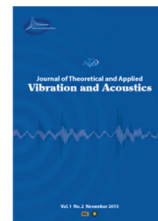




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Increasing the efficiency of an electrostatic precipitator using fuzzy adaptive state-feedback controllers

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ABSTRACT

In recent years, electrostatic precipitators have been widely utilized in waste gas treatment processes across various plants and factories. Nevertheless, enhancing the efficiency of electrostatic precipitators requires additional research focused on the design of controllers to manage the input voltages. The present study introduces a fuzzy adaptive state-feedback controller for an electrostatic precipitator. Initially, the mathematical modeling of the electrostatic precipitator is examined. A state-feedback controller is developed using both the system error and its derivative to enhance the system's efficiency. The gradient descent method and the chain derivative rule are employed to adaptively adjust the control parameters. Subsequently, a fuzzy system comprising a singleton fuzzifier, product inference engine, and center average defuzzifier is implemented to enhance control performance. Ultimately, the simulation results are presented to demonstrate the effectiveness and capability of the proposed approach in comparison with other methods. More specifically, the recommended control strategy can quickly bring the system's performance to its desired efficiency level.

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1. Introduction

An electrostatic precipitator (ESP) is widely utilized as an air purification device to eliminate particles from gas during waste gas treatment in thermal power plants, cement factories, and various other industrial facilities. For instance, X. Yan [1] conducted a numerical design for a self-pumped ESP aimed at particle collection. Xu et al. [2] explored how activated carbon injection

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combined with a low-temperature electrostatic precipitator affects the adsorption of condensable particulate matter in the flue gas of a coal-fired power plant with ultra-low emissions. Zhu et al. [3] examined six types of two-stage electrostatic precipitators featuring different charger and collector units to enhance the overall control of PM 2.5 capture and ozone emissions. A coupled multi-physics model integrating electric, flow, and particle fields was developed by Li et al. [4]. In this study, the impact of three distinct designs of corrugated dust collector plates is analyzed on the airflow patterns, the electric field distribution, dust removal efficiency, and particle trajectories in an electrostatic precipitator. Qi et al. [5] introduced a technology for evaporation of charged droplets to enhance electrostatic dust removal, aiming to achieve zero discharge of desulfurization wastewater and effectively eliminate fine particles. Krupa et al. [6] conducted experimental research on the influence of injecting sodium bicarbonate and calcium hydroxide sorbents at dry and low temperatures on the concentration and size distributions of precipitated particles, as well as the fractional collection efficiency and morphology of the particles. The deposition behaviors of weld fume particles within an electrostatic precipitator were explored through numerical simulations by Song et al. [7]. The efficiency of a two-stage electrostatic precipitator featuring an ionizer with a surface dielectric barrier discharge was experimentally examined by Tański et al. [8]. Shi et al. [9] introduced a detailed numerical model to explore the characteristics of the electric field and particle movement in an ESP within temperature ranges of 400 to 600 °C. Yu et al. [10] developed a triangular prism-multiple tubular wet electrostatic precipitator to address the high costs of existing air purification technologies.

State feedback and Proportional Derivative (PD) controllers have been widely utilized to create straightforward systems for tracking reference points. For example, Tolun and Tutsoy [11] explored the modeling and performance evaluation of PD controllers for electric autonomous vehicles amid environmental uncertainties. Tripathy et al. [12] introduced a dual-mode PI/PD controller designed to manage the frequency in unified systems incorporating renewable and conventional power generation sources. Alansari et al. [13] examined a variable structure PD controller for controlling satellite attitudes, including its stability analysis and optimal performance. You et al. [14] introduced a finite time controller with a PD-like design for satellite attitude control. Xie and Sun [15] proposed a modified version of the PD controller intended for second-order nonlinear uncertain systems. Torres-García et al. [16] concentrated on analyzing the behavior of critical roots within a dynamical system equipped with a PD controller. Manikantan et al. [17] explored parameter identification in nonlinear systems utilizing a PD controller based on a limited set of experimental data. Sain et al. [18] demonstrated the effectiveness of a newly developed fuzzy PI/PD controller in both simulation and real-time applications for a nonlinear and unstable magnetic levitation system. Shayeghi et al. [19] designed a multi-stage proportional-derivative controller combined with a proportional-integrator controller to manage DC-DC buck converters. Han et al. [20] proposed an intelligent PD stabilizer based on a linear discrete-time extended state observer for motion control of a lower limb exoskeleton aimed at rehabilitation and power enhancement, employing a tracking differentiator with a sigmoid function.

Adaptive control is a technique that modifies control gains to account for system parameters that are variable or initially not well-defined. The ability of tensegrities to adaptively control was examined by Hong et al. [21] to prevent transitions between bistable states caused by structural instability due to loading. Lu et al. [22] addressed and resolved the issue of inverse optimal adaptive control for nonlinear systems facing parametric and dynamic uncertainties. Zhang et al. [23] introduced a partial-state feedback model reference adaptive control approach for uncertain

linear time-invariant systems affected by unmatched disturbances. Niu et al. [24] sought to enhance the tracking control performance of a three-stage valve within an electro-hydraulic servo system that experiences parameter uncertainties and other lumped unknown nonlinear factors, such as undisclosed dynamics and disturbances. Xu et al. [25] developed a singularity-free adaptive tracking control strategy for a general category of multi-input and multi-output uncertain discrete-time nonlinear systems featuring non-canonical control gain matrices. Qian et al. [26] introduced a model-free adaptive control approach for marine lead-bismuth-cooled nuclear reactors to tackle significant oscillatory processes. Li et al. [27] assessed network integration across the entire brain and examined how these metrics from graph theory were influenced by adaptive control. Liu et al. [28] addressed the challenge of calculating adaptive backstepping tracking controllers for uncertain nonlinear systems with unknown input saturation. Yin and Liu [29] introduced an adaptive multistep model predictive control strategy aimed at enhancing the fuel efficiency of tubular grid-connected solid oxide fuel cells, considering systemic thermodynamics and electrochemistry constraints. Chen et al. [30] proposed a composite adaptive robust control method for a pneumatic servo system with varying inertia to achieve effective tracking performance.

A fuzzy control system utilizes fuzzy logic as a mathematical approach that interprets analog input values through logical variables represented as continuous values ranging from 0 to 1. Zhang et al. [31] proposed a semi-active control algorithm for adaptive variable stiffness intelligent structures that combines a fuzzy control strategy with long short-term memory to reduce structural responses during earthquake excitations. Chu et al. [32] presented a fuzzy control method for managing temperature in gas flow systems that involves a mixture of cold and hot gases. Xu et al. [33] suggested a spatiotemporal fuzzy control method that considers both temporal and spatial dynamics for complex distributed parameter systems that are not well understood. A composite adaptive fuzzy control approach utilizing command-filtered backstepping and event-triggered mechanisms for nonlinear, nonstrict-feedback systems facing input saturation and time-varying full-state constraints was proposed by Hu et al. [34]. Zhang et al. [35] explored the hill-climbing algorithm alongside the fuzzy control tracking technique to identify the resonant frequency in a percussive ultrasonic drill. Acharya et al. [36] suggested an optimal rule-based fuzzy proportional integral regulator to manage the core power of a molten salt breeder reactor model. Song and Tong [37] examined a reinforcement Q-learning fuzzy optimal tracking control method for nonlinear underactuated unmanned surface vehicles subjected to external disturbances. Jia et al. [38] introduced a full-state constraint approach for stabilizing nonlinear systems using a fuzzy control method to approximate unknown functions. Utilizing a robust evolving cloud-based protocol, Lamraoui and Habbi [39] proposed a decentralized fuzzy control strategy for a strongly interacting thermal exchanger process. Du et al. [40] presented a dissipativity-based event-triggered fuzzy control concept for unreliable networked systems. Mahmoodabadi and Nejadkourki [41] recommended a fuzzy adaptive controller to regulate the joint variables' positions for a nonlinear 3DOF revolute-prismatic-prismatic manipulator. This paper introduces a novel fuzzy adaptive state-feedback controller designed to enhance performance and boost the efficiency of an electrostatic precipitator. The state-feedback controllers are formulated based on the system's operational efficiency.

Subsequently, fuzzy logic-based systems equipped with a singleton fuzzifier, center average fuzzified, and product inference engine are employed to adjust the control parameters. Simulation results demonstrate the effectiveness of the proposed strategy in improving the performance of the ESP. The structure of the paper is outlined as follows. Section 2 covers the mathematical modeling

of the electrostatic precipitator system being examined. A brief overview of the state-feedback controller is provided in Section 3. Section 4 offers a short introduction to the fuzzy logic-based controller. The results are showcased in Section 5, demonstrating the effectiveness of the proposed method. Finally, Section 6 presents the conclusions and discusses possible future work.

2. Modelling of the electrostatic precipitator

Devices known as electrostatic precipitators, or electrostatic air cleaners, utilize an electric charge to eliminate specific impurities—whether solid particles or liquid droplets—from air or other gases in smokestacks and flues. They have been extensively used to extract dust particles from industrial flue gases [42]. An ESP primarily comprises multiple electric-field stages arranged in a cascade powered by a high-voltage power supply unit. In the stage featuring a series of grounded parallel plates alongside high-voltage discharge wires, the discharge electrodes are connected to the high-voltage power supply's output, with equal spacing in the halfway plane of the collecting electrodes. Electrostatic precipitators play a crucial role in managing air pollution to reclaim valuable materials from industrial processes, especially in removing harmful particulate matter from waste gases at industrial sites and power generation stations [43-45].

When the negative DC high voltage is applied to the discharge electrodes, many ions and electrons are generated at the corona point. These ions and electrons interact with the dust particles in the gas, causing the particles to become charged. The charged particles, influenced by the Coulomb force, move towards and settle on the collecting plates, resulting in a current that flows from the collecting plates to the discharge electrodes and returns to the TR (Rectifier Transformer). Once the layer of deposited dust becomes sufficiently thick, the electric hammers powered by the vibrating motors strike the collecting plates, causing the dust to fall off. To model the efficiency of an ESP, one may determine the concentration of dust at the outlet by considering the initial dust concentration along with the collection efficiency, as described below.

$$C_o = (1 - E)C_{in} \quad (1)$$

In this context, C_o denotes the concentration at the outlet (mg/Nm^3), while C_{in} indicates the concentration at the input (mg/Nm^3), and E signifies the collection efficiency. When the input concentration remains constant, the concentration at the outlet is influenced by the collection efficiency. Over the past decades, several analytical models related to collection efficiency have been formulated, with the classical model proposed by Deutsch in 1992 being one of them.

$$E = 1 - \exp\left(\frac{-\omega A}{q}\right) \quad (2)$$

In this context, ω represents the speed at which dust particles migrate (in meters per second), A indicates the surface area of the collection plates (in square meters), and q refers to the volume flow rate of the gas (in cubic meters per second). Additionally, the collection efficiency has been expressed in an alternative format [46]:

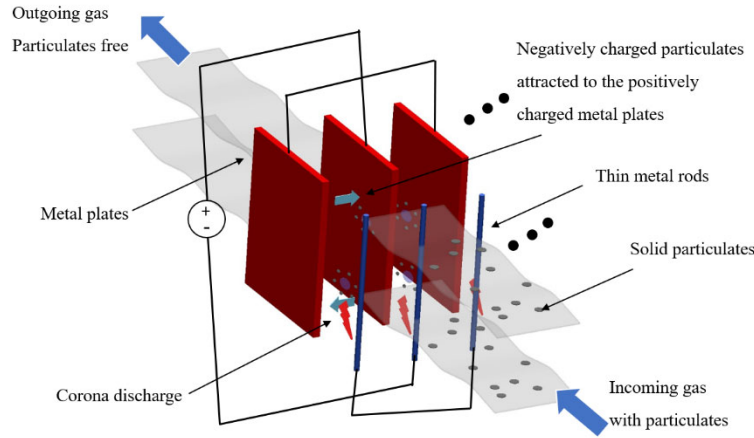


Fig. 1. Assignment of discharge electrodes and collecting electrodes.

$$E = 1 - \exp\left(\frac{-\omega L}{vb}\right) \quad (3)$$

where L refers to the length of the collecting plates in the direction of the gas stream (m), v represents the velocity of the gas flow (m/s), and b indicates the separation distance between the discharge electrode and the collecting electrode (m), as depicted in Figure 1. The migration velocity ω can be determined using the following formula.

$$\omega = \frac{\varepsilon_0 \varepsilon_s}{\mu(\varepsilon_s + 2)} d_p U^2 \quad (4)$$

where ε_0 is the permittivity of vacuum (8.85×10^{-12} F/m), ε_s refers to the specific permittivity, d_p is the particle diameter (m), and U denotes the electric-field intensity (V/m). It has been observed that the collection efficiency E is primarily influenced by distance b , length L , particle diameter d_p , gas velocity v , electric-field intensity U , and electric properties of dust particles. The numerical values for the constant parameters of the electrostatic precipitator are listed in Table 1. U is predominantly influenced by the secondary voltage, distance b , distance between two adjacent discharge electrodes, and the geometric configuration of the discharge electrode. Furthermore, E is also connected to various other aspects, including the count of the cascaded electric-field stages, the temperature and the pressure of the flue gas, the airflow distribution, the air leakage condition, the knocking results, and the power supply modes. However, within the context of an electrostatic precipitator, it is noteworthy that among the factors mentioned, only the secondary voltage varies during the operation of the electrostatic precipitator [47]. In controlling an ESP, aiming for the highest collection efficiency can result in significant electrical energy wastage if an excessive secondary voltage is required. This study presents a state-feedback approach that considers the requirements for outlet concentration. Specifically, a new fuzzy adaptive state feedback control strategy is introduced to enhance the effectiveness of an electrostatic precipitator. The configuration specifications for the ESP include a collection area of 90 m^2 , a rated secondary voltage of 72 Kv , and a rated secondary current of 800 mA .

Table 1. Values of the constant parameters for the electrostatic precipitator.

Definition	Parameter	Value
Specific permittivity	ϵ_s	1.00059
Particle diameter	d_p	$70 \times 10^{-6}(\text{m})$
Vacuum permittivity	ϵ_0	$8.85 \times 10^{-12} (\text{F/m})$
Instance between the discharge electrode and the collecting electrode	b	$7 \times 10^{-2}(\text{m})$
Gas flow velocity	v	1 (m/s)
Vacuum permeability	μ	1.256×10^{-6}
Length of collecting plates along the gas stream	L	$90 \times 10^{-3}(\text{m})$

A highly regarded controller, whose output is directly related to both the error signal $e(t)$ and its derivative $\dot{e}(t)$ is referred to as the state feedback or proportional plus derivative (PD) controller, designed to create a straightforward system for following reference inputs [48].

$$f(t) = k_p e(t) + k_d \dot{e}(t) \tag{5}$$

where, k_p and k_d represent non-negative coefficients for the proportional and derivative components, accordingly. In this study, the error signal and its derivative at time t_i are defined as follows.

$$e(t_i) = 1 - E(t_i) \tag{6}$$

$$\dot{e}(t_i) = \frac{e(t_i) - e(t_{i-1})}{t_i - t_{i-1}} \tag{7}$$

In this context, $E(t_i)$ represents the collection efficiency at a time t_i .

4. Adaptation of the state-feedback gains

Adaptation laws are frequently employed to adjust the control parameters in a timely manner. In this study, an adaptive method based on sliding mode control is utilized to adjust the proportional and derivative gains of the controller that was designed. The sliding mode control theory was first introduced by Utkin in 1997 [49], and since then, its theoretical framework and applications have been expanded in various fields of science and technology. Typically, the sliding surface associated with the system error is defined using the equation below [50].

$$S(e, t) = \left(\frac{d}{dt} + \delta \right)^{n-1} e \tag{8}$$

where, δ is a positive constant, and n represents the order of the system. Consequently, for a system of the second order, it is expressed as follows.

$$S = \dot{e} + \tilde{\delta} e \tag{9}$$

in which, $\tilde{\delta}$ is regulated by fuzzy parameters $\hat{\delta}$ as follows.

$$\tilde{\delta} = \delta + \hat{\delta} \tag{10}$$

where δ is a constant parameter. According to the relationships outlined above, the adaptive parameters are characterized as follows.

$$\dot{k}_p = -\tilde{\gamma}_1 S e \tag{11}$$

$$\dot{k}_d = -\tilde{\gamma}_2 S \dot{e} \tag{12}$$

where, $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ are respectively regulated by fuzzy parameters $\hat{\gamma}_1$ and $\hat{\gamma}_2$, as described below.

$$\tilde{\gamma}_1 = \gamma_1 + \hat{\gamma}_1 \tag{13}$$

$$\tilde{\gamma}_2 = \gamma_2 + \hat{\gamma}_2 \tag{14}$$

where, γ_1 and γ_2 denote constant parameters.

5. Fuzzification of the adaptive state-feedback parameters

Fuzzy logic [51] represents many-valued logic where the truth value of variables can be any real number ranging from 0 to 1 [52]. In contrast, Boolean logic restricts the truth values of variables to just the integer values 0 or 1. In real-life scenarios, there are many instances where it is impossible to ascertain whether a state is true or false. In such cases, fuzzy logic offers significant flexibility for reasoning. Fuzzy logic finds application in various fields, including control systems [53,54], image processing [55,56], natural language processing [57], medical diagnosis [58,59], and artificial intelligence [60,61].

In this study, fuzzy logic is employed to manage the control parameters, $\hat{\delta}$ and $\hat{\gamma}_i$ ($i=1,2$). The implemented fuzzy system features a singleton fuzzifier, a product inference engine, and a center average defuzzifier. It is evident that the product inference engine employs a rule-based inference approach with a union combination, using Mamdani's product implication and algebraic product for all t-norm operators, along with max for all s-norm operators [62].

Ultimately, the equation below can compactly express a mix of these components.

$$fuzzy\ parameter = \frac{\sum_{i=1}^N \bar{y}^i (\mu_A^i(e_i))}{\sum_{i=1}^N \mu_A^i(e_i)} \tag{11}$$

where, \bar{y}^i represents the centers of the output membership functions. N denotes the number of rules set to three in this case. Additionally, μ_A^i indicates the input membership functions, which are defined as triangular membership functions (see Figure 2). Furthermore, the fuzzy rules expressed in an if-then format concerning the error input and control parameters are shown in Table 2. It is important to note that stability is the most critical attribute of a closed-loop control system. For stability analysis to occur, mathematical models for the system must be used. Conversely, fuzzy control systems are typically formulated based on experiential human knowledge rather than mathematical models, making it challenging to assess the stability of these systems under such circumstances. However, C. Volosencu [63] has proposed some general concepts for the stability analysis of fuzzy controllers.

6. Results

In this section, the block diagram of the proposed feedback adaptive state feedback controller for the examined ESP is depicted in Figure 3. The simulation of the analyzed ESP is conducted, and the results will be presented. In this context, Figure 4 depicts the efficiency time history for three controllers: state-feedback, adaptive state-feedback, and fuzzy adaptive state-feedback. The preferred controller exhibits quicker performance with reduced overshoot and undershoot compared to the other controllers. Figs. 5 and 6 show the control coefficients for the proportional and derivative terms over time, which remain constant in the state-feedback controller. Additionally, Figures. 7, 8, and 9, respectively, illustrate the time responses of the control gains $\tilde{\delta}$, $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$. It is evident that the parameters $\tilde{\delta}$, $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ reach stable values of -19, 91, and 20 after 0.02s, 0.08s, and 0.08s, respectively. This convergence indicates the stability of the intended control approach schematically. Lastly, Fig. 10 shows the time responses of the control efforts provided by the state feedback, adaptive state feedback, and fuzzy adaptive state feedback controllers. These graphs clearly indicate that the suggested method outperforms the other two methods with significantly faster response and reduced overshoot and undershoot values.

Table 2. Fuzzy rule base for the regarded fuzzy parameters.

	$\hat{\delta}$	$\hat{\gamma}_1$	$\hat{\gamma}_2$
S	-10	50	-5
M	-20	-30	-7
B	-10	10	20

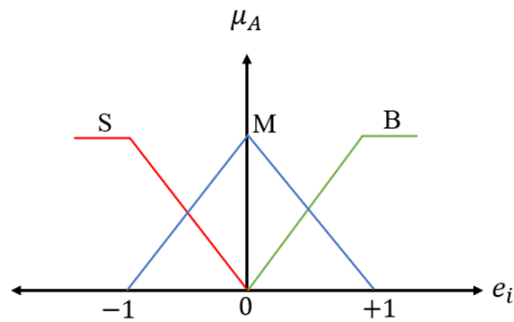


Fig. 2. Membership functions for the fuzzy variables.

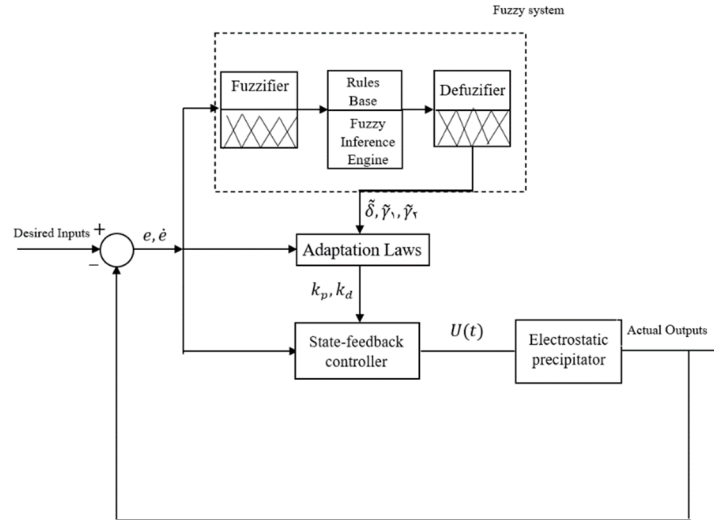


Fig. 3. Block diagram of the proposed feedback, adaptive state feedback controller designed for the considered ESP.

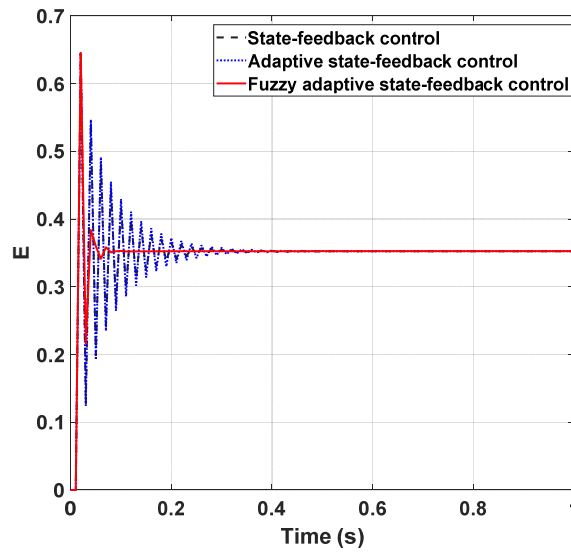


Fig. 4. Time variations of the efficiency of the considered ESP for different control approaches.

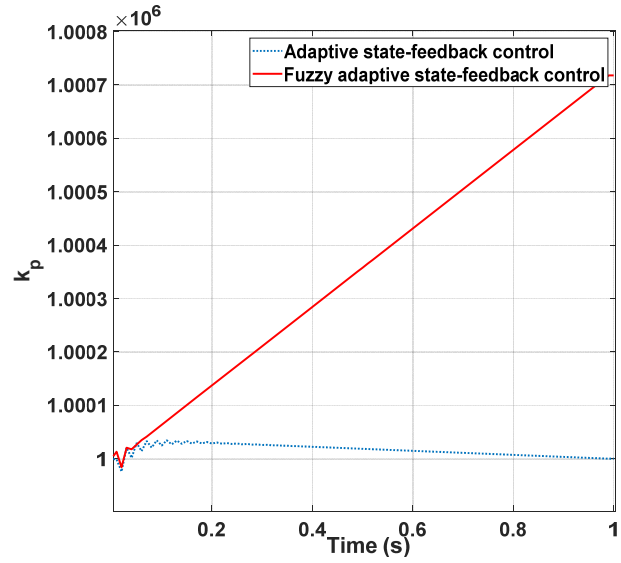


Fig. 5. Time variations of the proportional gain for different control approaches applied on the considered ESP.

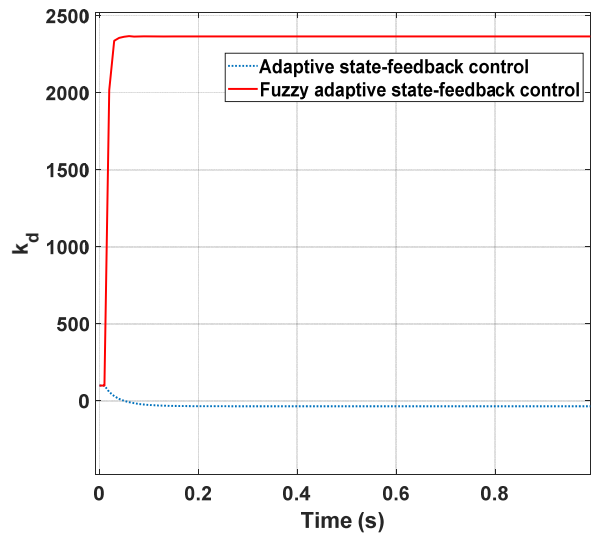


Fig. 6. Time variations of the derivative gain for different control approaches applied on the considered ESP.

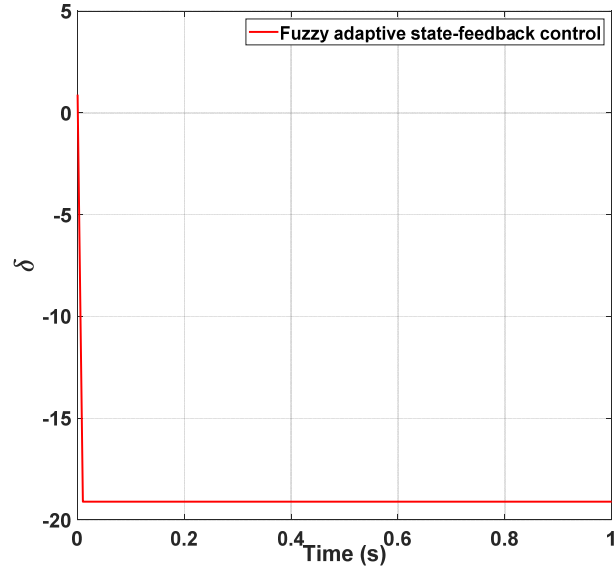


Fig. 7. Time variations of the sliding surface parameter in the introduced control approach for the considered ESP.

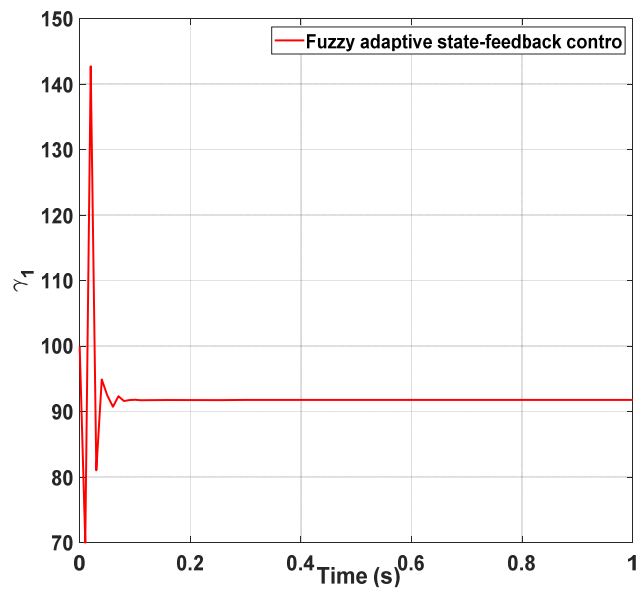


Fig. 8. Time variations of the first adaptive parameter in the introduced control approach for the considered ESP.

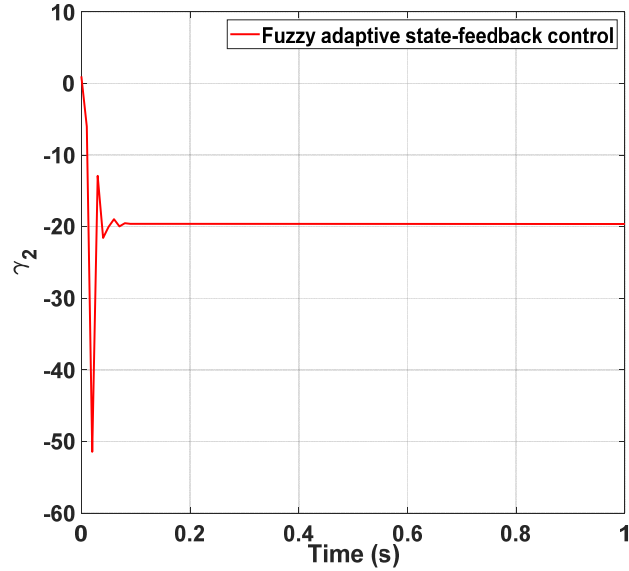


Fig. 9. Time variations of the second adaptive parameter in the introduced control approach for the considered ESP.

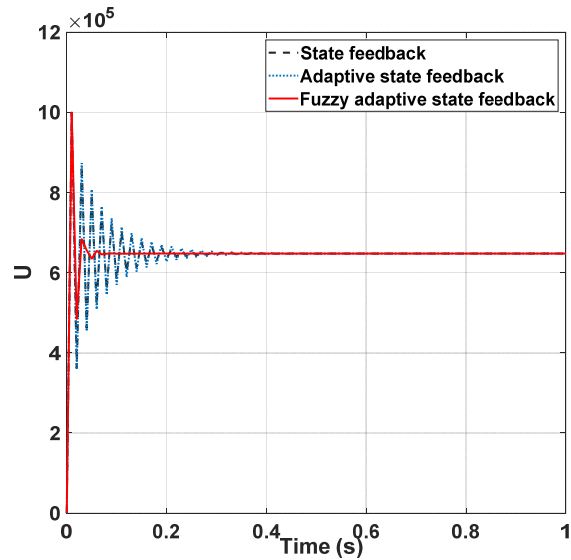


Fig. 10. Time variations of the control efforts for different control approaches applied on the considered ESP.

7. Conclusions and future works

A fuzzy adaptive state-feedback controller has been developed to achieve optimal collection efficiency and reduced energy consumption in electrostatic precipitators (ESPs). The adaptation process is founded on robust sliding mode surfaces and the gradient descent technique. The fuzzy system has been structured around triangular membership functions, a singleton fuzzifier, a center average defuzzifier, and a product inference engine. Additionally, simulation results demonstrate several advantages of the proposed method, including lower control effort and increased efficiency

compared to alternative approaches. Prospective projects connected to this study might be outlined as follows:

- (a) Implementing the proposed control strategy on a more precise model of the ESP,
- (b) Using fractional-order computations to enhance the control system's performance, and
- (c) Utilizing optimization algorithms to determine better values for the control parameters.

References

- [1] X. Yan, Numerical design of self-pumped electrostatic precipitators for particle collection, *Chemical Engineering Research and Design*, 186 (2022) 149-160.
- [2] Z. Xu, Y. Wu, X. Huang, S. Liu, M. Tang, S. Lu, Study on the control of condensable particulate matter by spraying activated carbon combined with electrostatic precipitator, *Atmospheric Pollution Research*, 13 (2022) 101544.
- [3] Y. Zhu, Z. Wei, X. Yang, S. Tao, Y. Zhang, W. Shangguan, Comprehensive control of PM 2.5 capture and ozone emission in two-stage electrostatic precipitators, *Science of The Total Environment*, 858 (2023) 159900.
- [4] Y. Li, Y. Wang, A. Chen, Flexible integration and segregation of large-scale networks during adaptive control, *Behavioural Brain Research*, 451 (2023) 114521.
- [5] C. Qi, X. Yang, J. Yao, W. Wang, Y. Dong, X. Xu, L. Cui, Effect of charged spray evaporation of desulfurization wastewater on fine particle removal efficiency of electrostatic precipitator, *Process Safety and Environmental Protection*, 179 (2023) 99-107.
- [6] A. Krupa, A.T. Sobczyk, A. Marchewicz, A. Jaworek, Fly ash and sorbent particles agglomeration and removal in system of electrostatic agglomerator and electrostatic precipitator, *Powder Technology*, 431 (2024) 119075.
- [7] W. Song, S. Tong, Fuzzy optimal tracking control for nonlinear underactuated unmanned surface vehicles, *Ocean Engineering*, 287 (2023) 115700.
- [8] M. Tański, A. Reza, D. Przytuła, K. Garasz, A. Tomaszewski, Electrostatic precipitator with Surface Dielectric Barrier Discharge ionizer, *Journal of Cleaner Production*, 404 (2023) 136990.
- [9] Y. Shi, M. Fang, Q. Wang, K. Yan, J. Cen, Z. Luo, Enhanced high-temperature particle capture through an electrostatic precipitator with assistant electrodes, *Separation and Purification Technology*, 324 (2023) 124550.
- [10] Z. Yu, J. Liu, R. Shen, G. Li, M. Zhu, C. Lv, Development and evaluation of a triangular prism-multiple tubular wet electrostatic precipitator for capturing moxibustion oil fumes, *Chemical Engineering Journal*, 475 (2023) 146440.
- [11] O.C. Tolun, O. Tutsoy, Modelling and performance-based PD controller of the electric autonomous vehicles with the environmental uncertainties, *Journal of engineering research*, 11 (2023) 100059.
- [12] S. Tripathy, M.K. Debnath, S.K. Kar, Optimal design of PI/PD dual mode controller based on quasi opposition based learning for power system frequency control, *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, 4 (2023) 100135.
- [13] A. Alansaari, I. Boiko, S. Swei, Variable-structure PD controller for satellite attitude: Stability analysis and design for optimal performance, *Journal of the Franklin Institute*, 360 (2023) 9728-9753.

- [14] L. You, Y. Dong, X. Bing, PD-like finite time controller with simple structure for satellite attitude control, *Defence Technology*, 26 (2023) 123-133.
- [15] W. Xie, Y. Sun, A new result on PD controller design for second order nonlinear uncertain systems, *Journal of the Franklin Institute*, 359 (2022) 7307-7318.
- [16] D. Torres-García, C.-F. Méndez-Barrios, S.-I. Niculescu, A. Martínez-González, Delay-difference approximation of PD-controllers. insights into improperly-posed closed-loop systems, *IFAC-PapersOnLine*, 55 (2022) 79-84.
- [17] R. Manikantan, C. Vyasrayani, M. Manjuprasad, Parameter Identification in Nonlinear Systems Using PD Controllers as Penalty Functions, *IFAC-PapersOnLine*, 53 (2020) 602-607.
- [18] D. Sain, B. Mohan, Simulation and real-time implementation of a nonlinear fuzzy PI/PD controller, *IFAC-PapersOnLine*, 53 (2020) 673-678.
- [19] H. Shayeghi, A. Rahnama, N. Takorabet, P. Thounthong, N. Bizon, Designing a multi-stage PD (1+ PI) controller for DC–DC buck converter, *Energy Reports*, 8 (2022) 765-773.
- [20] S. Han, H. Wang, Y. Tian, A linear discrete-time extended state observer-based intelligent PD controller for a 12 DOFs lower limb exoskeleton LLE-RePA, *Mechanical systems and signal processing*, 138 (2020) 106547.
- [21] H. Hong, H. Deng, Adaptive control to prevent transfer between bistable configurations of a tensegrity, *International Journal of Solids and Structures*, 284 (2023) 112503.
- [22] K. Lu, Z. Liu, H. Yu, C.P. Chen, Y. Zhang, A small-gain approach to inverse optimal adaptive control of nonlinear systems with unmodeled dynamics, *Automatica*, 159 (2024) 111360.
- [23] Z. Zhang, Y. Sang, X. Chen, Model reference adaptive disturbance rejection control using partial-state feedback, *Automatica*, 154 (2023) 111071.
- [24] S. Niu, J. Wang, J. Zhao, W. Shen, Neural network-based finite-time command-filtered adaptive backstepping control of electro-hydraulic servo system with a three-stage valve, *ISA transactions*, 144 (2024) 419-435.
- [25] Y. Xu, Y. Zhang, J.-F. Zhang, Singularity-free adaptive control of MIMO discrete-time nonlinear systems with general vector relative degrees, *Automatica*, 153 (2023) 111054.
- [26] H. Qian, M. Han, Model-free adaptive control of average coolant temperature in a novel marine small lead–bismuth-cooled reactor, *Annals of Nuclear Energy*, 195 (2024) 110162.
- [27] Y. Li, Y. Wang, A. Chen, Flexible integration and segregation of large-scale networks during adaptive control, *Behavioural Brain Research*, 451 (2023) 114521.
- [28] J. Liu, X. Chen, J. Yu, Simplified adaptive backstepping control for uncertain nonlinear systems with unknown input saturation and its application, *Control Engineering Practice*, 139 (2023) 105639.
- [29] L. Yin, D. Liu, Adaptive multistep model predictive control for tubular grid-connected solid oxide fuel cells, *Renewable Energy*, 216 (2023) 119062.
- [30] Y. Chen, G. Tao, Y. Yao, A composite adaptive robust control for pneumatic servo systems with time-varying inertia, *Control Engineering Practice*, 137 (2023) 105556.
- [31] Q. Zhang, D. Tang, Q. Quan, Y. Jin, Z. Deng, Hill-climbing & fuzzy combined control algorithm for a percussive ultrasonic drill, *Applied Acoustics*, 211 (2023) 109499.

- [32] J. Chu, Z. He, W. Wang, B. Li, G. Yang, Fuzzy control of temperature in gas flow control system based on mixed cold and hot gases, *International Communications in Heat and Mass Transfer*, 148 (2023) 107048.
- [33] B. Xu, X. Lu, Y. Bai, A spatiotemporal fuzzy control approach for complex distributed parameter system with application to thermal processes, *Journal of Process Control*, 127 (2023) 102993.
- [34] Y. Hu, W. Liu, B. Ma, Event-trigger-based composite adaptive fuzzy control for nonlinear time-varying state constraint systems with asymmetric input saturation, *European Journal of Control*, 75 (2024) 100892.
- [35] H. Zhang, L. Wang, W. Shi, Seismic control of adaptive variable stiffness intelligent structures using fuzzy control strategy combined with LSTM, *Journal of Building Engineering*, 78 (2023) 107549.
- [36] D. Acharya, A. Rai, D.K. Das, Optimal rule based fuzzy-PI controller for core power control of nuclear reactor, *Annals of Nuclear Energy*, 194 (2023) 110118.
- [37] W. Song, S. Tong, Fuzzy optimal tracking control for nonlinear underactuated unmanned surface vehicles, *Ocean Engineering*, 287 (2023) 115700.
- [38] F. Jia, J. Lu, Y. Li, F. Li, Fuzzy adaptive stabilization control for nonlinear systems with FSCs, *Fuzzy Sets and Systems*, 473 (2023) 108738.
- [39] O. Lamraoui, H. Habbi, Experimental investigation of evolving cloud-based fuzzy control of a pilot thermal exchanger under a decentralized framework, *Applied Soft Computing*, 148 (2023) 110883.
- [40] Z. Du, Y. Kao, J.H. Park, X. Zhao, Dissipativity-based event-triggered fuzzy control for unreliable networked systems via looped-functional, *Information Sciences*, 648 (2023) 119551.
- [41] M. Mahmoodabadi, N. Nejadkourki, An inverse dynamics based fuzzy adaptive state-feedback controller for a nonlinear 3DOF manipulator, *International Journal of Modelling and Simulation*, 44 (2024) 269-279.
- [42] A.A. González, M.B. Fayyad, T. Iváncsy, The effect of combining wavy and W-type collecting electrodes on the properties of electrostatic precipitators, *Journal of Electrostatics*, 123 (2023) 103818.
- [43] W. Choi, J. Han, J. Seong, H.J. Park, K. Han, W. Jung, W. Hwang, Performance of the porous media model for simulating flow through an electrostatic precipitator, *Chemical Engineering Research and Design*, 202 (2024) 147-160.
- [44] H. Fu, W. Xu, S. Li, Z. Liu, K. Yan, Convective heat transfer enhancement by corona discharge in a wire-cylinder electrostatic precipitator with the water-cooling system, *Journal of Electrostatics*, 125 (2023) 103845.
- [45] X. Pan, Z. Zhang, L. Cui, C. Ma, The distribution and movement characteristics of fine particles in an electrostatic precipitator with multi-field synergy, *Powder Technology*, 410 (2022) 117893.
- [46] Z. Li, C. Shao, Y. An, G. Xu, Energy-saving optimal control for a factual electrostatic precipitator with multiple electric-field stages based on GA, *Journal of Process Control*, 23 (2013) 1041-1051.
- [47] O. Ekin, K. Adamiak, Electric field and EHD flow in longitudinal wire-to-plate DC and DBD electrostatic precipitators: A numerical study, *Journal of Electrostatics*, 124 (2023) 103826.
- [48] P. Liu, H. Gu, Y. Kang, J. Lü, Global synchronization under PI/PD controllers in general complex networks with time-delay, *Neurocomputing*, 366 (2019) 12-22.
- [49] V. Utkin, Variable structure systems with sliding modes, *IEEE Transactions on Automatic control*, 22 (1977) 212-222.

- [50] H. Ríos, R. Franco, A.F. de Loza, A robust finite-time model reference adaptive controller for arbitrary order disturbed LTI systems, *ISA transactions*, 144 (2024) 319-329.
- [51] L.A. Zadeh, Fuzzy sets, *Information and Control*, 8 (1965) 338-353.
- [52] D. Sain, B. Mohan, Mathematical modelling of some simplest fuzzy two-term (PI/PD) controllers, *IFAC-PapersOnLine*, 55 (2022) 276-281.
- [53] A. Varshney, V. Goyal, Re-evaluation on fuzzy logic controlled system by optimizing the membership functions, *Materials Today: Proceedings*, (2023).
- [54] M. Woźniak, J. Szczotka, A. Sikora, A. Zielonka, Fuzzy logic type-2 intelligent moisture control system, *Expert Systems with Applications*, 238 (2024) 121581.
- [55] C. Chen, B. Liu, F. Song, J. Jiang, Z. Li, C. Song, J. Li, G. Jin, J. Wu, An adaptive fuzzy logic control of green tea fixation process based on image processing technology, *Biosystems Engineering*, 215 (2022) 1-20.
- [56] J.D. Franco, T.A. Ramirez-delReal, D. Villanueva, A. Gárate-García, D. Armenta-Medina, Monitoring of *Ocimum basilicum* seeds growth with image processing and fuzzy logic techniques based on Cloudino-IoT and FIWARE platforms, *Computers and Electronics in Agriculture*, 173 (2020) 105389.
- [57] C. Gupta, A. Jain, N. Joshi, Fuzzy logic in natural language processing—a closer view, *Procedia computer science*, 132 (2018) 1375-1384.
- [58] S. Cikalacandir, Y. Isler, Priority assessment of procuring medical equipment in Turkish hospitals using input-weighted fuzzy logic architecture, *Expert Systems with Applications*, 213 (2023) 119195.
- [59] W. Ding, H. Wang, J. Huang, H. Ju, Y. Geng, C.-T. Lin, W. Pedrycz, FTransCNN: Fusing Transformer and a CNN based on fuzzy logic for uncertain medical image segmentation, *Information Fusion*, 99 (2023) 101880.
- [60] Z.Y. Hamd, H.I. Almohammed, M.M. Lashin, M. Yousef, H. Aljuaid, S.M. Khawaji, N.I. Alhussain, A.H. Salami, R.A. Alsowayan, F.A. Alshaik, Artificial intelligence-based fuzzy logic systems for predicting radiation protection awareness levels among university population, *Radiation Physics and Chemistry*, 208 (2023) 110888.
- [61] J. Castro-Gutierrez, J.C. Gutiérrez-Estrada, J. Aroba, I. Pulido-Calvo, A. Peregrín, J.C. Báez, J.J. Bellido, L. Souviron-Priego, Estimation of jellyfish abundance in the south-eastern Spanish coastline by using an explainable artificial intelligence model based on fuzzy logic, *Estuarine, Coastal and Shelf Science*, 277 (2022) 108062.
- [62] L.X. Wang, *A course in fuzzy systems*. Prentice-Hall International, United States, (1999).
- [63] C. Volosencu, Properties of fuzzy systems, *WTOS*, 8 (2009) 210–228.