaystyle\int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{p+1-m}}d\tau & m \rangle p \rangle m-1 \\ \dfrac{d^m}{dt^m} f(t) & p = m \end{cases} \tag{22}$$

The $PI^\lambda D^\mu$ controller contains an order λ integrator and an order μ differentiator where λ and μ depicts any real numbers [33]. The transfer function of FOPID controller is expressed in Eqn (23).

$$G_1(s) = \frac{C(s)}{R(s)} = K_d s^\mu + K_p + \frac{K_i}{s^\lambda}, \qquad (\lambda, \mu > 0) \tag{23}$$

where *G₁(s)* represents the controller's transfer function, *R(s)* is an error, and C*(s)* is the output of the controller. Fig.8 depicts the block diagram of FO-PID controller.

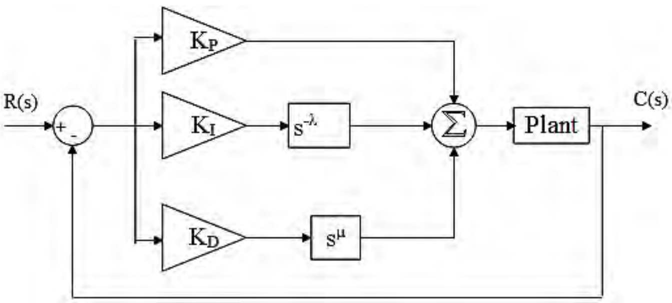

Fig. 8. Block Diagram of FO-PID Controller

The $PI^{-\lambda}D^{\mu}$ controller has the capability to refine the system's performance. The better control of the stochastic system defined by fractional order mathematical models is amongst the most significant advantages of the $PI^{-\lambda}D^{\mu}$ controller. FOPID controllers are less susceptible to changes in managed device parameters.

VI. TUNING OF FRACTIONAL ORDER (FO) PID CONTROLLER USING PARTICLE SWARM OPTIMIZATION

The algorithm for the PSO is focused on several particles in the population. Each particle is comprised of two speed and position parameters. The position is a solution in the solution space, and when analyzing optimization issues, the velocity defines the distance and direction of the next movement of the particle. Also, there is a fitness function for each particle to determine the particle's present location. This algorithm initializes a random particle group and then finds, by iteration, the approximate optimal solution and optimal solution [34]. Each particle is modified in every iteration using two "best" values. The first best solution obtained is *pbest.* The best value obtained so far by any particle in the population is another "best" value controlled by the particle swarm optimizer. Since this best value is a global best, it is regarded as gbest. The process of PSO Algorithm is outlined in Fig. 9.

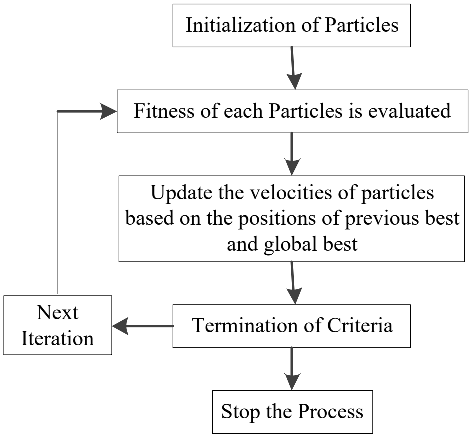

Fig. 9. Flowchart of Particle Swarm Optimization Technique

Every particle's changed velocity and position can be calculated according to Eqn (24) and Eqn (25), respectively:

$$V_{i+1} = rand() + V_i w \times C_1 \times ((p_{best})_i - X_i) + rand() + C_2 \times ((g_{best})_i - X_i) \tag{24}$$

$$X_{i+1} = V_{i+1} + X_i \tag{25}$$

where, learning factors are *'C_1'* and *'C_2'*, *'w'* is inertial weight, random number, *rand ()* has its value between 0 and 1.

This paper utilizes PSO algorithm to tune the controller gains of FOPID controller. TABLE II represents the PSO parameters. The performance index, ITAE, is used as the objective function for PSO-based Fractional Order PID tuning [35]. In other words, the aim of PSO-based optimization is to look for a collection of control gains so that there is a minimum performance index for the feedback control system. The performance index is defined to reflect the performance of the system of the configured FO-PID controller as a quantitative assessment. The ITAE function is detailed in Eqn (26)

$$ITAE = \int_0^{\infty} \left| e(t) \right| t dt \tag{26}$$

TABLE II
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

VII. SIMULATION RESULTS

To illustrate the comparison of the robustness of PI, PID controller with filter, 2 D-O-F PID and PSO optimized FO-PID controllers, step disturbance is created in system input at t = 0 sec. as shown in Fig.10. The output of the solid oxide fuel cell without any controller is depicted in Figure 11. TABLE III depicts the values of controller gains- Derivative gain (K_d), Proportional Gain (K_p), Integral Gain (K_i), order of integration (λ) and (order of derivative action (μ) obtained after tuning of PI, PI Fast, PIDF, 2-DOF PID and PSO-FOPID controllers respectively.

The output of SOFC system with various control schemes are being compared on the basis of time domain performance specifications viz. rise time, steady state error, settling time and overshoot. Figure 12-16. represents the output of SOFC with PI, PI fast, PID with filter, 2-DOF PID and PSO-FOPID controllers respectively. From TABLE IV, this is observed that, in the absence of any controller, the rise time (47.3678 sec), steady state error (99.1%), and settling time (86.3005 sec) obtained in system output are very high. The settling time is reduced to 19.7735 sec, 11.8796 sec, 1.8152 sec and 0.2 sec, respectively, with application of PI, PIDF, 2-DOF PID and PSO-FOPID controllers respectively. Further, the rise time has also decreased tremendously from 1.1612 with 2DOF-PID to 0.0806 sec with PSO-FOPID controller. The steady state error drastically reduces to 0% with PSO-FOPID controller. Thus, artificial intelligence optimized PSO-fractional order PID control scheme results in best values of time domain specifications i.e. overshoot, steady state error, settling time and rise time, and for SOFC system output.

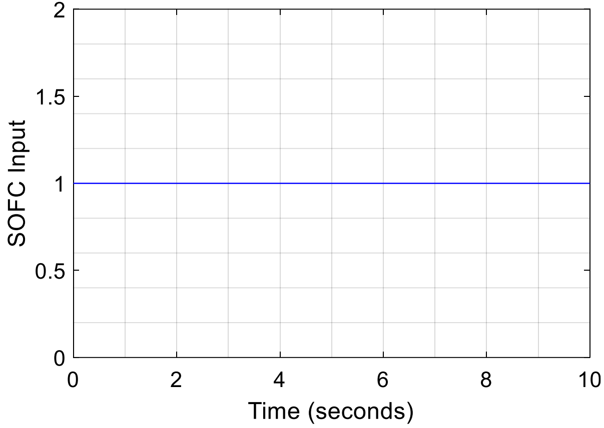

Fig. 10. SOFC Output with PIDF Controller

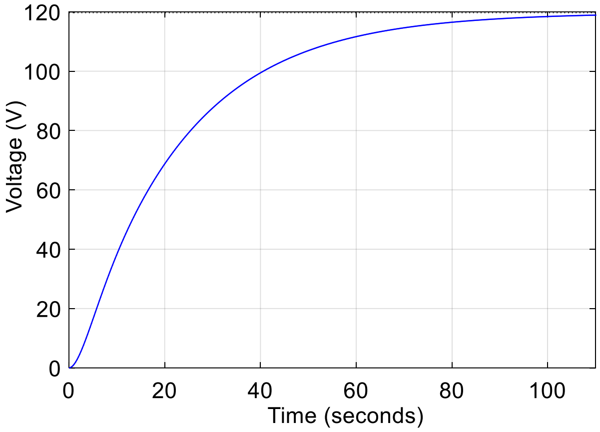

Fig. 11. SOFC Output without Controller

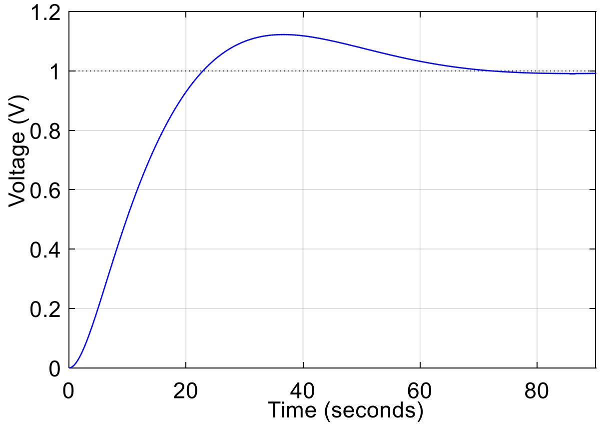

Fig. 12. SOFC Output with PI Controller

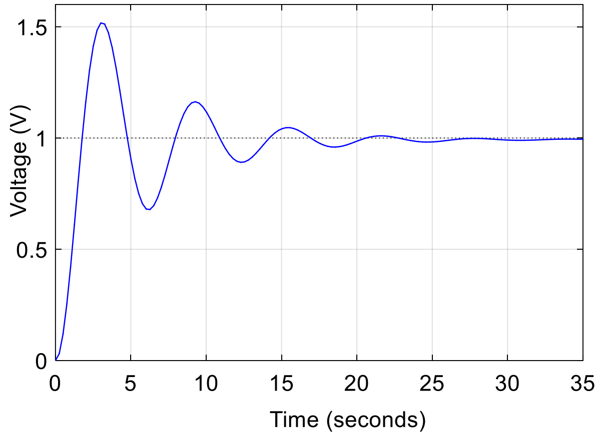

Fig. 13. SOFC Output with PI Fast Controller

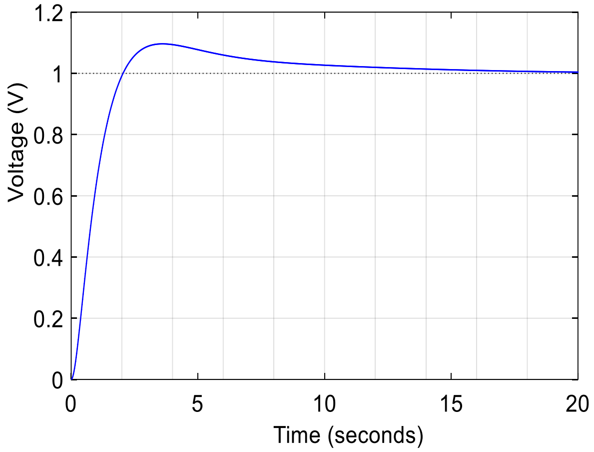

Figure 14. SOFC Output with PIDF Controller

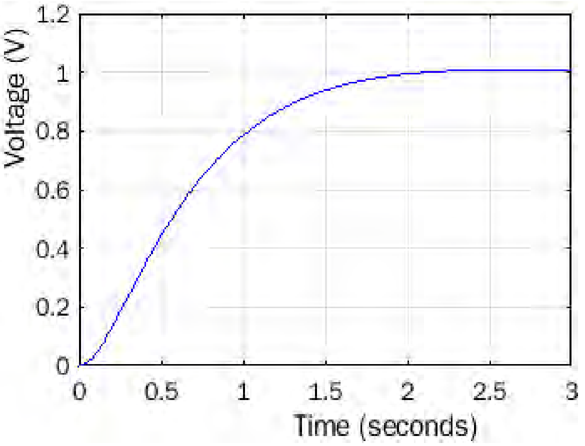

Fig. 15. SOFC Output with 2DOF PID Controller

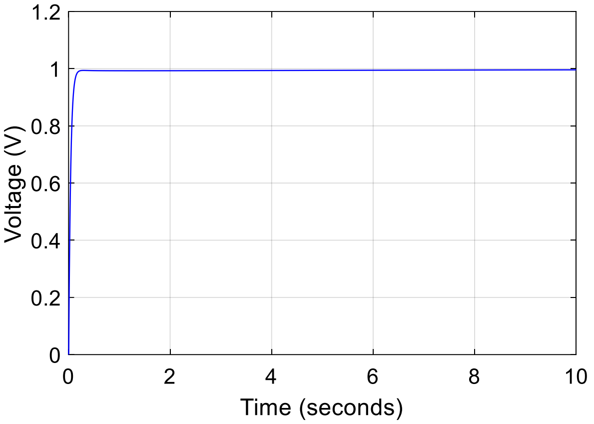

Fig. 16. SOFC Output with PSO-FOPID Controller

TABLE III
VALUE OF CONTROLLER GAIN PARAMETERS

Type of Controller	**Controller Parameters**				
	K_p	**K_i**	**K_d**	**λ**	**μ**
PI	0.0108	0.00112	NA	NA	NA
PI Fast	0.424	0.00742	NA	NA	NA
PIDF	0.226	0.0338	0.356	NA	NA
2DOFPID	0.397	0.0656	0.557	NA	NA
PSO-FOPID	1.10976	0.778	10.6678	0.198	0.99

TABLE IV
SOFC Output

Performance Specification	**SOFC OUTPUT**					
	No Controller	**Control Scheme**				
		PI	**PI FAST**	**PIDF**	**2-DOF PID**	**PSO-FOPID**
Rise Time (sec)	47.3678	15.7877	1.1870	1.3721	1.1612	0.0806
Settling Time (sec)	86.3005	63.5589	19.7735	11.8796	1.8152	0.2
Peak Overshoot (%)	0	12.2371	51.7062	9.6368	0.8583	0.296
Steady State Error (%)	119	0.9	0.5	0	1	0

VIII. CONCLUSION

SOFCs are gaining attention because of high electrical efficiency and high power density. However, its performance is affected by nonlinearity, minimal flow of fuels, unregulated voltage and changes in load disturbances. In this paper, five control schemes namely-PI, PI fast, PID with filter, 2-degreee of freedom PID and PSO tuned Fractional Order PID controllers are implemented for performance improvement of SOFC system subject to uncertainties in input conditions. The MATLAB simulation results indicate that, in the absence of any controller, the SOFC system behaviour is highly sluggish with large steady state error. The SOFC output with various controllers is compared quantitatively in terms of rise time, steady state error, settling time and overshoot. There is not much improvement in SOFC output with PI, PI Fast and PIDF controllers. However, with the 2-DOF PID and PSO-FOPID control schemes yields in far superior performance. With the PSO-FOPID controller, the best values of steady state error, rise time, settling time and overshoot are obtained. Thus, remarkable improvement in SOFC output is ensured with PSO-FOPID controller. This may be considered to be an efficient and effective way of regulating the SOFCs output voltage. Therefore, the proposed PSO optimized FO-PID controller is capable of handling output degradation in presence of input uncertainties.

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Swati Singh is research scholar at Amity School of Engineering & Technology, Noida. Her interests includes controller design and renewable energy systems.

Vijay Kumar Tayal received his M.Tech and Ph.D. from NIT, Kurukshetra. Presently he is Associate Professor in Department of Electrical & Electronics Engineering at Amity School of Engineering & Technology (ASET), Noida. His research interests are Robust and Fuzzy Controller Design and intelligent controller design

Hemender Pal Singh received his Ph.D. degree from Rohilkhand University Bareilly, UP. Presently he is Professor and Head of Department (HOD) inDepartment of Electrical & Electronics Engineering at Amity School of Engineering & Technology (ASET), Noida. His research interests are Optical Communication, and Instrumentation Systems.

Vinod Kumar Yadav received his Ph.D. from Indian Institute of Technology, Roorkee, Uttarakhand. He is currently Professor in Electrical Engineering at Delhi Technological University, New Delhi. He has his contributions in the areas of power system and renewable energy resources.